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Neotectonic activity in Caesarea, the Mediterranean coast of central Israel

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Abstract

Evidence for neotectonic activity along the coast of the southern Levant exists in the ancient harbor of Caesarea in central Israel, where large Herodian breakwaters are presently submerged 5–8 m below sealevel, whereas other contemporary coastal installations in the same area remain at sealevel. High-resolution seismic reflection surveys on the very shallow continental shelf encountered a series of coast-parallel faults that displace both the eolianite, which crops out along the coastal zone and the submerged breakwaters. The faults have 1–3 m of offsets, downthrowing their seaward flank and leaving their landward flank stable. We suggest that the subsidence of the ancient breakwaters was caused by neotectonic displacements on these faults and enhanced by solifluction. Records of historical earthquakes in the coastal Levant region and archaeological evidence of faulting are compatible with the geophysical findings. The neotectonic activity of the Mediterranean coast of Israel, which is a consequence of the Plio-Quaternary subsidence of the southeastern Mediterranean basin, has shaped the coast of the southern Levant even during the past 2000 years.

1. Introduction

Historical reports of neotectonic activity along the coast of the southern Levant are distinguished by numerous documents, scarce data and ambiguous interpretations. Although the region is characterized by low levels of seismic activity during the last decades, historical records suggest that numerous devastating tremors repeatedly hit the ancient coastal cities of the Levant during the past 2500 years (Källner-Amiran, 1950; Ben-Menahem et al., 1976; Poirier et al., 1980). The geomorphological evidence of these tremors, such as small linear escarpments or shallow, linear valleys, is masked by prolonged cultivation and urbanization in the region. Consequently, determination of neotectonic activity there is ambiguous and unresolved (Bartov et al., 1976). On the shallow continental shelf, on the other hand, geological evidence of the neotectonic deformation is well preserved, although the dating of submarine late Quaternary faults is commonly beyond the resolution required to correlate geological phenomena with historical events.

Ancient harbor installations provide outstanding markers for historical sealevels and neotectonic displacements in inhabited coasts during the last millennia. The Israeli coast is well suited to identify young structural deformations due to its rich historical and

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(a)

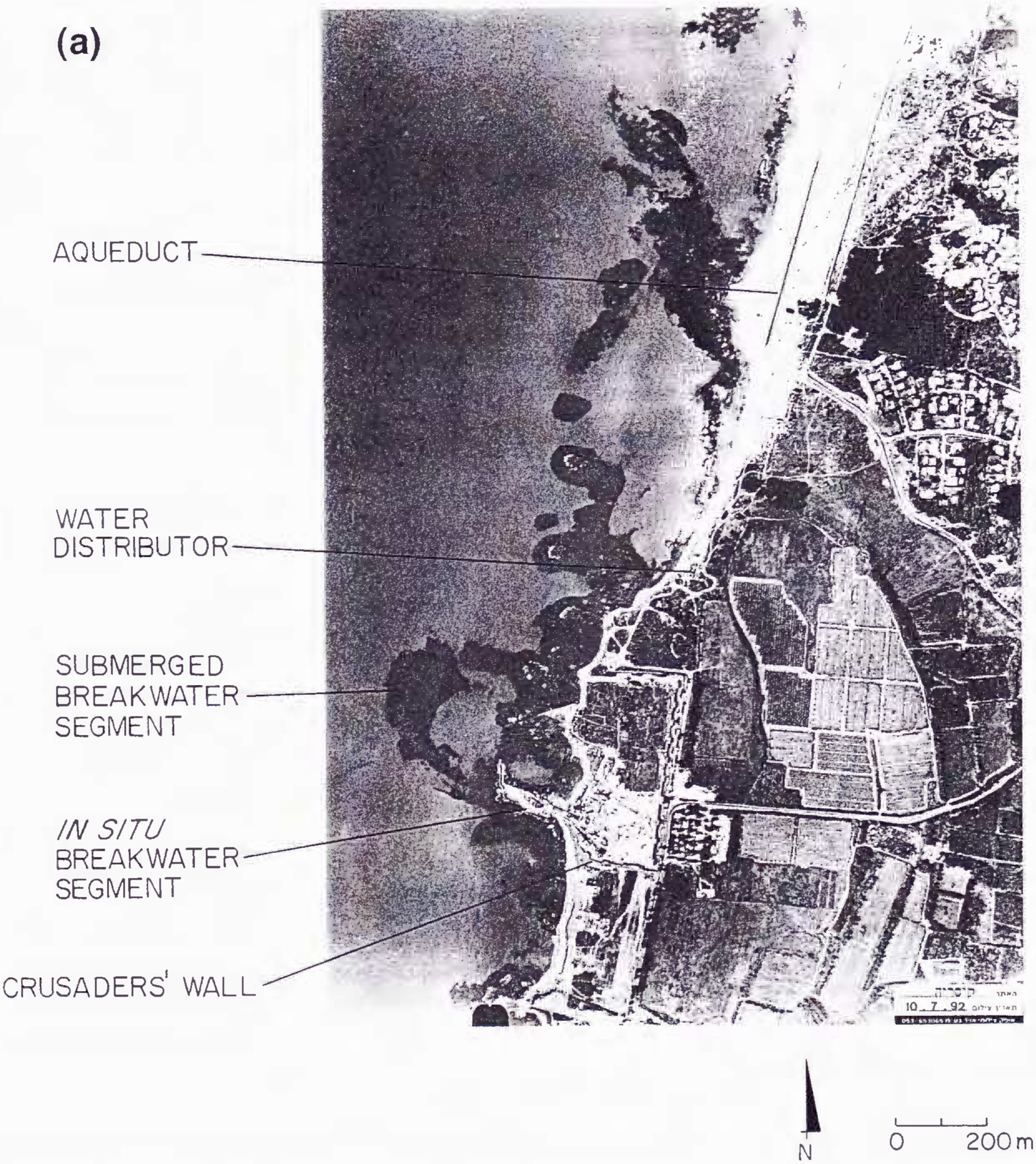

Fig. 1. (a) Aerial photograph of Caesarea and its ancient harbor. Although most of the breakwaters are submerged at present, their general layout can be readily discerned and the sections that are close to the present coastline seem to remain at their original level. Arrow shows the southern edge of the high aqueducts, where their destruction by wave erosion can be seen (courtesy Ofek Ltd.). (b) Location map, showing the general bathymetry of the continental margin of Israel, and the eolianite ridges along the continental shelf and the coastal plain.

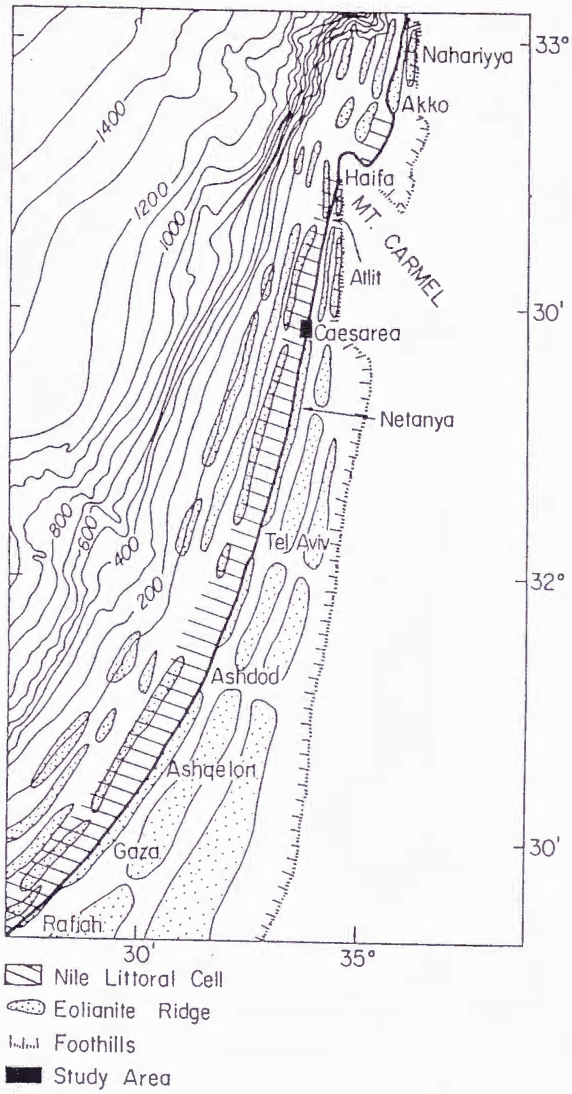

Fig. 1 (continued).

archaeological record and its small tidal range. Thus the installations around the ancient harbor of Caesarea Maritima are particularly well suited to document late Holocene neotectonic activity along the coastal zone of the southern Levant. The port of Caesarea was a large, open sea harbor that was built by King Herod the Great (37–4 B.C.) between 22 and 10 B.C. It was active during the Roman, Byzantine, Early Moslem and Crusaders periods, until it was razed in 1265 by the Sultan Baibars I (1223–1277), during the final throes of the Crusaders Kingdom. Archaeological markers of ancient sealevels, such as harbor installations or loading platforms, are abundant in Caesarea, but their value in neotectonic studies seemed to be uncertain. Some evidence indicated a similarity between the present sealevel and that of Roman times, within a precision of ± 30 cm, suggesting a period of prolonged tectonic quiescence (Mazor, 1974; Arad et al., 1978; Garfunkel et al., 1979).

Other evidence suggests 5–8 m of subsidence since post-Roman times, indicating a very high rate of tectonic deformation (Neev et al., 1973, 1976, 1978a,b; Flemming et al., 1978; Raban, 1983, 1992). The Herodian breakwaters are mostly submerged at present, except their near-shore sections, which are well exposed and are evidently at their original level (Fig. 1). The cause for the subsidence of the breakwaters offshore could be either artificial or natural. Critical structural data regarding that subsidence are best obtained in the breaker zone, in the transitional area between land and sea. Since that transition is located in water depths of less than 1.5 m, geological and geophysical data from there were difficult to acquire.

Here we report on a study of seismic reflection surveys that were collected in the shallowest part of the continental shelf off Caesarea using 3.5-kHz transducers and radio and satellite precision navigation systems. The use of a very light craft enabled data acquisition in water depths of as little as 0.5 m. The shallow water enables observation of some of the seafloor structural features. We merged our interpretation of the reflection data with the results of recent archaeological investigations to reconstruct the neotectonic deformation during the last 2000 yr.

2. Geological setting

The exposed geological sedimentary series on the coastal plain of the southern Levant are mostly calcareous sandstones and red loams of Late Pleistocene age, which are locally covered by unconsolidated sediment and cultivated soil. The predominant sandstone is eolianite, locally known as "kurkar", in which the sandy component is fine-grained quartz transported by the longshore current from the Nile

Delta. The eolianite is interbedded with extensive layers of loam — a soil composed of sand, silt, clay and organic matter, locally known as "hamra". The alternating layers of eolianite and loam underlie the entire coastal plain and the continental shelf of Israel (Avnimelech, 1962). The distribution of the eolianite is geomorphologically conspicuous because it forms a series of low ridges and shallow troughs that trend nearly parallel to the present coastline. The eolianite ridges are lithified relicts of Pleistocene coastal dunes. They are present in the coastal plain and the continental shelf of the Levant, from depths of 120 m below sealevel, to elevations of 80 m above it (Horowitz, 1979; Almagor and Hall, 1983; Nir, 1984; Eytam, 1988; Mart and Belknap, 1989). Caesarea and its harbor were built on an eolianite ridge along the present shore, but the distal sections of the breakwaters were constructed on unconsolidated sediment that fills an offshore trough adjacent to the ridge.

Numerous active faults are present along the continental margin of the southern Levant. Geophysical surveys revealed abundant evidence of faults that displace the uppermost sediments along the continental slope (Neev et al., 1976; Ben-Avraham, 1978; Mart, 1982). The faults were grouped into series of slope-perpendicular, strike-slip faults and slope-parallel normal faults, that downthrow their western, seaward flank. The strike-slip faults are correlated to the rejuvenation of Miocene faults (Mart et al., 1978), and the normal faults are associated with the subsidence of the southeastern Mediterranean basin (Mart, 1984). In spite of the abundant evidence for neotectonic activity along the continental margin, the coastal zone of the southern Levant is considered to be an area of low neotectonic activity and low seismic risk (Arie and Rabinowitz, 1989). Indeed, the region has not had a destructive tremor since its modern settlement, nearly 150 years ago, but a catastrophic earthquake occurred in the region in 1752. Furthermore, more than 2500 years of historical records indicate that the coastal plain of the southern Levant was repeatedly damaged by severe earthquakes, with an average recurrence time of about 350 years (Poirier et al., 1980). Subjective but valuable information regarding the effects of late Holocene tectonic activity can be derived from historical documents and texts. These records of catastrophic earthquakes should be scrutinized with care, because early chroniclers were biased and commonly exaggerated (Appendix A). Although most of the seismic activity in the Levant is associated with the Dead Sea rift, some historical records show that the hardest-hit communities were along the coast (Ambraseys, 1962), suggesting that some of the epicenters were in the southeastern Mediterranean Sea.

Commonly large faults leave surficial evidence of their occurrence, including small escarpments or offset features along discernible lineaments, but along the coastal plain of the southern Levant such features are difficult to assess. Bartov et al. (1976) concluded that most of the linear geomorphological features in the region were probably artifacts, and that it was virtually impossible to differentiate between man-made and neotectonic linear features. Since the region has been inhabited and cultivated for more than 10,000 years, this conclusion is hardly surprising. Structural evidence of the late Holocene tectonic activity along the coastal plain of the Levant is equivocal, in part because cultural activity modified or obscured geomorphic features. However, the proximal continental shelf is an outstanding area to look for evidence of neotectonic activity, because it is in the same tectonic domain as the coastal plain, but is less affected by anthropogenic modifications. Furthermore, archaeological evidence is present occasionally in the shallow shelf, and can provide information about the age and style of neotectonic deformation. Erosional effects of waves and sediment transport cannot be ignored in this environment, but human interference should be readily discernible.

3. Archaeological setting

Ancient harbors in the eastern Mediterranean Sea are excellent sites for measuring late Holocene land upheaval and neotectonic displacements, because the tides are less than ± 30 cm, because port installations can be archaeologically dated very accurately, and because relicts of breakwaters, docks and quays provide well-dated evidence for the contemporary sealevel. Caesarea is a remarkable site to measure neotectonic offsets due to its vast and sophisticated harbor complex. The harbor was operational almost continuously from the Herodian until the early

Byzantine period (1st to 4th century A.D.), and it was maintained and repaired repeatedly until the end of the Byzantine rule, in the 7th century. Thereafter, the harbor was used intermittently for additional 7 centuries until the end of the Crusades period. Many documents and relicts regarding the city and its harbor throughout these 13 centuries have been discovered, and the layout of the ancient construction has been deciphered by modern historians and archaeologists such as Hohlfelder and Oleson (1980), Raban (1983, 1989, 1992), Oleson et al. (1984) and Hohlfelder (1988).

Caesarea Maritima was one of the largest and most elaborate harbors of the Roman world. Taking advantage of the rocky shore, two large breakwaters were constructed, extending seaward from the coastal eolianite ridge. The breakwaters provided a safe anchorage and areas for docks and warehouses, that encompassed more than 20 hectares (ca. 50 acres). The southern breakwater extended more than 500 m to the west, then turned north for about 400 m. The enclosing arm, the northern breakwater, extended westward perpendicular to the coast for nearly 400 m (Figs. 1 and 2). Although Caesarea and its port were active intermittently for more than 12 centuries, the historical records indicate that the harbor did not maintain its nautical prominence continuously (Raban, 1992), and necessary repairs were delayed for many years (Hohlfelder, 1988). For example, it is known that the harbor was hazardous to ships in the Crusades period, and the city was served by boats that ran between the damaged port and ships that stood at anchor in the nearby open sea.

The archaeological findings at Caesarea present conflicting information, upon which the reconstruction of the coastal paleogeography between 2000 and 750 years ago can be carried out. Some evidence suggests an interval of lasting geological stability and invariable sealevel from Herodian times to the present (Mazor, 1974). For example, the large rectangular pond, or piscine, which probably served as a fish tank, that was quarried into the hard eolianite some 500 m south of the southern breakwater, could easily be made operational today because its water circulation system is located approximately at present sealevel (Fig. 3; Flinders, 1976; Raban, 1989). Similarly, a sluice channel, which was cut into the eolianite by Herodian engineers, at the base of the southern breakwater to generate currents to flush the harbor, is also at the present sealevel (Fig. 2). The findings that suggest structural and oceanographic stability are found either on land or at water depths of less than 2 m.

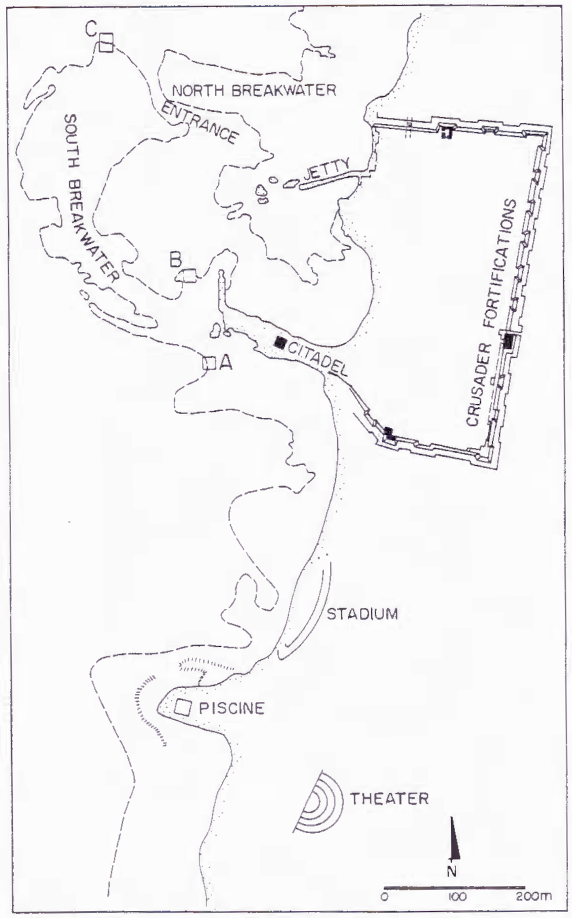

Fig. 2. General map of Caesarea and its harbor. The submerged parts are shown by dashed lines. Note the location of the sluice gate (*A*), the submerged landing platform (*B*), the eastern entrance tower (*C*), as well as the piscine and the stadium.

In contrast to the archaeological evidence on land, indicating structural invariability and similarity of sealevels between the Roman period and the present, evidence from marine archaeological excavations in the Herodian harbor of Caesarea indicate several meters of subsidence. Submerged segments of the breakwaters, such as quays and loading platforms, presently in water depths of 6–10 m, were probably constructed at shallower depths (Flemming et al.,

Fig. 3. The piscine of Caesarea is the elevation of its original sea level. This is one of the indications of neotectonic stability of the Caesarea coast since the Roman period. See Fig. 2 for location.

1978; Raban, 1983, 1992). A section of a loading platform on the southern breakwater, northwest of the citadel (Fig. 2), was discovered at depth of approximately 6 m. The citadel and the adjacent breakwater were constructed on hard eolianite, but the submerged landing platform was set on unconsolidated sediment (Raban, 1989). Its paved construction is clear evidence that it was originally a subaerial structure, and therefore its present location suggests at least 6 m of subsidence. More evidence for subsidence was found near the entrance to the harbor. There an intact segment of the original breakwater wall is preserved unbroken from its foundation, which was built on gravels placed on the seafloor, to its paved top (Fig. 2). The breakwater is approximately 3 m high, and presumably about one meter of the structure extended above the water line (Raban, 1989). At present the paved top of the breakwater is at depth of 4 m, suggesting subsidence of approximately 5 m. It is conceivable that, concurrent with the political decline of the Byzantine Empire, the Caesarea breakwaters deteriorated and were neglected for many years. Storm and earthquake damage may not have been repaired, and some of the ashlars (cut building stones) may have been removed and reused, so the collapse and apparent submergence of the breakwaters may not necessarily be conclusive evidence of geological subsidence (Hohlfelder, 1988).

4. The coastal faults of Caesarea

In order to reconcile the equivocal and apparently conflicting archaeological data, we conducted a detailed seismic reflection survey on the shallow continental shelf off Caesarea (Fig. 4), and made series of submarine observations. The survey encountered two distinct types of submarine terrains: a trough filled with unconsolidated sand is found between two ridges

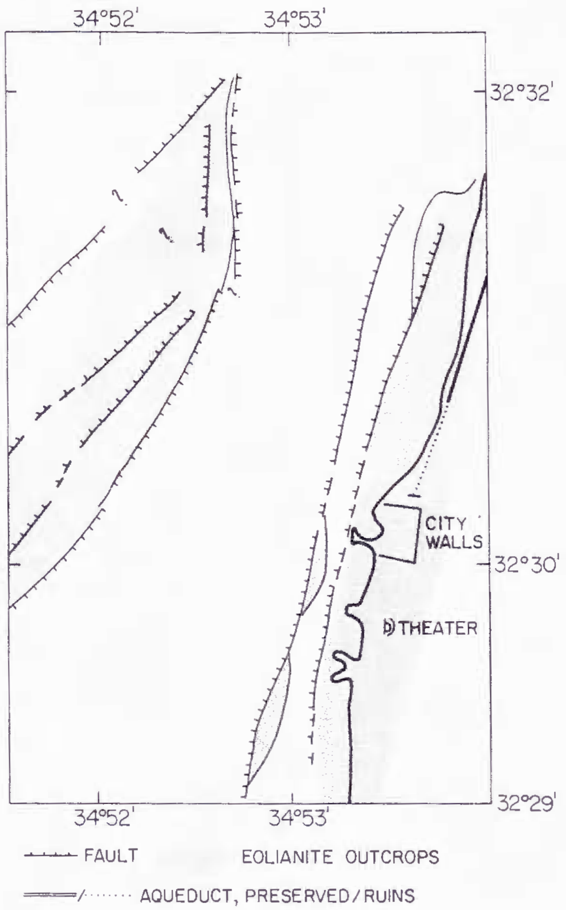

Fig. 4. Map of the offshore area of Caesarea investigated in the present survey. Aerial and marine outcrops of eolianite are gray, and the remainder of the marine area is covered by sandy unconsolidated sediment. Solid black line marks the boundary of the eolianite where it is not constrained by faults. Hatchures on the fault lines indicate the down-thrown block. The location of the southern edge of the high aqueducts along the coast is marked by a heavy line. Location of the seismic profiles shown in Fig. 5a and b is marked by the figure numbers.

of rocky outcrops of Late Pleistocene eolianite. Both the trough and the ridges are aligned in belts that trend nearly parallel to the shore. The near-shore rocky terrain, which comprises eolianite that is locally covered by beachrock and marine calcarenite, is at the present coastline, and is partly exposed and partly submerged. The distal rocky terrain is in 25–35 m of water depth (Fig. 4). The present morphology of the coastal eolianite ridge was shaped not only by nature, but by ancient quarrying and construction as well. Beachrock accumulates on many of the abraded surfaces and commonly masks the traces of anthropogenic activity. The surveys repeatedly traversed the submerged western edge of the coastal eolianite ridge, looking for structural offsets at the transition zone between the eolianite ridges and the trough. Encountered at the western edge of the coastal eolianite ridge is a system of faults trending approximately north–south, nearly parallel to the general orientation of the coastline, downthrowing the western flank of the coastal ridge (Fig. 5). The faults seem to offset the seismic reflectors by 1–3 m, and they coincide with small escarpments, also trending north–south, that truncate the coastal eolianite ridge (Fig. 5). The escarpments and the faulted offsets of the seismic reflectors are present north and south of the Herodian breakwaters, and their extrapolated extension transect the Herodian breakwaters (Fig. 6). Unfortunately large boulders that had formed the breakwaters scattered the seismic signal, so that the seismic records adjacent to the breakwaters are not coherent. Direct submarine observations of the eolianite escarpments support this interpretation (Neev et al., 1978a, 1987; Raban, 1983). Since the seismic reflection surveys uncovered the faults that extend into the area of the breakwaters, and since the faults traces are present at the boundary between the stable and submerged sections of the breakwaters, we infer that these faults have been active after the construction of the harbor of Caesarea, downthrowing the western block.

The coast-parallel faults that transect the breakwaters and cause their subsidence, are not the only faults off Caesarea. A N–S-trending fault in the trough, west of the ridge and the breakwaters, shows displacements of 4–6 m (Fig. 6). Furthermore, other faults, that transect the distal eolianite ridge, are associated with escarpments at the seafloor and offset seismic reflectors of the Late Pleistocene eolianite as well. Thus the fault that offsets the breakwaters of Caesarea is not a unique feature, but there is ample evidence for late Quaternary tectonic activity offshore Caesarea.

5. Regional neotectonic regime

The tectonic regime of the continental margin of the southern Levant has been shaped since the Early

Pliocene by the subsidence of the southeastern Mediterranean. Secondary faults, extending from the Dead Sea Rift, play a subsidiary role in the tectonic framework. Consequently the structure of the continental margin is controlled by two principal fault systems. One system, trending NNE–SSW, runs along the continental shelf and slope, and corresponds with the edge of the southeastern Mediterranean basin (Neev et al., 1976). The second fault system, WNW–ESE trending, extends across Israel and its continental margin (Mart, 1984). The tectonic effects of the basinal subsidence (Stanley, 1977) are indicated by the numerous normal faults at the continental margin, that downthrow their western, seaward flank, and cause abundant slumps (Almagor and Garfunkel, 1979). Many of the faults deform the

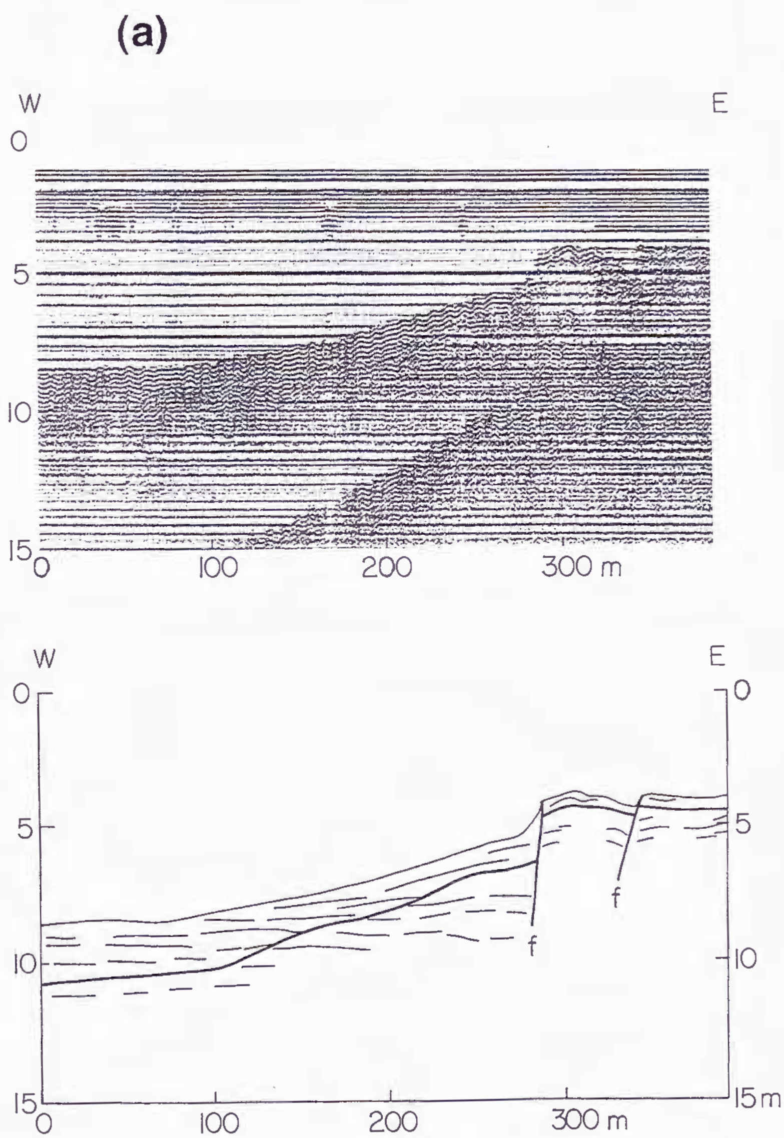

Fig. 5. Seismic reflection profiles (top) and their interpretation (bottom) across faults (f) in the shallow continental shelf at Caesarea, north of the Herodian mole (a), and south of it (b), show that the western block was downthrown by approximately 2 m. See Fig. 4 for location.

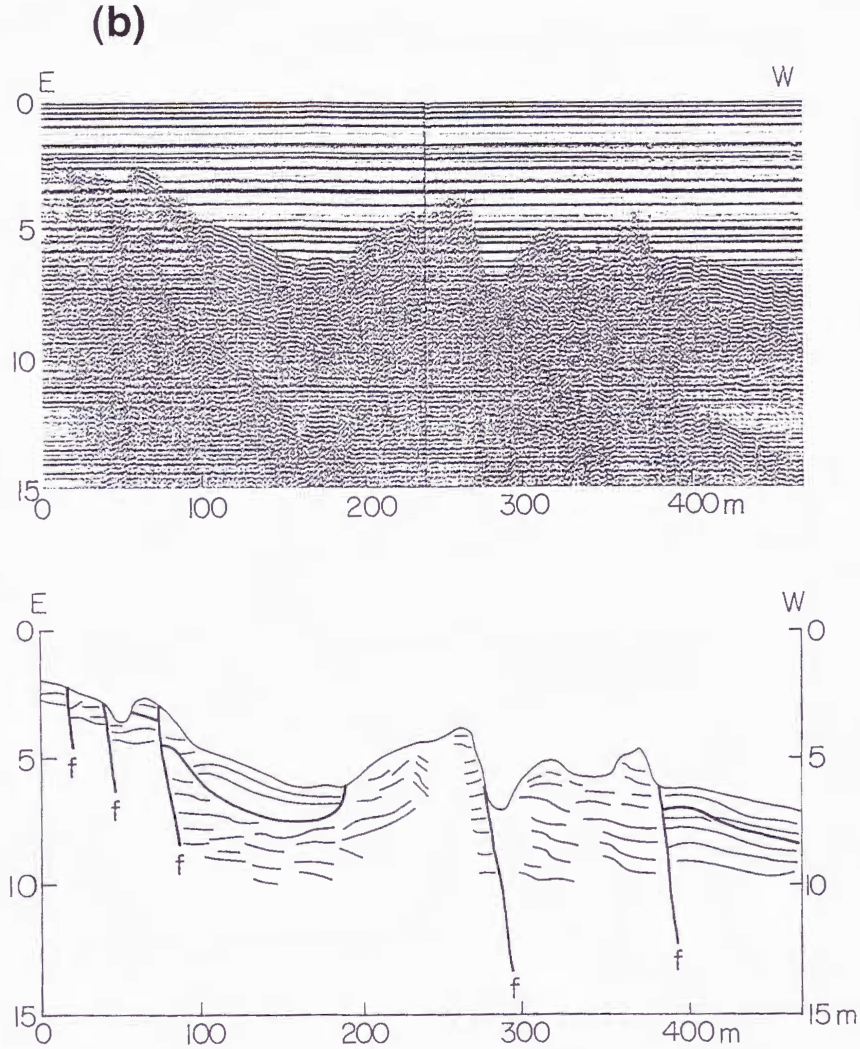

Fig. 5 (continued).

uppermost sediment at the seafloor, suggesting their young age, but the determination of that age cannot be determined more precisely than late Quaternary.

Geological and archaeological data have led to conflicting interpretations of the neotectonic regime and the reconstruction of the sealevel in the Caesarea area during the last 2000 years. Neev et al. (1973) first reported the presence of coast-parallel faults in the offshore zone near Caesarea, and subsequently Neev et al. (1978a,b, 1987) estimated a vertical displacement of 6 m across the fault that transects the Herodian breakwaters, and estimated that the cumulative neotectonic offset of the coastal faults was at least 20 m (Neev et al., 1978a). Indications for neotectonic activity in Caesarea were also reported by Raban (1983), who described evidence of 6 m down-to-the-west throw on a fault that displaces the western segments of the Herodian breakwaters. Raban (1992) argued that the breakwaters had already subsided in the 2nd century. Numerous shipwrecks on the relicts of the southern breakwater are evidence that the safe Herodian haven became a poorly protected anchorage in the late Roman and the Byzantine periods.

An opposing view argues against neotectonic activity along the southern Levant coast in historical times. Mazor (1974) and Ronen (1980) argued that the evidence for structural displacements is either misinterpreted and unreliable, or is man made and should be considered an artifact. Mazor (1974) concluded that the archaeological relicts on land, which seem to have maintained their original levels, such as the piscine or the flushing channels, are evidence that the Herodian breakwaters in Caesarea have not subsided, but that the submerged breakwaters were originally built at their present depths. Other supporters of the tectonic stability in the region argued that little variation in the groundwater level in ancient wells in the coastal plain suggests that significant tectonic offsets have not occurred there during the last 3000 years (Nir and Eldar, 1987).

We suggest that the neotectonic deformation in Caesarea in the last 2000 years is such that the coastline is also the boundary between two structural domains. The shallow continental shelf has subsided due to faulting, whereas the coastal plain remained static. Convincing evidence of the neotectonic stability of the coastal plain of Caesarea is provided by the water supply system of the city, which included a series of channels on raised aqueducts (Oleson et al., 1984). The aqueducts are approximately 7 km long, and run from a regional distribution unit at southern Mt. Carmel westwards across the coastal plain, then southwards along the coast (Fig. 7). The aqueduct system consists of two parallel and joined-together

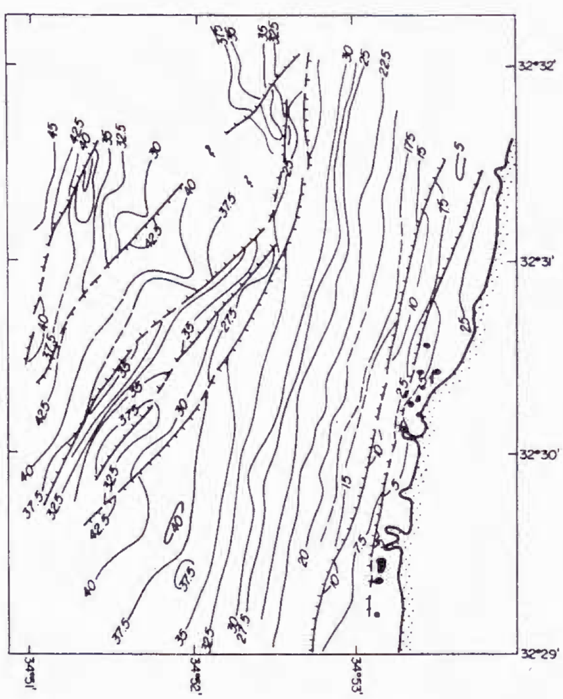

Fig. 6. Structural contour map of the top of the eolianite layer in the proximal shelf off Caesarea showing two main trends of neotectonic faults toward northeast–southwest and north–south. The N–S-trending faults are predominant close to the shore, and both systems are present in the distal eolianite outcrops.

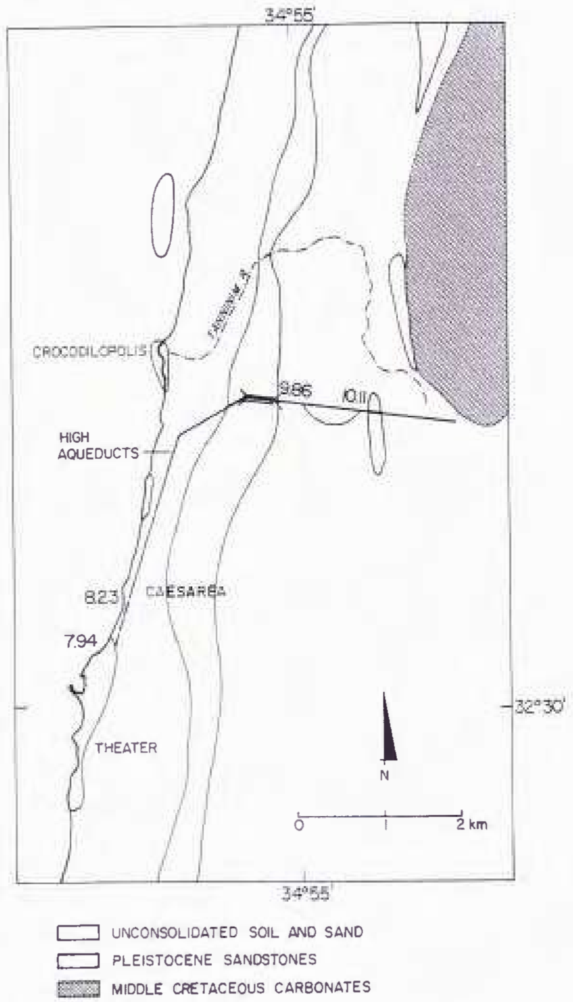

Fig. 7. Generalized geological map of the coastal plain of Caesarea and southern Mt. Carmel, and of the high aqueducts of Caesarea. Numbers along the aqueduct mark the elevation of the base of the water channel of the Herodian aqueduct.

channels, built on two series of columns and vaults. The left part of the system is dated to the Herodian period, about 10 A.D., and the right segment was built in 130–135 A.D. by the legions of the Roman emperor Hadrian. The younger aqueduct exactly matched the design of its predecessor, column for column and vault for vault, and was supported against the older structure. In spite of its age and repeated repairs, the present average gradient of the aqueduct system, from its source to the distribution system at the city walls (Fig. 7), has remained unchanged at 0.04%, the gradient recommended by Vitruvius [1]. Due to ancient repairs of the aqueducts (Porath, 1990), the precision of the altimetric measurements is not better than ± 0.25 m, and it avoided a few locations where subsidence in the marshes was discerned. The gradient measurements verified previous observations that no significant changes in the elevation of the water source or the coast have occurred in the last 2000 years (Reifenberg, 1950; Raban, 1989).

The only destroyed segment of the high-level aqueduct is located approximately 750 m north of the Herodian city, where severe wave erosion has occurred. The common explanation of this erosion is that the destruction of that 400-m-long segment occurred as a consequence of the construction of the Herodian harbor. Reifenberg (1950), Inman (1978) and Nir (1985) suggested that the large breakwaters interfered with the northward transport of littoral sand by longshore currents. The consequent depletion of sand enhanced coastal erosion north of the harbor and thus the aqueduct was damaged (Fig. 1). However, this hypothesis fails to account for the two-stage construction of the aqueduct system. Breakwaters smaller that the Herodian ones, which have been constructed in the Israeli coast in the last 35 years, led to coastal erosion within a few years of their construction (Carmel et al., 1985; Nir, 1989). Therefore, had the engineering design of the early aqueduct been inefficient, and indications of coastal erosion should have been discernible after 120 years, it seems illogical that Hadrian's engineers would have built a doomed structure.

The juxtaposition of the two aqueducts suggests that although the collapse of the high aqueduct north of Caesarea was indeed caused by coastal erosion, these erosional processes were not initiated by construction of the Herodian harbor and its breakwaters. Furthermore, the travelers El-Muqqadasi and El-Idrisi (quoted by Reifenberg, 1950) indicate that the high-level aqueduct was still functioning in the 7th century, but it was defunct in the 8th. Porath (1990) suggested that the aqueduct was operational to the time of the Arab conquest. Our measurements found out that the elevation of the water channel of the aqueduct north of the destroyed segment is 8.23 m above mean sea level, and 7.94 m to the south (Fig. 7), sloping at 0.36%. The unchanged gradient of the aqueduct across the damaged section, and the nearly intact condition of the submerged massive foundations of the aqueduct vaults there, suggest that the structure was not destroyed by a major earthquake. A plausible, though speculative, explanation is that 2000 years ago the coastal eolianite ridge was wider than at present, and thus it protected the aqueduct from coastal erosion, even though the upper parts of the ridge were probably quarried off. Only after the western section of the ridge was downfaulted could waves reach the aqueduct and erode the columns in the destroyed segment. Downfaulting of the western segment of the eolianite ridge in Caesarea that led to the coastal erosion of the aqueduct could be related to the earthquake that shook the coastal plain of the southern Levant in 672 A.D. soon after the Moslem conquest (Appendix A). This interpretation is somewhat supported by historical reports that in 1261 an earthquake caused submergence of islands between Acre and Tripoli, so that subsidence of eolianite islands in the shallow continental shelf of the Levant might have also occurred (Appendix A).

There is a discrepancy between the amount of subsidence of the breakwaters of the Herodian harbor of Caesarea and the amount of throw on the coastal faults measured in the present survey. We measured cumulative displacement of 1–3 m along the faults, compared with the subsidence of the archaeological relicts in the harbor of 4–6 m. It is possible that engineering failure in the harbor was triggered by the neotectonic offset, and supple-

[1] Marcus Vitruvius Pollio, who lived in the time of Julius Caesar and Augustus, in the 1st century B.C., authored the celebrated work *De Architectura*, an authoritative, ten volumes treatise on engineering and applied arts.

mented by the constructional load. The 1100-m-long breakwater system exerted a very heavy load on their foundations. They were approximately 12 m wide and more than 4 m high. Towers and storage facilities that were built on the breakwaters, further increased the structural load on their foundations (Raban, 1989). The foundations of the proximal part of the breakwaters were on lithified eolianite, but further seaward the breakwaters were founded on unconsolidated sand in the inter-ridge trough. Assessing the combined effects of the prolonged constructural load and the abrupt seismic shock, and in view of the differential offsets along the same fault in the harbor and adjacent areas, it seems reasonable to presume that the excessive subsidence of the breakwaters is artificial. Engineering-induced processes, such as differential compaction or solifluction (Davis, 1983), could have contributed to the amount of subsidence of the Herodian breakwaters in Caesarea. The occurrence of the recent fault plane along the contact between rock and unconsolidated sediments could raise another explanation to the observations. It could be argued that displacements in the shallow continental shelf off Caesarea are slumps, triggered by remote and poorly define earthquakes. In view of the numerous slumps along the continental slope of Israel (Almagor and Garfunkel, 1979), such an argument is valid. However, the faults off Caesarea are not restricted to the rock–sediment contact, but they commonly traverse the rocky eolianite ridges and the troughs of unconsolidated sediment. Furthermore, the orientational similarity of the faults on the continental shelf with regional faulting systems and the gentle gradient of the terrain suggests that the seismic displacement occurred along the fault planes in the studied area.

6. Conclusions

Seismic reflection profiles across the shallow continental shelf show evidence of late Quaternary tectonic activity in the coastal zone of the southern Levant, as indicated by faulting of Late Pleistocene eolianites. The present coastline in Caesarea is shaped by one of these faults. Merging geophysical data with archaeological information enables determination of offset along one of the faults, and timing of the displacement. Neotectonic downthrow of the Herodian breakwaters suggests that the coastal fault was active in the past 2000 years and that its western flank subsided. Aqueducts maintained their gentle gradient during that time indicating that the eastern flank of the coastal fault was not displaced then. Consequently flushing channels of the harbor and the present level of the piscine favor the interpretation that only the western flank of the coastal fault subsided, while its eastern flank remained firm. This pattern of displacement probably is related to the subsidence of the southeastern Mediterranean basin and its margin that generated repeated normal faulting along the continental slope of the southern Levant (Neev et al., 1976; Mart, 1984). Merging of geophysical data with archaeological observations also confirms the importance of historical records in earthquake damage on the coastal plain of Israel.

Acknowledgements

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Appendix A. Historical Levantine earthquakes with possible epicenters in the southeastern Mediterranean

Efforts to estimate the damage, casualties and magnitude of a natural disaster from surviving literary accounts should be attempted with great caution. Ancient writers commonly did not have specific data on the various catastrophes they reported, and often

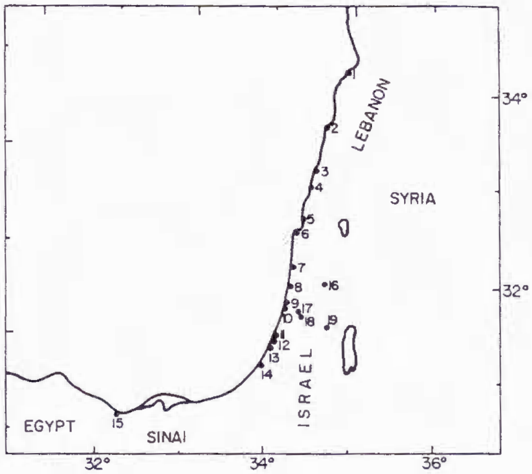

Fig. 8. General chart of the Levant and the location of some of the historically significant cities. *1* = Tripoli; *2* = Beirut; *3* = Sidon; *4* = Tyre; *5* = Acre; *6* = Haifa; *7* = Caesarea; *8* = Appolonia; *9* = Tel Aviv; *10* = Jaffa; *11* = Yavne; *12* = Ashdod; *13* = Ashqelon; *14* = Ghaza; *15* = Pelusium; *16* = Nablus; *17* = Ramle; *18* = Lydda; *19* = Jerusalem.

they used stock phrases and descriptions in their accounts to describe the events. In the absence of other information, however, such texts are useful, but should never be considered definitive, and archaeological data, when available, can provide more reliable indicators. The following list, compiled from previous catalogues (Källner-Amiran, 1950; Ambraseys, 1962; Ben-Menahem et al., 1976; Poirier et al., 1980; Russell, 1985; Seismological Bulletin, 1985; Armijo et al., 1986), indicates the tremors that might have affected the coasts of the southern Levant (Fig. 8). We restrict the catalogue to possible southeastern Mediterranean epicenters, and earthquakes that affected the Jordan Valley and the Dead Sea rift were not included. Excluded also are seismic events that affected Antioch, which, although it is not far from the Mediterranean coast of northern Syria, is located on the northern extension of the Dead Sea rift as well. The tectonic significance of damages attributed to tsunamis are even more ambiguous, because the tidal waves could have originated either along the Levant margin, or in the Anatolian or Hellenic margins. These events were marked by asterisks to indicate that ambiguity.

Years B.C.	
*590	– Destruction at Tyre. Tsunami.
*525	– Destruction at Tyre and Sidon. Tsunami.
*140–138	– Damage in Acre and Tyre. Partial subsidence of Tyre island. Tsunami(?)
*92	– Damage to coastal cities in Egypt, Israel, Syria and Cyprus by tsunamis.
*20–26	– Flooding at Pelusium. Submarine epicenter?
A.D.	
19	– Destruction at Sidon.
*115	– (December 13) Destruction of Antioch. Caesarea and Yavne hit by a tsunami.
130	– Strong earthquake in Palestine. Caesarea, Lydda and Emmaus damaged.
*306	– Destruction at Tyre and Sidon. Tsunami.
348	– Destruction of Beirut.
363	– Earthquake casualties in Ghaza, Nablus and Jerusalem, destruction of Appolonia. Associated with an earthquake along the Dead Sea rift (?).
*502	– Destruction at Acre, Tyre, Sidon and Beirut; damage from tsunami in Lebanon and northern Palestine.
*551	– (July 9) A great tsunami hit the coast from Tripoli to Caesarea. Destruction of Beirut. Sea receded for two miles.
672	– Strong earthquake in Ashqelon, Ghaza and Ramle.
*746	– (January 18) Tsunami hit the Levant coast.
*881	– Tsunami hit Acre.
*1032	– Tsunami at Ghaza and Ashqelon.
*1034	– (January 5) Acre hit by tsunami. The sea receded and returned after an hour (according to Yahia of Antioch). Destruction in Ramle.

1063 – (July) Earthquake damaged Latakie, Tripoli and Acre.

*1068 – (March 18) Tsunami hit Ashdod and Yavne on the southern coast of Israel. Sea receded and returned violently. Destruction in Ramle.

1091 – (September 17) Many towers fell from the ramparts of the coastal cities.

*1114 – Widespread tsunami damage to the coastal cities.

1127 – Destruction at Tyre.

1170 – (June 29) Disastrous earthquake damage and loss of life. Caesarea was damaged; partial collapse of the walls of Tyre.

1261 – Damages along the coast of Lebanon. Submergence of islands between Tripoli and Acre (date and exact location uncertain).

*1303 – (August 8) Damage in Egyptian, Palestinian and Syrian coastal cities. Tsunami hit Alexandria, Ghaza and Acre. Probable eastern Mediterranean source.

*1402 – Tsunami hit the Lebanese coast. Destruction at Acre and Tyre. The sea receded a mile (?) and then invaded the land.

*1496 – Tsunami at Jaffa; the sea receded for the distance "of a day's walk." Damage in Jaffa, Ramle and Ghaza, as well as Jerusalem.

1752 – Destructive earthquake along the coast of Syria and Palestine.

*1759 – (October 30) Damages in Beirut. Unconfirmed report of 2.5 m tsunami in Acre. Probable eastern Mediterranean epicenter.

*1856 – (October 12) Tsunami at Haifa, probably due to an earthquake near Crete.

1873 – (February 14) Tyre damaged.

1903 – (March 29/30) Earthquake felt in Ghaza and Jaffa.

1908 – (December 28) Earthquake in Alexandria. Probable offshore epicenter.

1940 – (January 27) Earthquake in Haifa.

1951 – (January 30) Earthquake felt throughout Israel. Epicenter probably off the coast of Tel Aviv. $M = 5.7$?

1955 – (September 12) Off coast of Alexandria. $M = 6.1$.

1957 – (July 18) Off the coast of Sidon. Felt from Jaffa to Tripoli.

1984 – (August 24) Felt in many places in northwestern Israel. Epicenter 30 km southeast of Haifa. $M = 5.1$.

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