GEOLOGICAL SOCIETY SPECIAL PUBLICATION NO. 146

Coastal Tectonics

EDITED BY

IAIN S. STEWART
Brunel University, UK

AND

CLAUDIO VITA-FINZI
University College London, UK

1998

Published by

The Geological Society

London

Ancient coastal installations and the tectonic stability of the Israeli coast in historical times

EHUD GALILI & JACOB SHARVIT

Israel Antiquities Authority, Marine Archaeology Branch, P.O. Box 180, Atlit 30350, Israel (e-mail: udi@israntique.org.il)

Abstract: Coastal archaeological structures are often used to identify coastal displacements and relative land–sea changes. Settlement of foundations and collapse of coastal stone-built structures, however, can sometimes lead to misinterpretations of sea-level changes or neotectonic activity. Coastal rock-cut installations, on the other hand, because they are cut into the bedrock, are not threatened by settlement or collapse and can serve as reliable indicators for detecting land–sea changes. A detailed survey of rock-cut installations along the Israeli coast shows that coastal pools, channels and quarries cut within the last 2500 years are today found at present-day sea level or very close to it and are still able to function. Archaeological and geological indications of major neotectonic activity along the Israeli coast during historical times were re-examined in this study, and were found to be inconsistent with the new data presented. The study concludes that the Israeli coast is relatively stable and that no significant neotectonic movement (> 0.2 m per 1000 years) has occurred during historical times.

Underwater and coastal research carried out in recent decades along the Israeli coast has revealed a vast amount of diverse data that contribute to our understanding of geological and geomorphological processes in the coastal region, as well as shedding light on the ancient navigation practices, commerce and material cultures of coastal communities. Despite this, major disagreements have emerged as to the extent of the neotectonic contribution to recent coastal changes. Relying on archaeological evidence, this study will re-examine the issue of the tectonic stability of the Israeli coast during historical periods.

Scholars have argued that destruction of ancient harbours and coastal installations in Israel is associated with neotectonic activity that occurred in historical times (Raban 1976, 1981, 1985; Neev *et al.* 1978, 1987; Adler 1986; Neev & Emery 1991). This was based mainly on archaeological structures found today at elevations that prevent proper functioning, and on geological and geomorphological studies. However, ancient coastal structures may be displaced from their original elevation relative to sea level by various mechanisms, such as sea-level changes, tectonic activity, erosion and collapse, and settlement of foundations in unconsolidated sediments (Fig. 1). Various combinations of these mechanisms are also possible. In using archaeological records to re-assess the tectonic stability of the coast, this study has tried to disregard equivocal evidence, and instead uses only reliable data that allow the contribution of tectonics to be isolated from the impact of erosion, settlement and eustatic change.

Stone-built coastal structures, as distinct from rock-cut ones, are constantly weathered, eroded, and undermined, and are often displaced from their original elevation by waves and tidal currents. Also, many of the stone-built structures were originally constructed on the sea bottom in antiquity and, therefore, cannot serve as reliable markers for vertical coastal displacement. Coastal rock-cut installations, in contrast, are better indicators of the tectonic contribution to relative sea-level changes. This is because (a) they are cut into the bedrock and, therefore, are not threatened by settlement or collapse, and (b) although there are difficulties in dating the rock-cut installations (Blackman 1973), most scholars agree that the majority of them along the Israeli coast were hewn between 500 BC and AD 1300. It is also widely agreed that in the last 2500 years there were no significant eustatic sea-level changes in the Mediterranean (Flemming *et al.* 1978).

Many rock-cut installations have been discovered along the Mediterranean coasts (Blackman 1973). Figure 2 illustrates the main types of these installations along the Israeli coast and their association with sea level. Their use in identifying neotectonic activity can be relatively reliable if one is aware of the limitations of relying on these indicators alone. In particular, it is worth noting that the functions of many rock-cut installations are not yet clear. Also, rock-cut pools, channels or quarries located above present-day sea level do not necessarily indicate vertical coastal displacement, because many of them could have functioned a few metres above sea level. Pools at elevations of up to 2.5 m above sea level, for

GALILI, E. & SHARVIT, J. 1998. Ancient coastal installations and the tectonic stability of the Israeli coast in historical times. *In*: STEWART, I. S. & VITA-FINZI, C. (eds) *Coastal Tectonics*. Geological Society, London, Special Publications, **146**, 147–163.

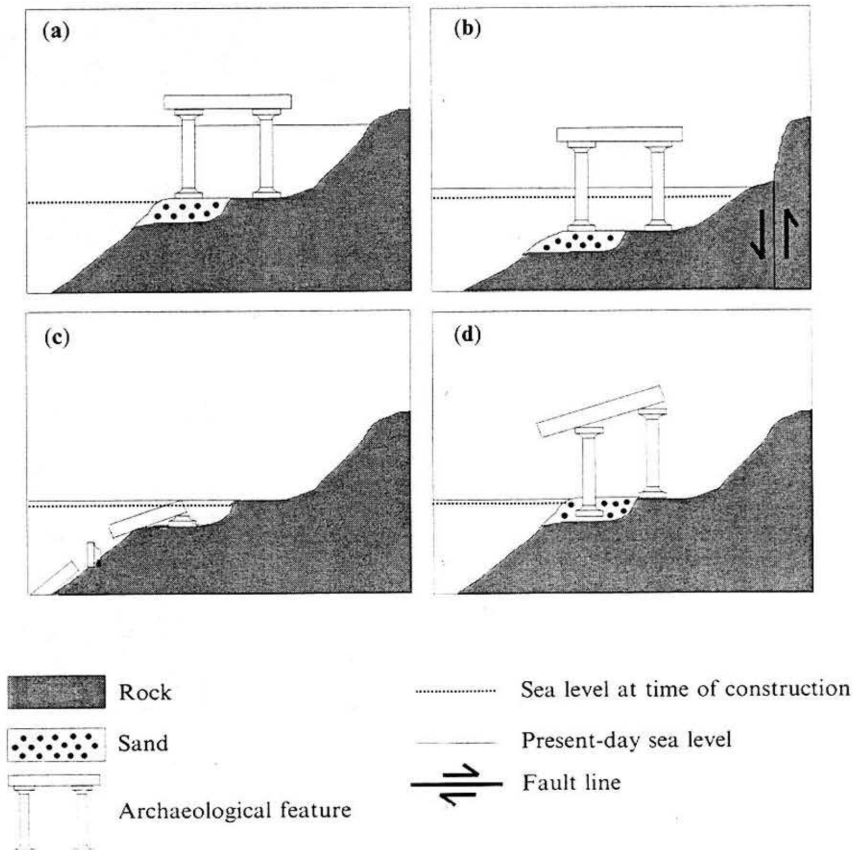

Fig. 1. Main types of coastal changes affecting man-made structures: (**a**) sea-level changes; (**b**) tectonic activity; (**c**) erosion and collapse; (**d**) settlement of foundations in unconsolidated sediments.

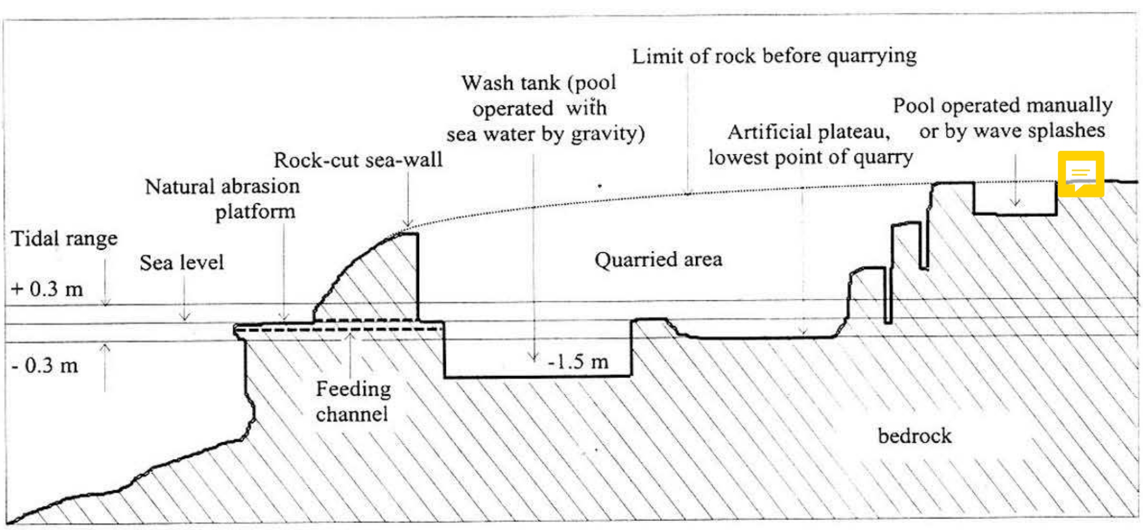

Fig. 2. Schematic cross-section depicting the main types of rock-cut installations along Israel's Mediterranean coast and their typical relation to sea level.

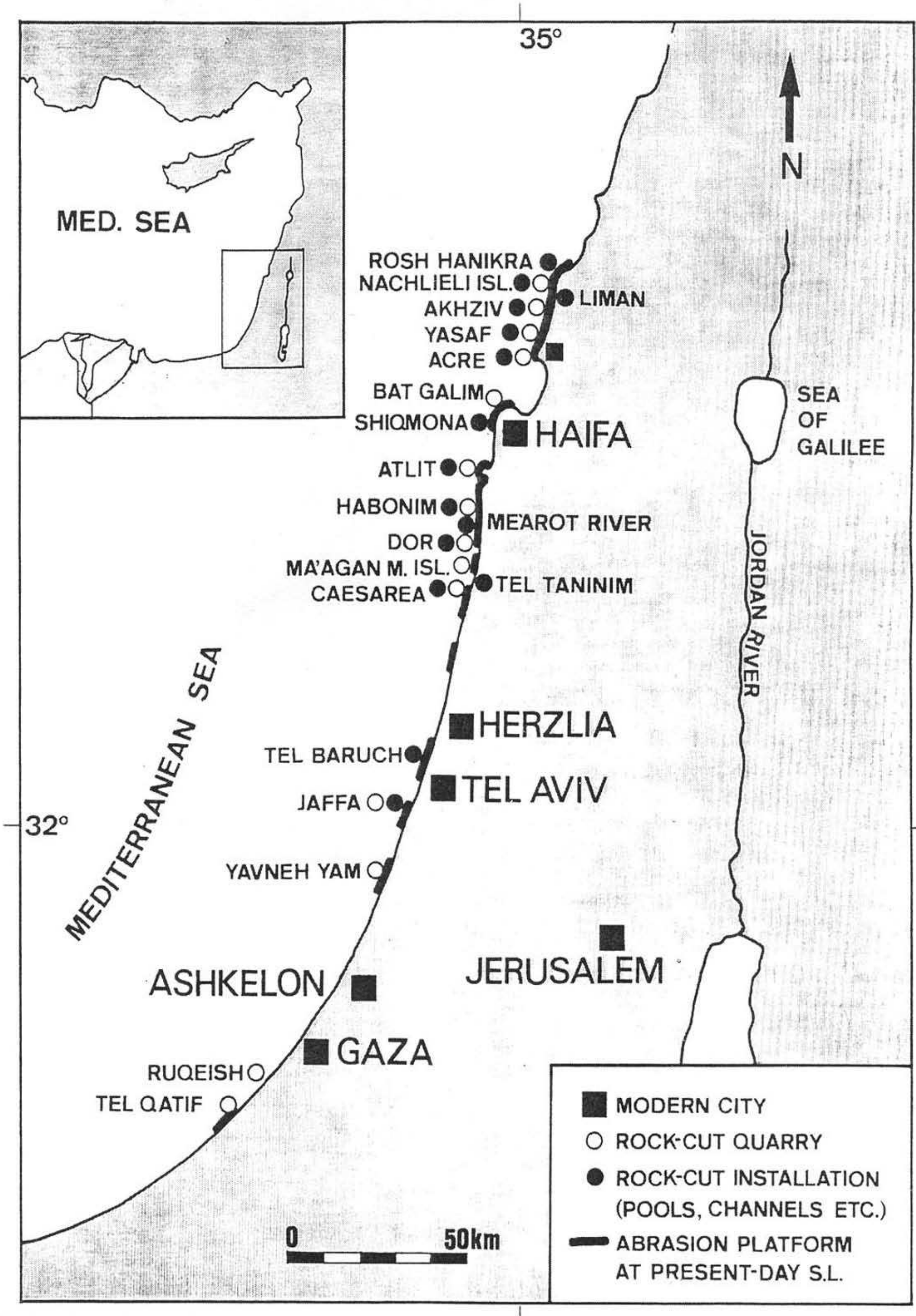

Fig. 3. Map of the study area showing the location of sea-level markers (rock-cut installations, abrasion platforms) discussed in the paper.

example, can be fed naturally by wave splash, and can be manually maintained at even higher elevations. Coastal pools that operated with seawater through gravity (wash tanks) and still function today, however, are good indicators of stable tectonic conditions. Many of the pools situated along the Israeli coast (e.g. Akhziv, Yasaf River, Shiqmona, Caesarea, Fig. 3) have retained their functioning conditions: the floors of the pools lie about 1.5 m below present-day sea level, their upper rims are very close to present-day sea level, and their feeder channels still supply seawater.

Rock-cut seawalls (commonly called wave traps) were left behind by ancient quarrymen to protect the working area from water penetration and wave splash (Fig. 2). The rock was cut at sea level and the seaward edge was left at its original height, forming a seawall. These rock-cut seawalls can thus be good indicators for sea level or tectonic movements, if significant differences in elevations are observed. Within the quarries, building stones were excavated down to the lowest level that economically justified the invested effort. Theoretically, building stones could also have been quarried as deep as 1.5 m below sea level (employing techniques similar to those used in excavation of the coastal pools). However, it seems reasonable to assume that the ancient quarrymen cut the stones as far down as sea level, rarely to a level slightly lower than low tide, and certainly no lower than 0.5 m below sea level. Excavation of stones deeper than 0.5 m below sea level probably required a greater investment that did not justify the effort. Thus, a quarry or any other rock-cut installation that is today submerged at a considerable depth that prevents functioning can be used as a reliable indicator for vertical coastal subsidence.

Rock-cut installations along the Israeli coast

Having taken into account the limitations and reliability of some of the archaeological evidence, and after clarifying the main principles of using rock-cut installations as shoreline markers, we now present an overview of rock-cut installations found along the Israeli coast, discussed from north to south (Fig. 3).

Western Galilee

The coastal *kurkar* (aeolian calcareous sandstone) ridge and offshore islands in western Galilee underwent extensive quarrying for building stones in antiquity. Large areas were levelled, leaving behind wide rock-cut abrasion platforms. In some cases, a rock-cut seawall was left in the western side of the quarries for protection from waves. In some of the quarries, secondary rock cuttings were made to create pools for various purposes. The quarries and rock-cut installations were described in detail by various scholars (Flemming *et al.* 1978; Raban 1986*a*; Spier 1993). To exploit the quarry efficiently, the kurkar and beachrock were usually excavated to sea level at the time of functioning or slightly lower. Today, the lowest levels in the quarries are in most cases located at sea level, or very close to it, and rarely 0.3–0.5 m below sea level. Rock-cut pools were reported from Nahlieli Island (33°4′20″N, 35°4′50″E), the Liman coast (33°3′26″N, 35°6′24″E), Akhziv (33°2′58″N, 35°5′58″E), Akhziv south, Yasaf River (32°57′30″N, 35°4′30″E) (Spier 1993), and also on Segavion Island located about 1500 m off the Akhziv coast (33°2′30″N, 35°4′5″E). In all cases, the elevations of the pools are close to present-day sea level and in some cases the floors of the pools are lower than sea level, to allow water penetration by gravity. At Akhziv, for example, 50 m northwest of the ancient *tell* (a local term for a large, artificial mound resulting from settled ancient site), a trapezoid-shaped pool (20 m long, 12 m wide and 0.9 m deep) with subdivisions (Raban 1986*a*) still functions today, and two rock-cut channels lying at present-day sea level continue to supply it with seawater. Elsewhere, some pools located at elevations of up to 1 m above present-day sea level were probably fed by seawater manually or by wave splash.

Acre

Demand for building stones resulted in an almost total destruction of the available exposed kurkar ridge in the vicinity of ancient Acre (32°56′10″N, 35°4′20″E to 32°55′10″N, 35°3′45″E). In particular, almost all of the kurkar coastal exposures from the western shores of the ancient city to the Yasaf River (a few kilometres to the north) were extensively quarried. A levelled platform (5–100 m wide) was thus formed and lies today at sea level (A in Fig. 4). In places, a rock-cut raised seawall on the seaward edge of the quarry prevented water from penetrating into the working area (C in Fig. 4). Rock-cut pools of various sizes and shapes are found on the hewn sandstone platform near the ancient city walls and west of the modern city. The foundations of the Crusader city walls were laid on top of the platform (B in Fig. 4, Fig. 5). All the rock-cut quarries, pools and city-wall foundations are located at modern sea level or very close to it. In a few places, the floors of the pools and the lower surfaces of the quarries lie 0.3–0.7 m below present-day sea level.

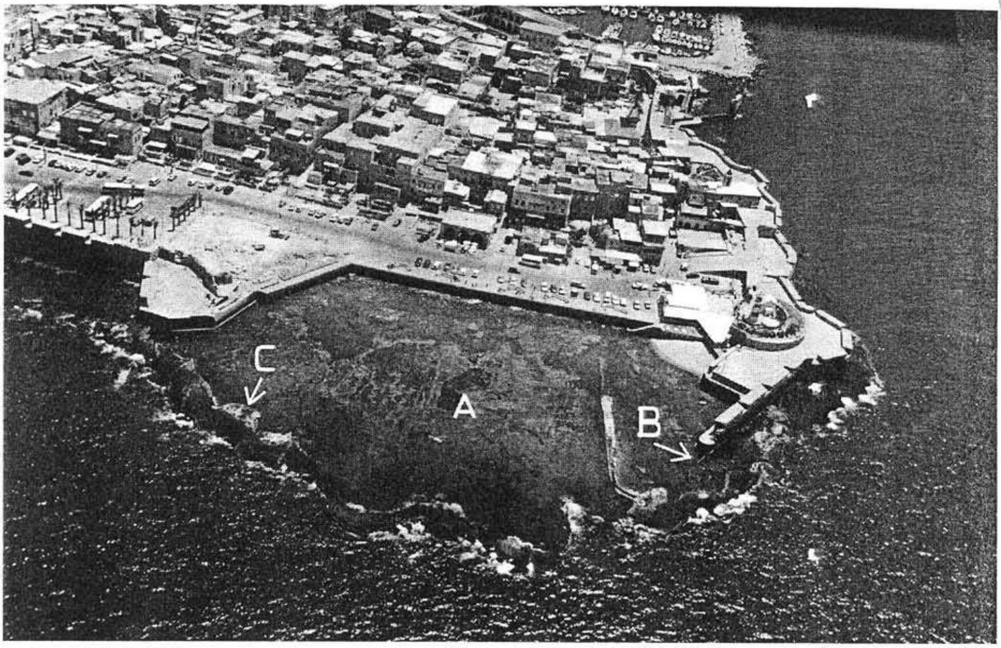

Fig. 4. Aerial view of Acre showing (A) the levelled platform of the ancient kurkar quarry, (B) the Crusader city wall's foundations, and (C) a rock-cut seawall. All the archaeological rock-cut installations are today found at elevations that allow them to function.

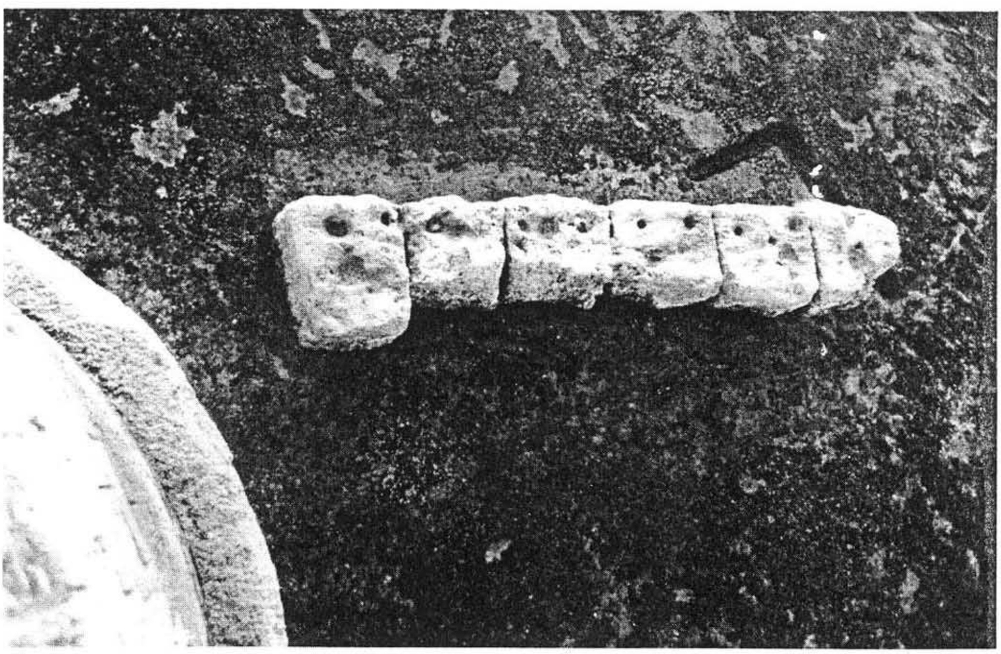

Fig. 5. Detailed view of city wall at Acre.

Bat Galim

In a few places along the 600 m long stretch of beach at Bat Galim (32°5′5″N, 34°58′37″E), extending from the promenade in the south-west to the municipal beach in the northeast, limestone quarries are found at present-day sea level. In some places the excavations reach as far as 0.3 m below present-day sea level (Flemming *et al.* 1978).

Shiqmona–Haifa

About 80 m west of the Shiqmona tell (32°50′ 7″N, 34°57′5″E), a round pool, 4.5 m in diameter (Fig. 6) is cut into the limestone abrasion platform (Spier 1993). The two channels that convey seawater by gravity into the pool still function today. The bottom of the pool is about 1.5 m below present-day sea level and its upper rim is at the elevation of the abrasion platform. Traces of purple dye found at Shiqmona were reported by Elgavish (1994) and Karmon & Spanier (1988). Hence, the pool may have been used in the Roman–Byzantine periods for storing live *Murex* shells for the manufacture of purple dye.

Atlit

At Atlit (32°42′20″N, 34°55′50″E), foundations of the Crusader city walls that were constructed on the levelled kurkar rock are found close to modern sea level (Flemming *et al.* 1978; Ronen & Olami 1978). The western quay of the Phoenician harbour is at present-day sea level, as are sections of the northern breakwater (Flemming *et al.* 1978; Ronen & Olami 1978 (sites 80/4 and 80/6), Raban 1985). In the western section of the Atlit peninsula, pre-Crusader rock-cut pools and quarries were reported (Ronen & Olami 1978 (site 82)). The elevations of these installations are slightly (0.5–0.8 m) higher than present-day sea level. About 1 km southwest of the Crusader fortress, on Melah Island (32°42′N, 34°55′40″E), channels, rock-cuttings and pools are found (Ronen & Olami 1978 (site 99)). Eight hundred metres south of Melah Island, rock cuttings and channels are also found (Ronen & Olami 1978 (site 100)).

Me'arot River outlet

Two parallel channels (*c.* 30 m long, 0.6 m wide, 0.6 m deep) trending east–west are found on the northern side of a kurkar peninsula at the Me'arot River outlet (32°40′10″N, 34°54′45″E). A few metres north of the channels, a row of square-shaped rock-cut depressions (*c.* 0.4 m × 0.4 m × 0.3 m) are aligned parallel to the channels. The seaward outlets of the channels are located 0.2–0.3 m above present-day sea level and during storms they still supply seawater to the backshore (Galili & Sharvit 1994). In antiquity, therefore, they may have been used for salt production.

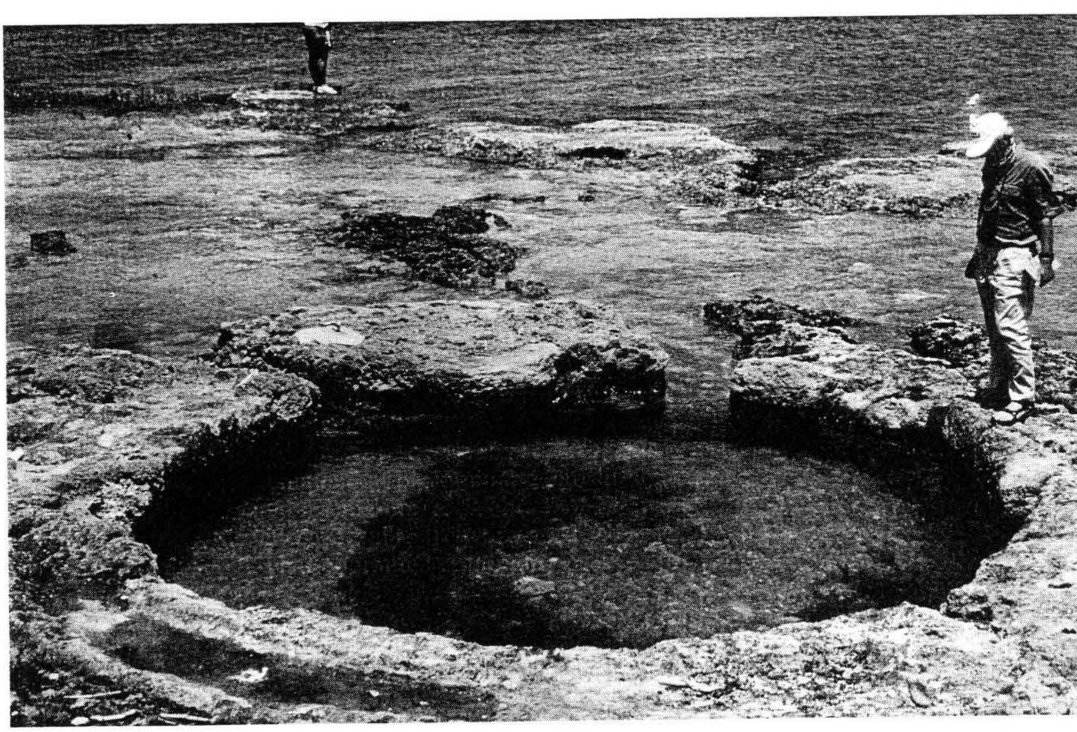

Fig. 6. An ancient rock-cut *Murex* shell piscina at Shiqmona-Haifa, located at an appropriate elevation for modern functioning.

Habonim

Two small (*c.* 1.5 m × 2.5 m × 0.2 m) rectangular pools are cut into an abrasion platform north of Habonim (32°38′50″N, 34°55′15″E). The elevation of the upper parts of the pools lies at present-day sea level, and their floors lie at 0.2 m below sea level. Two rock-cut channels (*c.* 25 m × 0.4 m × 0.3 m), whose function is unclear, occur at an elevation of 0.5–1.8 m above present-day sea level.

The coastal kurkar ridge at Habonim was extensively quarried in antiquity for building stones and a quarry extends a few hundred metres along the coast (32°N, 34°55′15″E to 32°37′40″N, 34°55′15″E). Some of the huge stones (2 m × 1 m × 1 m) are still *in situ*. The elevations of the quarried areas range from 3 m above present-day sea level to the present-day sea level. In some places inside the quarries, pools of various shapes and sizes are observed at elevations of 0.5–2.5 m above present-day sea level; these pools are still fed by wave splash.

Dor

The site of Dor has been surveyed by various scholars, and the coastal archaeology and geology has been described in detail (Flemming *et al.* 1978; Sneh 1981; Sneh & Klein 1984; Raban & Galili 1985; Spier 1993). Along a 1800 m long stretch of coast (32°37′20″N, 34°54′55″E to 32°36′20″N, 34°50′45″E), located to the south, west and north of the ancient tell, many rock-cut installations and quarries are found. The installations consist of pools, channels and seawalls. In most cases, the installations lie at or above present-day sea level. The floors of a few pools and channels lie 0.1–1.5 m below present-day sea level (Sneh 1981).

Yonim Island

On Yonim Island, offshore of Ma'agan Michael (32°33′12″N, 34°54′6″E), there are rock-cuttings (quarries?) and two rock-cut pools (5 m × 3 m × 0.25 m and 7 m × 6 m × 0.6 m). The floors of the pools are *c.* 1 m above present-day sea level (Spier 1993). According to Flemming *et al.* (1978), the rock cuttings similarly correlate relatively well with present-day sea level.

Tel Taninim

On abrasion platforms west of the archaeological site of Tel Taninim (32°32′20″N, 35°54′6″E), and on the southern bank of Taninim River north of the tell, a few rock-cut pools are found (Spier 1993). All of the pools are located at elevations close to present-day sea level.

Caesarea

On an abrasion platform west of the Roman theatre at Caesarea (32°29′50″N, 34°53′15″E), lies an entire complex of pools and channels (Flinder 1976, 1985; Flemming *et al.* 1978). A large (35 m × 17 m × 1.5 m), rectangular rock-cut pool (Fig. 7), believed to be a piscina (Flinder 1976), and associated smaller pools and channels, are found today at present-day sea level or very close to it. The large pool and the channels that supply seawater to it by gravity still function today.

To the south of Caesarea (32°29′35″N, 34°53′10″E), on an abrasion platform nicknamed 'the horseshoe rock', two rock-cut pools (5.5 m × 9 m × 0.3 m and 6.2 m × 3.7 m × 1 m) are found (Spier 1993). The upper parts of the pools lie at present-day sea level.

Tel Baruch

At Tel Baruch (32°6′55″N, 34°46′4″E), two rock-cut pools (2 m × 3 m × 0.5 m) are found at elevations *c.* 0.5 m above present-day sea level (Spier 1993).

Jaffa south

Quarries of kurkar for building stones are found on a abrasion platform south of Jaffa (32°1′50″N, 34°44′30″E) at present-day sea level. Small pools (1 m × 2 m × 0.3 m) are located inside the quarries.

Yavneh Yam

At Yavneh Yam (31°55′40″N, 34°41′50″E (Fig. 8), kurkar quarries are situated on the coastline at, and up to 0.5 m above, present-day sea level. Small (1 m × 0.7 m × 0.2 m), rock-cut pools within the quarries also lie at present-day sea level.

Ruqeish

A beachrock quarry at Ruqeish (31°25′N, 34°20″E) is situated at present-day sea level (Oren 1992).

Tel Qatifa

At Tel Qatifa (31°24′N, 34°18′E), a beachrock quarry is located at present-day sea level (E. Oren, pers. comm.).

Fig. 7. A Roman rock-cut pool at Caesarea situated at an elevation suitable for use at present-day sea level.

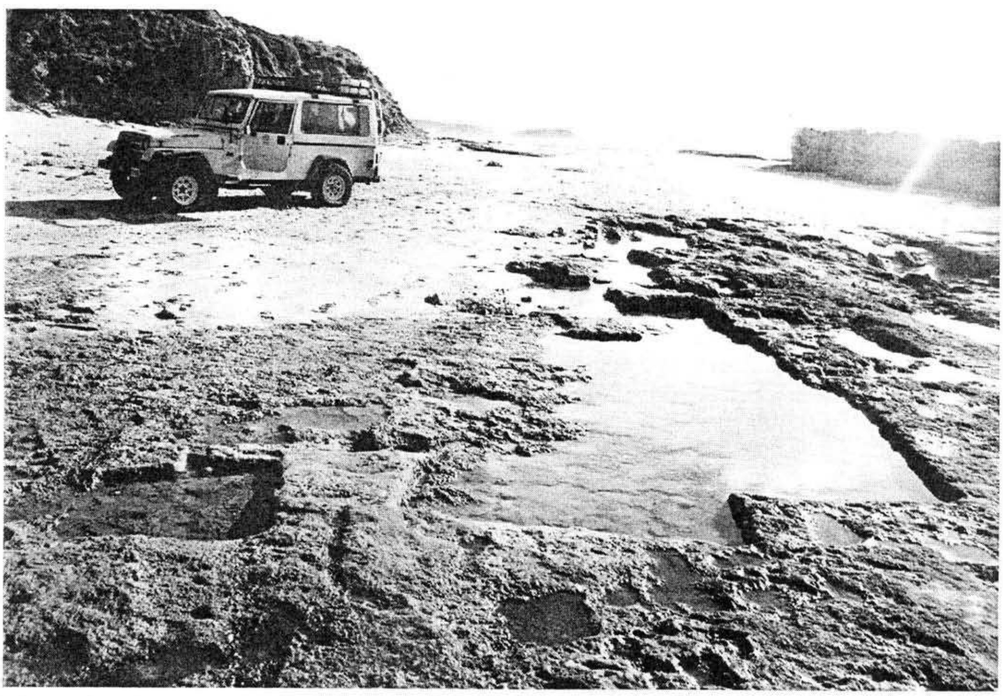

Fig. 8. An ancient kurkar quarry at Yavneh-Yam, located at present-day sea level.

Observations from other parts of the southeastern and eastern Mediterranean coasts

Coastal rock-cut quarries and seawalls situated close to present-day sea level were reported by Frost (1973) at Sidon (Lebanon) and Arwad (Syria). Rock-cut plateaux (probably quarries) lying at present-day sea level and slightly lower (−0.2 m) were observed by the present authors at Alexandria (Egypt) (31°13.1′N, 29°55.5′E). However, a comprehensive underwater and coastal study is needed in these regions before any conclusions concerning neotectonic activity can be reached.

Summary

This review of rock-cut installations along the Israeli coast shows that ancient pools and channels, originally operated by gravity with seawater, are still found today at elevations suitable for operation. The lowest parts of coastal quarries and rock-cut seawalls in the study area are found at sea level, or very close to it. No rock-cut installation (quarry, pool, seawall, or channel) has been found in the study area submerged at a depth that prevents its functioning. Although the floors of some pools and channels are slightly below present-day sea level or below the tide limit, such an elevation is needed for proper functioning of the installations and does not indicate tectonic subsidence.

Because no submerged rock-cut installations have been found on the sea bottom in Israel, we should consider the possibility that such installations have been eroded and, therefore, have disappeared. From our observations, however, it is evident that preservation of archaeological sites on the shallow continental shelf and foreshore zone along the Mediterranean coast of Israel is generally very good. Although high-energy coastal erosion processes are active in the foreshore region, thick sand deposits, originating from the Nile delta, appear to have covered the sites for thousands of years and thereby protected them from marine erosion and destruction by marine organisms. However, sand quarrying along the coast, the construction of the Aswan High Dam and the development of other marine projects (ports, marinas, etc.) have all artificially reduced the availability of sands. As a result, bedrock is being exposed on the sea-bottom and in the foreshore for the first time in thousands of years, and many archaeological sites are being discovered in a perfect state of preservation.

Given these circumstances, if significant vertical neotectonic movements had occurred in the last 2500 years (as previous studies have suggested), we might expect to find some of the rock-cut installations well preserved on the sea floor, yet this is not the case. Instead, it seems that the ancient rock-cut installations more or less coincide with present-day sea level. This is also evident from other coastal installations that appear to have retained their original elevation with respect to sea level, and have not settled, eroded or collapsed.

Other coastal indicators along the Israeli coast

Coastal wells

The Pleistocene aquifer of Israel's coastal plain drains westward from adjacent foothills to the Mediterranean, which controls its level in a steady-state condition of flow (Galili & Nir 1993). The initial groundwater table slope is in the order of 1:1000 (Kafri & Arad 1978). The water level within the coastal wells, therefore, is close to sea level, or is slightly higher. Because the water table is tilting seaward at a gradient of 1:1000, the further inland a well is located, the higher the water level is within it (*c.* 0.1 m elevation for every 100 m distance). Assuming that, in antiquity, the water table in the coastal region was also slightly above sea level (though by how much would depend on the distance of a well from the ancient coastline), it is possible to reconstruct former sea levels by studying the ancient wells. Recent studies of ancient coastal wells along the Israeli coast (Nir & Eldar 1986; Nir 1997; Tuweg 1997; S. Eliezer pers. comm.) have shown that there has been no significant neotectonic activity in the coastal zone during historical time. Instead, all vertical variations of water levels recorded in the coastal wells are within the range of global eustatic fluctuations.

Coastal stone-built structures

In spite of the potential for erosion and collapse along the Israeli coast, many stone-built coastal structures have retained their position relative to sea level, and could still function today. Examples include: the protective Crusader (eleventh–twelfth century AD) seaward city wall at Ashkelon (Mazor 1974); the foundations of Moslem (thirteenth century AD) fortifications at Herzlia–Appolonia (Mazor 1974); the high aqueduct and the Roman quay on the southern breakwater at Caesarea (Olami & Peleg 1977; Raban 1981, 1984); the northern breakwater and western quay of the Phoenician (third–sixth century AD) harbour and the foundations of Crusader city walls at Atlit's north bay (Flemming *et al.* 1978; Ronen & Olami 1978; Raban 1984, 1985); and the foundations of the Crusader city walls (B in Figs 4 and 5), the Roman southern breakwater and head of the eastern Moslem (ninth–tenth century AD) breakwater ('Tower of Flies') (Fig. 9) at Acre (Flemming *et al.* 1978; Raban 1985). At Acre, stone-built structures (as distinct from rock-cut ones) that

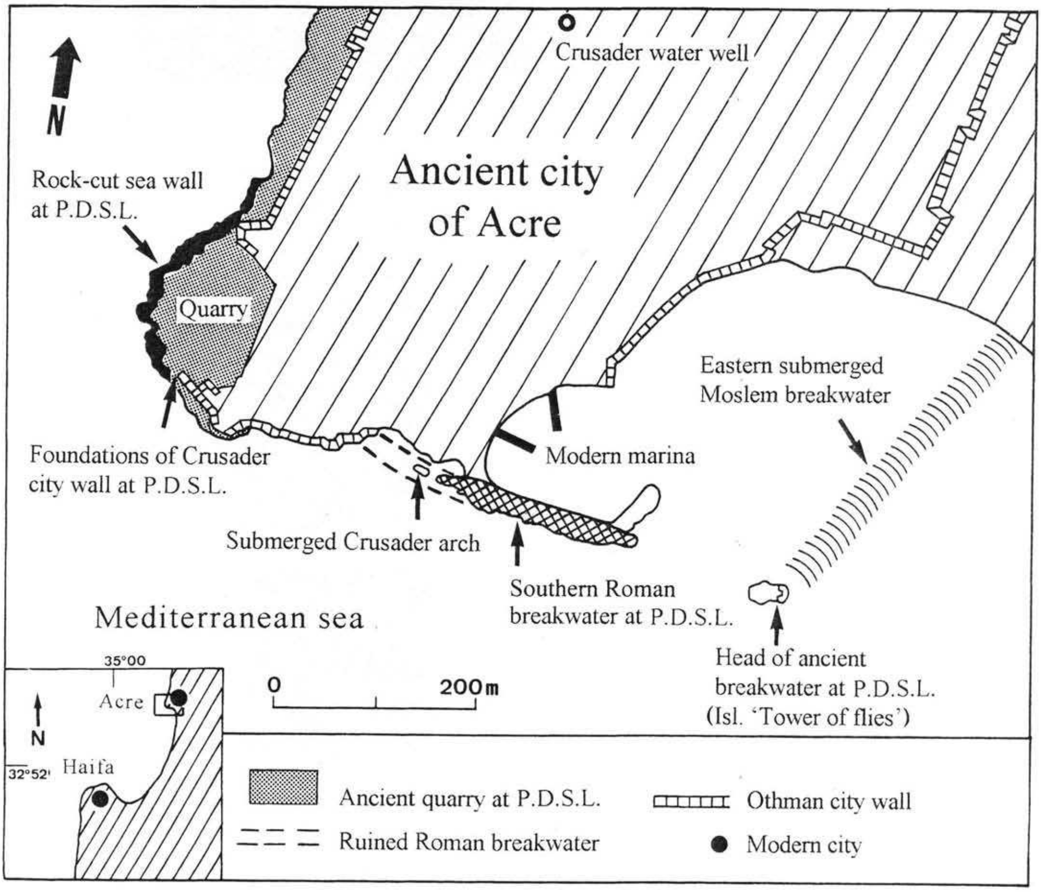

Fig. 9. Map of the Acre peninsula showing the location of archaeological features that have retained their elevation relative to sea level and those that underwent settlement. P.D.S.L., present-day sea level.

did not retain their original elevations are usually those that were constructed on unconsolidated sediments and later underwent settlement and erosion.

Geomorphological markers

A survey of geomorphological features cut into bedrock (notches and abrasion platforms) in the study area (Fig. 3) reveals no evidence of submerged or emerged rock-cut notches (see Flemming *et al.* 1978). In contrast, numerous well-developed notches are found at present-day sea level, and similarly, all observed abrasion platforms in the study area coincide remarkably well with present-day sea level (see Lipkin & Safriel 1971). These data suggest relatively stable sea-level conditions in the last few thousand years (see Flemming *et al.* 1978) and indicate that the study area is tectonically stable.

Discussion

In this section, we re-examine the geological and archaeological basis of previous indications of neotectonic activity at key sites within the study area and discuss possible alternative interpretations based on the results of our observations presented above.

Caesarea

Previous scholars have identified several archaeological indications of neotectonic activity. In particular, ruins of the western section of the Herodian-Roman (first century BC–first century AD) harbour are found submerged at a depth of 5–6 m below sea level (Raban 1981), though most of the ancient harbour constructions that were built on top of the kurkar ridge, have maintained their original elevation (Raban 1976, 1981). Roman shipwrecks from the second century AD are found on top of the submerged Herodian breakwater, indicating that it was already ruined some 200 years after its construction (Raban 1976). In addition to the submerged portion of the harbour, a platform made of hewn stones was also found at a depth of 5 m below sea level (Raban 1976).

West of the modern harbour, offshore sub-bottom sounding profiles revealed a stair-like feature on the sea floor (Neev *et al.* 1973; Mart 1996*b*). Several boreholes in and around the harbour (Fig. 10) reveal a kurkar horizon that appears to be at a different elevations off the coast and on land (Neev *et al.* 1973). Both these geological observations have long been interpreted to indicate that a post-Roman neotectonic fault,

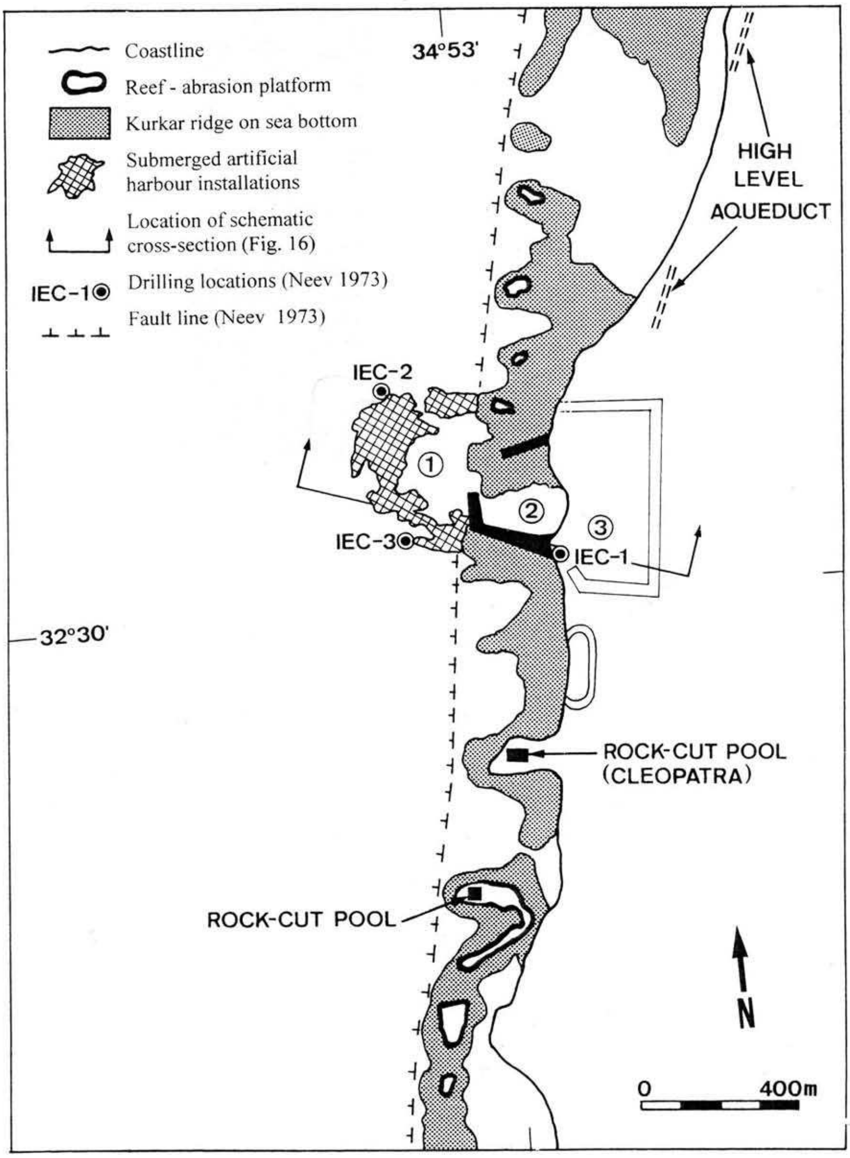

Fig. 10. Map showing the main offshore archaeological features of the Caesarea region, locations of boreholes and proposed fault mentioned in the text (modified after Neev *et al.* (1973)). (1) submerged western part of the Roman harbour built in the open sea on top of sand; (2) central part of the Roman harbour built on top of the kurkar ridge; (3) eastern onshore part of the Roman harbour.

trending N–S, is responsible for the subsidence of the western section of the Herodian harbour (Neev *et al.* 1973, 1987; Raban 1976, 1981; Nir 1985; Mart 1995*a*; Raban & Mart 1995).

This archaeological and geological evidence for neotectonic activity, however, is open to re-interpretation. First, the existence at Caesarea of a stone-built platform made of hewn stones 5 m below present-day sea level does not necessarily indicate tectonic subsidence. Ancient port builders had the knowledge and capability to build structures on the sea bottom. Some of these structures were constructed of huge stones that had been laid carefully on the sea floor, as is the case with Acre's ancient 'Tower of Flies' breakwater head (Raban 1985). Indeed, the Roman historian Josephus Flavius described in detail the construction of the Caesarea harbour, noting: 'He (Herod) first lowered into 20 fathoms of water blocks of stone mostly 50 feet long, 9 deep and 10 broad, sometimes even bigger. When the foundations had risen to water level, he built above the surface a mole 200 feet wide' (Whiston 1960, p. 453). Thus, it should not be surprising to find the stone-built platform on the sea bed at Caesarea.

Second, although the stair-like feature observed in the seismic profiles seaward of the modern harbour at Caesarea has been identified as the tectonic fault responsible for the Herodian harbour's destruction (Neev *et al.* 1978; Mart 1996*b*), the coincidence of this feature with the western boundaries of the submerged kurkar ridge (Fig. 10) is highly suspicious. We suggest that this feature may represent a typical sub-bottom topographic profile of the western edge of the kurkar ridge, rather than a tectonic fault (see Arad *et al.* 1978). However, even if we accept the assumption that the seismic profile shows a fault rather than the ridge edge, the only conclusion that can be inferred from this is that faulting occurred after the formation of the sandstone ridge. The ridge was formed thousands of years before the Roman period and so any association of the fault with the destruction of the Herodian harbour is highly speculative.

Third, geologists have shown that there is a good correlation and continuity between offshore and onshore drill cores, with no indication of intervening faulting (Arad *et al.* 1978). Although the kurkar horizon does appear at different elevations in the boreholes, it does not necessarily indicate faulting, as a westward tilting of the kurkar layer is also possible.

Finally, as noted above, ancient coastal installations in the Caesarea region have maintained their original elevation with respect to sea level. These include the rock-cut pool of the palace (Cleopatra pool; Fig. 7), the rock-cut pools south of Caesarea (see above), port installations (Raban 1981) and an aqueduct (Olami & Peleg 1977). On Yonim Island, north of Caesarea, rock-cut installations reported by Raban (1976) indicate the stability of this offshore zone. Relying on the same data, however, Raban (1986*b*) suggested that the offshore region of Caesarea and Ma'agan Michael island ('Hayonim' Island) is tectonically unstable.

Overall, it seems that both archaeological and geological evidence support tectonic stability of the Caesarea region over the last 2000 years. If this is the case, what then caused the destruction of the western section of the Herodian harbour? Judging by the available data, we suggest the following sequence of events (Fig. 11). Originally, the western section of the Herodian harbour in Caesarea was built in the open sea on unconsolidated sediments (Fig. 11b), but subsequent marine erosion, followed by settlement of the foundations into the sediments, then caused subsidence of the west section of the Caesarea harbour (Fig. 11c) (Galili & Sharvit 1995*a*, *b*). A similar mechanism was also responsible for the destruction of the southern breakwater of the Phoenician port of Atlit (Galili & Inbar 1986).

Acre

At Acre, subsidence at a rate of 0.6 m per 1000 years is thought to have occurred since about AD 1300 (Flemming *et al.* 1978). A study of rock-cut installations, however, suggests no indications of neotectonic activity in the western Galilee coastal region (Raban 1986*a*). Despite a submerged Crusader vault (arch) (Fig. 9) (Flemming *et al.* 1978) that was previously associated with post Mameluke neotectonic subsidence (Neev *et al.* 1987), as discussed above, other rock-cut installations (mainly quarries and seawalls) (A and C in Fig. 4) and stone-built structures at Acre (Fig. 9) have more or less retained their original elevations. Furthermore, a Crusader well recently excavated a few hundred metres inland of Acre coast has revealed a water-table level 0.6 m above present-day sea level. Considering the distance of the well from the coastline, this elevation coincides fairly well with present-day sea level (see observations above). Hence, if any post-Crusader tectonic submergence had occurred in the region, we would expect to find all these archaeological features below present-day sea level, but this is not the case. The submerged Crusader vault is not a reliable indicator of neotectonic subsidence, because it could originally have been constructed on the sea bottom as the foundation

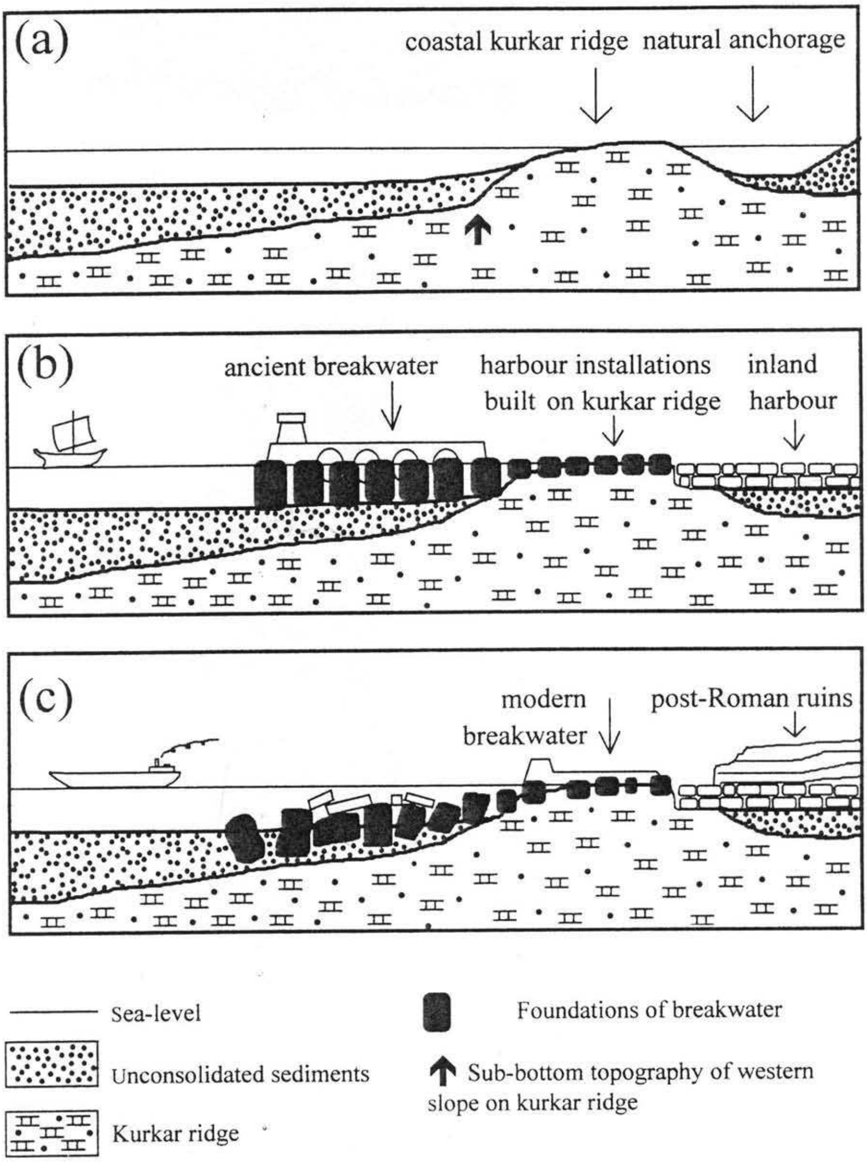

Fig. 11. Schematic cross-sections of Caesarea port: (**a**) the region before the Herodian period; (**b**) the Herodian harbour installations; (**c**) present-day features in the harbour.

for a building. In any case, it is most unlikely that most of the archaeological features in the vicinity of this vault retained their elevation with respect to sea level and only the vault underwent tectonic subsidence.

Although onshore archaeological and geomorphological features in the Acre region and in western Galilee indicate no significant neotectonic activity in the past thousands of years, E–W trending submarine faults and canyons have been observed offshore of Acre, Yasaf River, Shavai Zion, Ein Sara and Akhziv (Galili & Eytam 1988; Galili & Sivan 1998). Here, 1–2 m high, 300–600 m long submarine scarps indicate that E–W striking faults observed on land (Kafri 1972; Mero 1983; Sivan 1996) continue offshore. Considering that the kurkar which the faults cut is likely to have formed in prehistoric times (possibly early Holocene or before), 2 m of vertical displacement within the Holocene period corresponds to a vertical displacement rate of only 0.2 m per 1000 years. This is the same order of magnitude as changes in eustatic sea level in the last 2500 years and tidal fluctuations (Flemming *et al.* 1978; Goldsmith & Gilboa 1986), so it is likely that such a tectonic contribution would be hard to identify within our present study.

Dor

Archaeological indications of neotectonic activity at Dor were reported by Flemming *et al.* (1978), Neev & Bakler (1978), Sneh (1981) and Sneh & Klein (1984). However, in a review of archaeological and geomorphological studies, Sneh (1981) noted that any tectonic movement that had occurred in the Dor region during the last 3000 years was not obvious, and in any case did not exceed a few tens of centimetres (*c.* 0.1 m per 1000 years). Flemming *et al.* (1978) reported solution notches 0.3–0.9 m above present-day sea level as an indication of neotectonic activity at Dor. These features are not typical wave-cut notches that can serve as a reliable markers for former sea levels, but are instead small horizontal grooves cut in a man-made structure. Sneh (1981) suggested that these grooves could be marks cut at a later stage of the structures. Alternatively, they could be traces of preferential weathering in the *kurkar* layers and, therefore, not suitable sea-level markers.

Another alleged indication of neotectonic vertical displacement at Dor is a series of pools on Shehafit Island found at an elevation of 1 m above present-day sea level (Flemming *et al.* 1978). The function of many of the rock-cut pools is not yet clear; some of them may have been used for short-term fish storage and could have functioned above sea level (Spier 1993). Others could have been used for salt production, and as such should have been originally located above sea level to prevent waves from interfering with the dehydration process. Thus, the emergent pools at Dor cannot be reliable indicators for uplift. Our observations at Dor demonstrate that rock-cut coastal installations are found at elevations consistent with present-day sea level. Furthermore, no coastal abrasion platforms or notches were observed on the sea bottom or above sea level. An uplifted plateau described by Sneh (1981) as a Flandrian (mid-Holocene) marine terrace and reported at 3–4 m above present-day sea level at Dor (Neev *et al.* 1987) was examined in the course of this study. We suggest that this feature is a product of differential erosion of the archaeological site. The bedrock must have been artificially levelled in antiquity, and the installations and buildings then erected on top of it. With the bedrock being more resistant to weathering than the archaeological layers, years of differential erosion by wave splash is likely to have eroded the ancient buildings and structures and left behind a levelled platform.

Atlit

The most ancient archaeological feature located along the Israeli coast is the early sixth millennium BC well uncovered at the submerged Neolithic site of Atlit-Yam (Galili *et al.* 1993). The reconstructed ancient water level in the well indicates that sea level at the time of occupation was about 16 m lower than present-day sea level (Galili & Nir 1993). This well, and a series of fifth millennium BC. Pottery Neolithic sites submerged today at depths of 1–7 m, allow reconstruction of the Holocene sea-level curve for the Carmel coast (Galili *et al.* 1988). This resulting curve more or less coincides with the global eustatic changes proposed elsewhere (e.g. Van Andel 1990; Stanley 1995). As a result, it seems reasonable to conclude that during the last 8000 years no major vertical tectonic displacement has taken place in the region (Galili *et al.* 1988).

Several scholars (e.g. Gvirtsman *et al.* 1986; Neev *et al.* 1987; Mart 1996*a*) have suggested that neotectonic faults, with generally E–W or N–S trends, are responsible for subsidence in the area north of Atlit. For example, Neev *et al.* (1987) claimed that the Neolithic Atlit-Yam village, situated in the north bay of Atlit, subsided as a result of neotectonic activity. Mart (1996*a*), however, supported the interpretation by Galili *et al.* (1988) that the Neolithic well at Atlit-Yam indicates tectonic stability of the region during the last 8000 years. Adler (1986) stated that the Phoenician harbour installations in the north bay of Atlit are today submerged as a result of neotectonic activity that occurred in the last few thousand years. As mentioned above, however, the western quay of the Phoenician harbour in the northern bay and sections of the northern breakwater are found today at sea level. Foundations of the Crusader wall remain today situated at a proper elevation relative to sea level (Flemming *et al.* 1978, Ronen & Olami 1978). It is most unlikely that the whole section north of the Atlit peninsula underwent subsidence during the historical period, as suggested by Adler, whereas the western quay and the northern breakwater retained their original elevations. Today, the uppermost sections of the southern breakwater of the Phoenician harbour at Atlit are submerged at a depth of 1–1.5 m. Given the stability of associated features in the area, we suggest that its foundations underwent settlement because they were constructed on unconsolidated sediments (Galili & Inbar 1986). In summary, we conclude that no significant neotectonic activity had taken place during the last 8000 years in the Atlit region.

Yavneh-Yam (Palmachim)

Neev *et al.* (1987) suggested that the western sec tion of the early to middle Bronze Age (thirtieth–fifteenth century BC) rampart at Yavneh-Yam is now submerged under the sea as a result of neotectonic subsidence and showed the approximate location of drowned man-made structures that were previously observed by Z. Ben-Avraham (pers. comm. in Neev *et al.* (1987, fig. 23)). However, extensive (and continuing) underwater surveys carried out in the course of this study failed to reveal offshore man-made structures in the location proposed by Neev *et al.* (1987). In contrast, as discussed above, rock-cut quarries at Yavneh-Yam are located at suitable elevations for functioning (Fig. 8), and abrasion platforms on offshore reefs similarly coincide with present-day sea level.

Conclusions and implications

The available archaeological coastline markers existing along the Israeli coast were re-examined in this study, which has focused particularly on the possibility that significant tectonic activity occurred in the region during the last 2500 years. Minor vertical displacements of rock-cut installations identified in the study area (on the coast and on offshore islands) appear to vary within the range of eustatic and tidal variations. None of this archaeological evidence indicates rates of tectonic movement exceeding 0.2 m per 1000 years in the coastal region during historical times. Geological and geomorphological observations support our claim that the coast and adjacent seafloor in the region have been relatively stable in the last few thousand years. However, because by its nature the accuracy of this study is limited, minor tectonic displacement (less than 0.2 m per 1000 years) is possible. We suggest that the main reason for the destruction of coastal installations and harbour constructions along the Israeli coastline is not neotectonic activity, but differential settlement and marine erosion.

The potential tectonic instability of the Israeli seaboard during historical times, as suggested by previous studies (e.g. Neev *et al.* 1973, 1978, 1987; Flemming *et al.* 1978; Neev & Bakler 1978; Gvirtzman *et al.* 1986; Levy *et al.* 1986; Neev & Emery 1991; Mart 1996*a*), is a crucial consideration for planning large-scale coastal development projects such as nuclear power stations. However, the results of this study suggest that the Israeli coast is tectonically relatively stable. However, planners should take into consideration the possibility of exceptional events, such as earthquakes and tsunamis (Nir 1985; Amiran *et al.* 1994), and structures should be properly constructed to guard against the effects of marine erosion and differential settlement. Coastal archaeological sites, in particular, should be protected from weathering and erosion, as many are currently undergoing rapid destruction. Sand quarrying and the construction of marinas, ports and other coastal developments, are the main reasons for accelerated marine erosion in historical times, so the availability of sand along the coastal zone is crucial to the survival and protection of modern coastal installations, and the preservation of ancient coastal sites. A large-scale action plan is needed, therefore, to prevent the reduction of sand resources along the coastline and shallow continental shelf.

We wish to thank M. Weinstein-Evron, D. Neev, Y. Nir, D. Sivan, V. Spier, A. Kotser, E. Stern, N. Flemming and an anonymous referee for their assistance and helpful comments, and C. Vita-Finzi and I. Stewart for their useful remarks.

References

ADLER, E. 1986. The subsidence of the kurkar ridges in the Carmel coast (in Hebrew). *Teva VaAretz*, **4**, 13–16.

AMIRAN, D. H. K., ARIEH, E. & TURCOTTE, T. 1994. Earthquakes in Israel and adjacent areas: macroseismic observations since 100 BC. *Israel Exploration Journal*, **44**, 260–305.

ARAD, A., ECKER, A. & OLSHINA, A. 1978. The young (post lower Pliocene) geological history of the Caesarea structure. *Israel Journal of Earth Sciences*, **27**, 142–146.

BLACKMAN, D. J. 1973. Evidence of sea level changes in ancient harbour and coastal installation. *In*: BLACKMAN, D. J. (ed.) *Marine Archaeology*. Colston Papers, **23**. Butterworths, London, 115–139.

ELGAVISH, J. 1994. *Shiqmona on the Seacoast of Mount Carmel* (in Hebrew). Hakibbutz Hameuhad Publishing House, Tel Aviv.

FLEMMING, N., RABAN, A. & GOETSCHEL, C. 1978. Tectonic and eustatic changes on the Mediterranean coast of Israel in the last 9000 years. *In*: GAMBLE, J. C. & YORKE, R. A. (eds) *Progress in Underwater Science, Vol. 3 (New Series) of the Report of the Underwater Association, Proceedings of the 11th Symposium of the Underwater Association*, 18–19 March 1977. British Museum (Natural History), London, 33–93.

FLINDER, A. 1976. A piscina at Caesarea – a preliminary Report. *Israel Exploration Journal*, **26**, 77–80.

——1985. The piscinas at Caesarea and Lapithos. *In*: RABAN, A. (ed.) *Proceedings of the First International Workshop on Ancient Mediterranean Harbours, Caesarea Maritima*. BAR International Series **257**, 173–178.

FROST, H. 1973. The offshore island harbour at Sidon and other Phoenician sites in light of new dating evidence. *International Journal of Nautical Archaeology and Underwater Exploration*, **2**, 75–94.

GALILI, E. & EYTAM, Y. 1988. Young faulting in the shallow continental shelf: evidence from northern Israel. *Proceedings of the Annual Conference of the Israel Geological Society, Ein Boqeq*, 30–31 (Hebrew/English).

—— & INBAR, M. 1986. Underwater clay exposures along the Israeli coast and submerged settlements off the Carmel coast (in Hebrew). *Proceedings of the 5th Coastal Symposium*. Technion–Israel Institute of Technology, Haifa, 39–48.

—— & NIR, Y. 1993. The Submerged Pre-Pottery Neolithic water well of Atlit-Yam, northern Israel, and its palaeoenvironmental implications. *The Holocene*, **3**, 265–270.

—— & SHARVIT, J. 1994. Classification of underwater archaeological sites along the Mediterranean coast of Israel: finds from underwater and coastal archaeological research. *In*: ANGELOVA, C. (ed.) *Actes du Symposium International Thracia Pontica V*, Sozopol 1991, 269–296.

—— & ——1995*a*. The destruction of ancient coastal installations and the stability of the Israeli coast during historical times. *In*: GALIL, B. S. & MART, Y. (eds) *Proceedings of the 7th Annual Symposium on the Mediterranean Continental Margin of Israel*, National Institute of Oceanography, Haifa, 28–32 (Hebrew/English).

—— & ——1995*b*. The destruction of ancient coastal installations and the stability of the Israeli coast during historical times. *In*: ARKIN, Y. & AVIGAD, D. (eds) *Proceedings of the Israel Geological Society Annual Meeting, Zikhron Ya'aqov*, 27, 34 (Hebrew/English).

—— & SIVAN, D. 1998. Young tectonic activity in the Galilee coasts – the rate of vertical displacement according to underwater and coastal archaeological and geological finds. *In*: WEINBERGER, R. GAVRIELI, I., YECHIELI, Y., PORAT, N. & AYALON, A. (eds) *Proceedings of Annual Meeting, Mizpeh Ramon, Israel Geological Society* (Hebrew/English).

——, WEINSTEIN-EVRON, M., HERSHKOVITZ, I., GOPHER, A., KISLEV, M., LERNAU, O., KOLSKA HOROWITZ, L. & LERNAU, H 1993. Atlit-Yam: a prehistoric site on the sea floor off the Israeli coast. *Journal of Field Archaeology*, **20**, 133.

——, —— & RONEN, A. 1988. Holocene sea-level changes based on submerged archaeological sites off the northern Carmel noast in Israel. *Quaternary Research*, **29**, 36–42.

GOLDSMITH, V. & GILBOA, M. 1986. Tides in Israel (in Hebrew). *Horizons in Geography*, **15**, 21–46.

GVIRTZMAN, G., KLANG, A., ADLER, E., MICHAELSON, H. & KASHAI, E. 1986. The Atlit faults system: left latteral strike-slip faults and rotation of southern Carmel (in Hebew). *Proceedings of the Israel Geological Society Annual Meeting, Ma'alot*, 58–59.

KAFRI, U. 1972. *Nahriya*, geological map, scale 1:50 000. Geological Survey of Israel, Jerusalem.

—— & ARAD, A. 1978. Paleohydrology and migration of the ground-water divide in regions of tectonic stability in Israel. *Geological Society of America Bulletin*, **89**, 1723–1732.

KARMON, N. & SPANIER, E. 1988. Remains of a purple dye industry found at Tel Shiqmona. *Israel Exploration Journal*, **38**, 184–187.

LEVY, Z., NEEV, D. & PRAUSNITZ, M. W. 1986. Late Holocene tectonic movements at Akhziv, Mediterranean coastline of northern Israel. *Quaternary Research*, **25**, 177–188.

LIPKIN, Y. & SAFRIEL, U. 1971. Intertidal zonation on rocky shores at Mikhmoret (Mediterranean Israel). *Journal of Ecology*, **59**, 1–30.

MART, Y. 1995. Caesarea Maritima: unique evidence for earthquake patterns and sea level fluctuations in the Late Holocene. *In*: HOLUM, G. (ed.) *Proceedings of International Symposium Caesarea Maritima – Retrospective after Two Millennia*, 23–25.

——1996*a*. Faults at the proximal continental shelf off Atlit, central Israel, and their neotectonic significance. *Geo-Marine Letters*, **16**, 41–48.

MART, Y. 1996*b*. *Destructive earthquakes in historic times on the continental shelf off Caesarea.*, CMS News, Report 23, University of Haifa, Centre for Maritime Studies, 7–10.

MAZOR, E. 1974. On the stability of the Mediterranean coast of Israel since Roman times: a discussion. *Israel Journal of Earth Sciences*, **23**, 149–151.

MERO, D. 1983. *Subsurface Geology of Western Galilee and Zevulun Plain*. Tahal Consulting Engineerings Ltd, Tel Aviv.

NEEV, D. & BAKLER, N. 1978. *Young Tectonic Activities along the Coast of Israel* (in Hebrew). Hof Ve-Yam, Ha Kibbutz Hameuhad Publishing House, 9–30.

—— & EMERY, K. O. 1991. *Three oscillatory tectonic movements at Caesarea: one Byzantine and two Post Byzantine*. Report GSI/3/90, Ministry of Energy and Infrastructure, Geological Survey of Israel, Jerusalem, 1–25.

——, BAKLER, N. & EMERY, K. O. 1987. *Mediterranean Coasts of Israel and North Sinai. Holocene Tectonism from Geology, Geophysics and Archaeology*. Taylor and Francis, New York.

——, ——, MOSHKOVITZ, S., KAUFMAN, A., MAGARIZ, M. & GOPHNA, R. 1973. Recent faulting along the Mediterranean coast of Israel. *Nature*, **245**, 254–256.

——, SHACHNAI, E., HALL, J. K., BAKLER, N. & BEN-AVRAHAM, Z. 1978. The young (post Lower Pliocene) geological history of the Caesarea structure. *Israel Journal of Earth Sciences*, **27**, 43–64.

NIR, Y. 1985. The destruction of the Roman high level aqueduct and the Herodian harbour at Caesarea. *In*: RABAN, A. (ed.) *Proceedings of the First International Workshop on Ancient Mediterranean*

Harbours Caesarea Maritima. BAR International Series, **257**, 185–194.

——1997. Middle and Late Holocene sea-levels along the Israel Mediterranean coast – evidence from ancient water wells. *Journal of Quaternary Science* **12(2)**, 143–151.

—— & ELDAR, I. 1986. *Ground water table levels in ancient wells as indications for ancient sea levels, and for neotectonic changes in the Mediterranean coastal region of Israel*. GSI/34/86 Report, Geological Survey of Israel, Jerusalem, 1–28 (in Hebrew).

OLAMI, Y. & PELEG, Y. 1977. The water supply system of Caesarea Maritima. *Israel Exploration Journal*, **27**, 127–137.

OREN, E. 1992. Ruqeish. *In*: STERN, E. (ed.) *The New Encyclopedia for Archaeological Excavations in Israel, Vol. 4*. The Israel Exploration Society, Ministry of Defence, Carta Press, Jerusalem, 1293–1294.

RABAN, A. 1976. *Marine archaeological research at Caesarea: location of evidence for level changes of ancient building remnants* (in Hebrew). Final Report 2/76, Maritime Studies, University of Haifa, 7–58.

——1981. The Ancient Harbours of Caesarea (in Hebrew). *Qadmoniot*, **55–56**, 80–88.

——1984. The ancient harbours of Erez-Israel in Biblical times (in Hebrew). *In*: SCHILER, A. (ed.) *Zeev Vilnai Book*. Jerusalem, 241–253.

——1985. The ancient harbours of Israel in Biblical times (from the Neolithic period to the end of the Iron Age). *In*: RABAN, A. (ed.) *Proceedings of the First International Workshop on Ancient Mediterranean Harbours, Caesarea Maritima*. BAR International Series, **257**, 11–44.

——1986*a*. Rock cut installations off the western Galilee coast (in Hebrew). *In*: YEDAYAH, M. (ed.) *Kadmoniot HaGalil Hama'aravi*. Ministry of Defence Publication, 209–234.

——1986*b*. Archaeological evidence for ancient sea levels in the Mediterranean coast of Israel. *In*: *Proceedings of the Israel Geological Society Annual Meeting, Ma'alot*, 102–105.

—— & GALILI, E. 1985. Recent maritime archaeological research in Israel. *International Journal of Nautical Archaeology*, **14**, 321–356.

—— & MART, Y. 1995. Caesarea, field trip no. 5 (in Hebrew). *In*: ARKIN, Y. (ed.) *Israel Geological Society Annual Meeting, Zikhron Ya'aqov, Field Trips Guidebook*, 89–103.

RONEN, A. & OLAMI, Y. 1978. *Atlit Map*. Archaeological Survey of Israel, Jerusalem, 37–58 (Hebrew/English).

SIVAN, D. 1996. *Paleogeography of the Galilee coastal plain during the Quaternary*. (in Hebrew) PhD thesis, Hebrew University, Jerusalem.

SNEH, Y. 1981. *The paleogeography and the history of the coast of Dor in the Holocene period*. (in Hebrew). MA thesis, Haifa University.

—— & KLEIN, M. 1984. Holocene sea level changes at the coast of Dor, Southeast Mediterranean. *Science*, **226**, 831–832.

SPIER, V. 1993. *Methods of growing and holding fish in fish ponds (piscinas) and in other facilities along the coasts of Israel and Italy in the Roman period*. (in Hebrew). MA thesis, University of Haifa.

STANLEY, D. J. 1995. A global sea-level curve for the late Quaternary: the impossible dream? *Marine Geology*, **125**, 1–6

TUWEG, R. 1997. Level of the well bottoms in the area of the internal harbour at Caesarea as an indirect index for locating sea level changes (in Hebrew). *Proceedings of the Annual Meeting Mediterranean Continental Margins of Israel*, 6–7.

VAN ANDEL, T. H. 1990. Addendum to 'Late Quaternary sea-level changes and archaeology', *Antiquity*, **64**, 151–152.

WHISTON, W. 1960. *The Complete Works of Josephus Flavius, Wars of the Jews I xxi 6*. Cregel Publications, MI.