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Ancient coastal wells of Caesarea Maritima, Israel, an indicator for relative sea level changes during the last 2000 years

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Abstract

During the detailed excavations of ancient Caesarea, Israel, East Mediterranean, 64 coastal water wells have been examined that date from the early Roman period (with the oldest occurring in the 1st century AD), up to the end of the Crusader period (mid-13th century AD). The depths of these coastal water wells establish the position of the ancient water table and therefore the position of sea level for the first century AD up to 1300 AD. The connection between the coastal water table and changes in sea level has been established from modern observations in several wells on time scales of days and months and this is used to reconstruct sea level during historical time. The results indicate that during the Byzantine period, sea level at Caesarea was higher by about 30 cm than today. The Late Moslem and Crusader data shows greater fluctuations but the data sets are also much smaller than for the earlier periods. The consistency of the data indicates that the near-coastal well data from Caesarea provides a reliable indicator of sea-level change, with an accuracy of about 10–15 cm. These results are consistent with observations for earlier periods and, with comparisons to model-predicted glacio-hydro isostatic sea-level change, indicate that ocean volumes have been constant for much of the past 2000 years. The well data is also consistent with an absence of significant vertical tectonic movement of the coast at Caesarea over about 2000 years.

Keywords: sea-level change; archaeological indicators; Roman to Crusader period; Caesarea; Israel; Mediterranean; isostasy

1. Introduction

Since the termination of the last deglaciation, sea-level change at tectonically stable sites located far from the former ice margins has generally been small, being determined by the glacio-hydro-isostatic response of the earth to the recent deglaciation and by any incremental changes in ocean volume. Observations of this change are nevertheless significant because (i) they provide constraints on the mantle response function to surface loading, (ii) they provide constraints on the fluctuation in ocean volume over the past 6000–7000 years, (iii) they define the reference surface for measuring rates of vertical tectonic movement, and (iv) they provide a reference

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surface for evaluating the functions of coastal archaeological remains [1]. The Mediterranean region—with a small tidal range, outside of the immediate range of the impact of the past ice sheets on Late Holocene sea level, and with ample archaeological remains that bear witness to past sea levels [2]—provides a particularly suitable region for examining these various contributions to local sea level. In this paper, we use observations of the depths of coastal water wells from Caesarea (Israel) constructed between the Early Roman period and Crusader times, to establish sea-level fluctuations for the first century AD up to 1300 AD.

The connection between the coastal water table and changes in sea level is well known, with the former in free aquifers responding to daily sea-level fluctuations. In this study, this close connection has been precisely measured on time scales of days and months for the Caesarea area (Fig. 1a). The direct relationship established between the modern water table and measured nearby sea level provides the validity of using water-table depths in ancient wells for reconstructing sea level during historical time.

Caesarea has had nearly 1300 years of continuous occupation during which many wells were dug. The major construction at the site took place under King Herod of Judea between 22 and 10 BC. During the entire Roman and subsequent Byzantine periods from the 1st to 7th century AD, the city flourished into one of the largest cities on the eastern Mediterranean coast and became the capital of the province of Palestine. This Roman–Byzantine period was unique in that most water was supplied from external sources, using aqueducts (both channels and pipelines), although water wells were also in use. During the subsequent occupational periods, local water

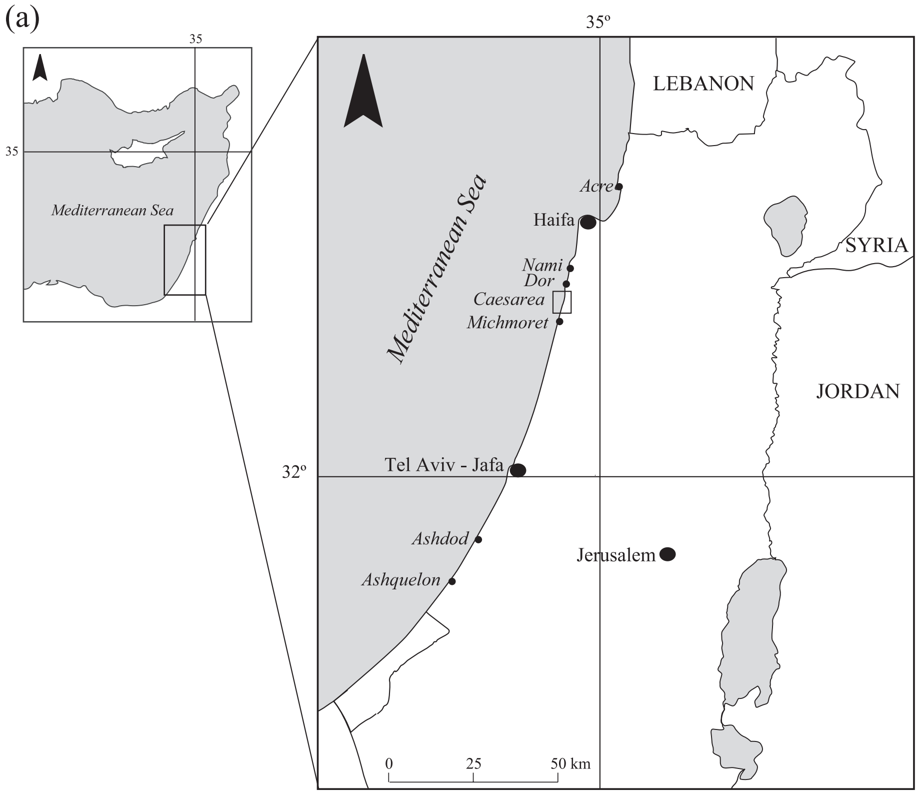

Fig. 1. Location maps: (1a) The coast of Israel at the Eastern Mediterranean. (1b) Air photo of Caesarea Maritima. (1c) Detailed map of Caesarea (almost the same scale as the air photo). Numbers 1–64 are the location sites of the excavated ancient wells (see Table 1), A and B are ancient wells in which the modern water table had been measured (Figs. 3 and 4) and 55/0 and 55/a are modern monitoring wells (Fig. 8).

(b)

Fig. 1 (*continued*).

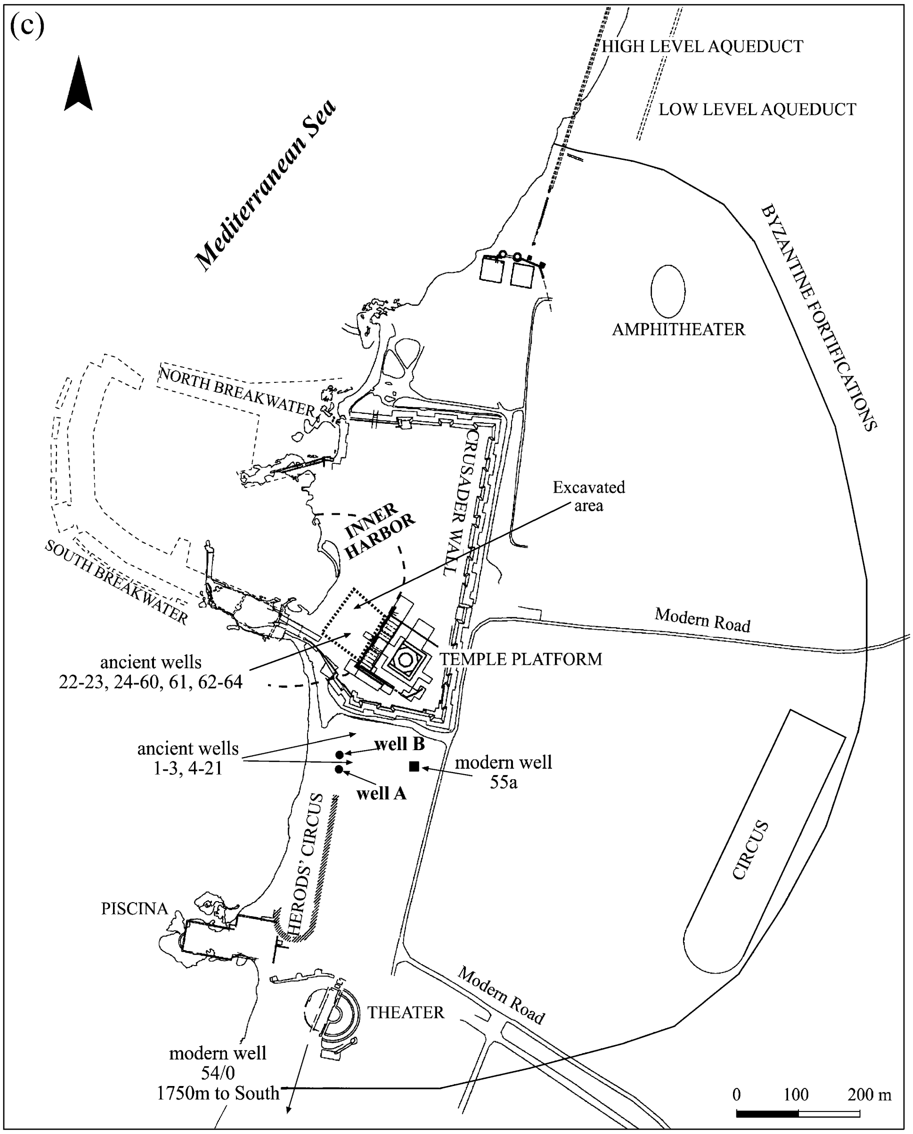

Fig. 1 (*continued*).

sources such as springs, wells and cisterns were increasingly used [3], particularly during the Moslem occupation. After the city was occupied by the Moslems in 640 AD, its importance diminished and it is hardly mentioned in the contemporary sources. The Moslem period is divided into the Umayid (640–750 AD), Abbaside, (750–960 AD) and Fatimide (960–1001 AD) intervals. The Abbaside rulers superimposed a different urban plan of much smaller size on the Roman–Byzantine city. The town was described by Moslem geographers in 985 and 1047 (al-Maqdisi and Nasir-I-Khusrau, respectively, translated by Le Strange [4]) as having a water supply based on wells and cisterns. This same water supply continued to be used after the Crusader occupation of the city at 1101 AD. Later, in 1265, the Mamluks conquered Caesarea and razed it to ground, never to be rebuilt.

As part of detailed excavations of ancient Caesarea carried out in the 1990's, 64 coastal wells have been examined (Fig. 2 and Table 1). The elevation of the base of each well has been measured and related to the Israeli height datum. These wells date from the early Roman period (with the oldest occurring in the 1st century AD), up to the end of the Crusader period (mid-13th century AD). Of these, 43 are from the inner harbor and the remainder are from outside the Crusader walls but within ~150 m of the coast (Fig. 1b and c). Such a large number of reliably dated wells within an excavated area of about 0.5 km^2 spanning a time interval of about 1300 years, provides a high-density, high-resolution, database for establishing sea level along this section of the coast once the relation between the water table and sea level is known. It is the modern high-resolution measurements of both water-table and sea-level change that establish this relation for the present and which are used here to estimate the palaeo sea levels from the archaeological data.

Previous research along the Israeli coast has already used ancient wells from several locations for reconstructing palaeo sea levels [5–8] during the interval 9000–2000 (calendar) years BP. (The radiocarbon ages from the earlier studies have been converted in this paper to calendar ages using the polynomial calibration curve of Bard [9] and the typologically or culturally dated cultural periods used here correspond to the calendar time scale.) Wells from later periods were investigated by Nir and Eldar [10] who excavated six ancient wells from Ashquelon in the south to Michmoret in the central coast (Fig. 1), dated from the Persian period (about 2500 BP) to the Crusader period. The earlier well data suggested that local sea level was at about − 1 m at ~ 2500 BP, rising to the present level by 2000–1500 BP. This information was used by Sivan et al. [11] to establish sea-level change along the Israel coast up to about 2000 years ago and the new data from Caesarea extends the record into the beginning of the second millennium AD.

2. Methodology

2.1. Archaeological methods

A well that functions during changing climate and ground-water conditions must meet a number of criteria that would have been understood by the original builders. These include the requirement that water can be drawn at times of low water-table level and, for near-coastal sites, that at times of extreme

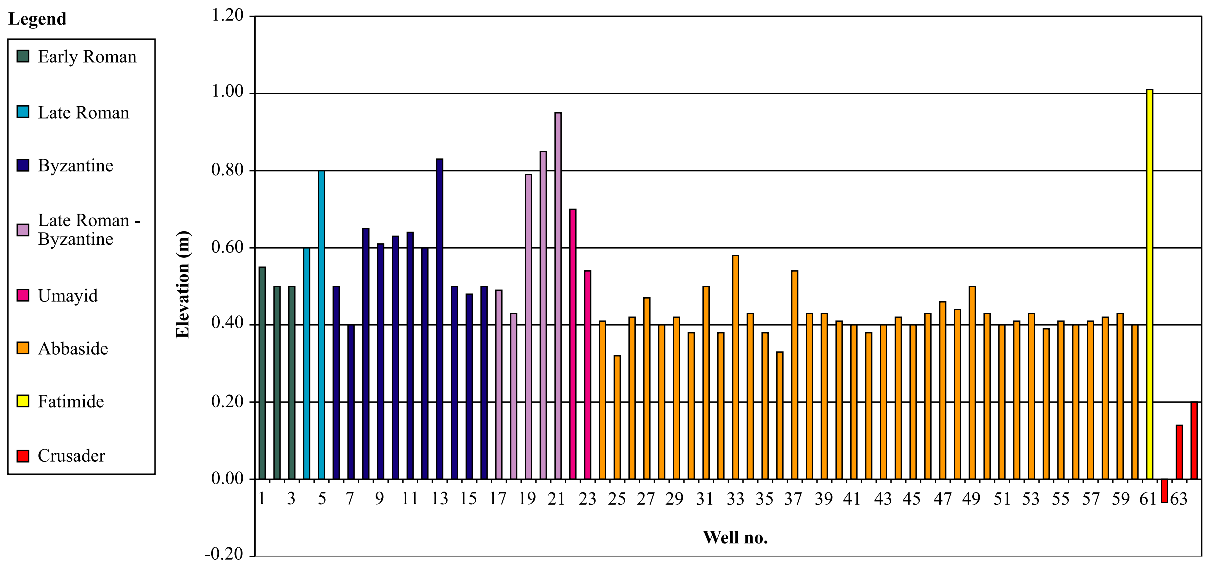

Fig. 2. The elevations of the well bottoms of Caesarea along a time axis. Numbers of wells and cultural periods are according to Table 1. The figure summarizes the data in the chronological order of the cultural periods but data within each period are not in chronological order. The duration of each of the successive historical periods is not the same.

Table 1
Relative sea level estimates (also plotted in Fig. 6)

Well number	Century date	Cultural period	Start of period	End of period	Mean period age	Age years BP	Half period range	Base elev.	Water-table level	Palaeo sea level	Mean time	Sigma time	Mean rsl	rms rsl
1	1st century	Roman (6–324 AD)	0	100	50	1950	50	0.55	0.85	0.05	1950	33.5	0.017	0.029
2	1st century		0	100	50	1950	50	0.5	0.8	0		33.5		
3	1st century		0	100	50	1950	50	0.5	0.8	0		33.5		
4	3–4th century	Late Roman	200	400	300	1700	100	0.6	0.9	0.1		67		
5	4th century		300	400	350	1650	50	0.8	1.1	0.3	1650	33.5	0.200	0.153
6	4–5th century	Byzantine (324–640)	300	500	400	1600	100	0.5	0.8	0		67		
7	5–6th century		400	600	500	1500	100	0.4	0.7	−0.1	1500	67	0	
8	5–7th century		400	700	550	1450	150	0.65	0.95	0.15				
9	5–7th century		400	700	550	1450	150	0.61	0.91	0.11				
10	5–7th century		400	700	550	1450	150	0.63	0.93	0.13				
11	5–7th century		400	700	550	1450	150	0.64	0.94	0.14				
12	5–7th century		400	700	550	1450	150	0.6	0.9	0.1	1445	100.5	0.076	0.12
13	6th century		500	600	550	1450	50	0.83	1.13	0.33				
14	6th century		500	600	550	1450	50	0.5	0.8	0				
15	6–7th century		500	700	600	1400	100	0.48	0.78	−0.02				
16	6–7th century		500	700	600	1400	100	0.5	0.8	0				
17		Late Roman–Byzantine	200	700	450	1550	250	0.49	0.79	−0.01		167.5		
18			200	700	450	1550	250	0.43	0.73	−0.07		167.5		
19			200	700	450	1550	250	0.79	1.09	0.29		167.5		
20			200	700	450	1550	250	0.85	1.15	0.35	1550	167.5	0.202	0.229
21			200	700	450	1550	250	0.95	1.25	0.45		167.5		
22	7–8th century	Umaid (640–750)	640	750	695	1305	55	0.7	1	0.2	1305	36.85	0.120	0.11
23	7–8th century		640	750	695	1305	55	0.54	0.84	0.04				
24	9th century	Abbasid (750–960)	750	960	855	1145	105	0.41	0.71	−0.09				
25	9th century		750	960	855	1145	105	0.32	0.62	−0.18				
26	9th century		750	960	855	1145	105	0.42	0.72	0.08				
27	9th century		750	960	855	1145	105	0.47	0.77	0.03				
28	9th century		750	960	855	1145	105	0.4	0.7	−0.1				
29	9th century		750	960	855	1145	105	0.42	0.72	−0.08				
30	9th century		750	960	855	1145	105	0.38	0.68	−0.12				
31	9th century		750	960	855	1145	105	0.5	0.8	0				
32	9th century		750	960	855	1145	105	0.38	0.68	−0.12				
33	9th century		750	960	855	1145	105	0.58	0.88	0.08				
34	9th century		750	960	855	1145	105	0.43	0.73	−0.07				
35	9th century		750	960	855	1145	105	0.38	0.68	−0.02				
36	9th century		750	960	855	1145	105	0.33	0.63	−0.17				
37	9th century		750	960	855	1145	105	0.54	0.84	0.04				
38	9th century		750	960	855	1145	105	0.43	0.73	−0.07				
39	9th century		750	960	855	1145	105	0.43	0.73	−0.07				
40	9th century		750	960	855	1145	105	0.41	0.71	−0.09				
41	9th century		750	960	855	1145	105	0.4	0.7	−0.1				
42	9th century		750	960	855	1145	105	0.38	0.68	−0.12	1145	70.35	−0.079	0.049
43	9th century		750	960	855	1145	105	0.4	0.7	−0.1				
44	9th century		750	960	855	1145	105	0.42	0.72	−0.08				
45	9th century		750	960	855	1145	105	0.4	0.7	−0.1				
46	9th century		750	960	855	1145	105	0.43	0.73	−0.07				

Table 1 (*continued*)

Well number	Century date	Cultural period	Start of period	End of period	Mean period age	Age years BP	Half period range	Base elev.	Water-table level	Palaeo sea level	Mean time	Sigma time	Mean rsl	rms rsl
47	9th century		750	960	855	1145	105	0.46	0.76	− 0.04				
48	9th century		750	960	855	1145	105	0.44	0.74	− 0.06				
49	9th century		750	960	855	1145	105	0.5	0.8	0				
50	9th century		750	960	855	1145	105	0.43	0.73	− 0.07				
51	9th century		750	960	855	1145	105	0.4	0.7	− 0.1				
52	9th century		750	960	855	1145	105	0.41	0.71	− 0.09				
53	9th century		750	960	855	1145	105	0.43	0.73	− 0.07				
54	9th century		750	960	855	1145	105	0.39	0.69	− 0.11				
55	9th century		750	960	855	1145	105	0.41	0.71	− 0.09				
56	9th century		750	960	855	1145	105	0.4	0.7	− 0.01				
57	9th century		750	960	855	1145	105	0.41	0.71	− 0.09				
58	9th century		750	960	855	1145	105	0.42	0.72	− 0.08				
59	9th century		750	960	855	1145	105	0.43	0.73	− 0.07				
60	9th century		750	960	855	1145	105	0.4	0.7	− 0.1				
61	11th century	Fatimide (960–1001)	960	1000	980	1020	20	1.01	1.31	0.51	1020	13.4	0.51	
62	12th century	Crusader (1001–1265)	1000	1265	1132.5	867.5	132.5	− 0.06	0.24	− 0.56	867.5	88.77	− 0.407	0.14
63	12th century		1000	1265	1132.5	867.5	132.5	0.14	0.44	− 0.36				
64	12th century		1000	1265	1132.5	867.5	132.5	0.2	0.5	− 0.3				

Past water-table level is calculated as base elevation + 30 cm and palaeo sea level is past water table − 80 cm, according to Eq. (2) in the text. Mean time gives the age (years BP) for the chronological intervals selected and sigma time is the sigma for this age (1 sigma value is two-thirds of half range).

tides or strong off–on shore winds, neither salination nor collapse of the saturated sediments in the lower part of the well occurs. Our working hypothesis is therefore that a functioning well must contain at least 30–40 cm of potable water under all conditions, as is the case in modern wells in the area. This is the minimum water column required to secure an effective draw of water with the jars used at the time of well construction. In most cases, the wells were dug vertically in uncemented sediments and the walls supported by logs to prevent sand collapse during excavation. In cases where the wells were dug in the calcareous sandstone (locally named kurkar), they were cut vertically with no need of support. When the well reached its effective depth, the upper part of the shaft was extended above the living level by a few courses of stonework to act as a protective barrier. If, later, the living floor was raised for any reason, the stonework's upper level would also have been raised.

Dating the period of well use is based on high-resolution archaeological stratigraphy of the well surroundings and on the typology of the latest pottery shards found at the bottom of the well. A special effort has been made to identify floors or other living surfaces adjoining the wells in order to determine the time of use. The fill inside the well has been excavated down to its base and the lowest levels establish the time the well ceased being used as a water supply and reverted to a household garbage container. When stratigraphic data is not available, the cultural material from the bottom of the well (mainly fragments of pottery vessels) has been used to establish the date of use.

The construction period of the 64 wells examined (Table 1) span 1300 years. Fig. 2 summarizes the results in the chronological order of the cultural periods but within each interval, the wells cannot be ordered in a time sequence. The duration of each of the successive historical periods is not constant, the Byzantine period, for example, lasted 300 years, while the Abbaside period spans two centuries. Thus, the distribution of the data is not homogeneous in time but the density of information in most intervals is sufficient to establish whether the bottom levels of the ancient wells have changed from one cultural period to another.

2.2. Relation between modern water table and sea level

The relationship between the water-table level and sea level is established from modern observations of this relationship in two of the ancient wells in two separate experiments. In the first, the present-day measurements consist of twice-daily observations of the water level in two domestic Roman–Byzantine wells (see locations of wells A and B in Fig. 1c) over a 3-month period (August–November) in 2001. Both wells lie close to the coast. The water levels in these two wells, about 50 m apart, were measured manually almost simultaneously (usually within 6–7 min of each other) and the measurements have been referred to the Israeli height datum. The two water-table curves present a very high degree of correlation (Fig. 3) indicating that results from one well will be representative of the other wells at similar close distances to the coast. Also, both wells indicate that the water table is between 50 and 70 cm above mean sea level for this interval. Based on this demonstration that the well levels are representative of the locality and are correlated to the sea levels, in the second experiment, continuous measurements were carried out in one of the wells for a further 3 months (January–March) in 2002, using a tide gauge that recorded water-table fluctuations every 5 min with a precision of 1 cm (Fig. 4). These measurements have also been referred to the Israeli height datum.

Since 1996, the Survey of Israel has digitally monitored sea level at three locations on the Mediterranean coast at 5-min intervals and 1-cm resolution. The instruments at the three sites of Tel Aviv, Ashdod, and Ashqelon are identical and the comparison of results shows that the sea-level changes recorded at these three sites are in phase and of the same amplitude. Thus, the Tel Aviv record provides a representative record of sea-level change for Caesarea. Fig. 4 compares this record with the water-table record from Caesarea for the 3 months in 2002. The covariance analysis of the two functions indicates the following relationship between well level H_1 and sea level ζ_1 of (Fig. 4)

$$H_1(t) = 0.51 \times \zeta_1(t)(t+8) \tag{1}$$

where t is time in hours. The water-table response lags the sea level by ~ 8 h and the correlation coefficient for the two levels is 0.82. At low frequencies, from days to weeks, the correlation is enhanced with the sandy sediments acting as a low-pass filter but for the present purposes, the above result is adequate to demonstrate that the well level responds directly to changes in the nearby sea level.

Both sets of well-level measurements indicate that the present water-table occurs on average about 0.5–0.6 m above mean sea level (MSL), but occasionally reaches +0.7 to +0.8 m above MSL (Figs. 3 and 4). Seasonal variations in mean sea level are recorded by the Tel Aviv tide gauge, as illustrated in Fig. 5 for the 5-

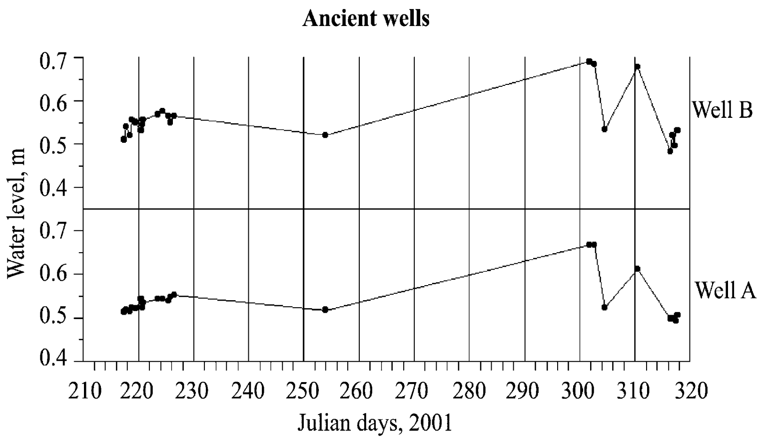

Fig. 3. Daily, non-continuous but nearly simultaneous measurements of the water table over a three month period at two ancient wells in the area of ancient Caesarea, south of the inner harbor (for location see Fig. 1c) and close to the shore. The measurements are referred to the Israeli height datum.

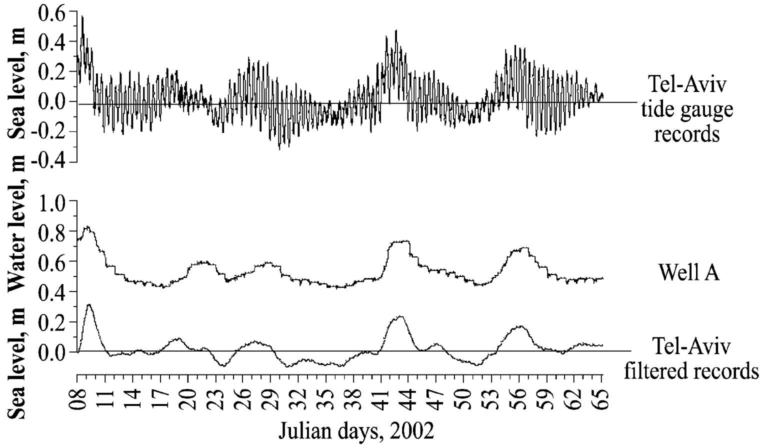

Fig. 4. (a) Daily continuous water-table changes during 3 months, in one of the above-mentioned ancient wells in Caesarea, measured by a mariograph (tide gauge) and (b) the filtered data to remove the tidal and other near-diurnal signals. (c) The data are compared to the similarly filtered, continuous records of sea level obtained from the Tel Aviv tide gauge for the same period. The sea level record is filtered and the curve is compared to the water-table curve during the same period.

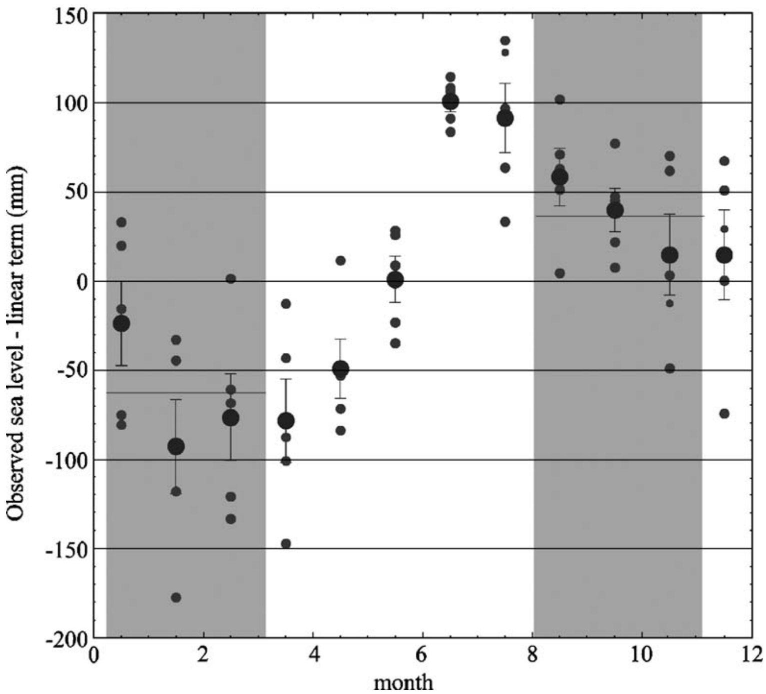

Fig. 5. Monthly mean sea level estimates for the period 1996–2000 recorded by the Tel Aviv tide gauge (data from the PSMSL database, www.pol.ac.uk.psmsl). A linear rate of change has been removed from the 5-year record before monthly mean values (corresponding to mid-month) have been calculated. The two shaded intervals correspond to the two 3-month periods of monitoring the relationship between well and sea level (Figs. 3 and 4). The points with error bars correspond to the monthly mean values and their standard deviations and the horizontal bars correspond to the mean values for the two three month intervals of well monitoring.

year period 1996–2000, with the summer levels being higher than the winter levels and typically the maximum levels occur at about 10 cm above the average level for the 3 months of the second experiment. We therefore adopt $+0.8 \pm 0.14$ m as the offset between the water table and the annual MSL.

2.3. Evaluating past water tables and reconstructing palaeo sea level

The inference of the palaeo sea level from the water level requires two further assumptions: (i) that the relationship between the two levels has remained constant with time and (ii) that the method of extracting the water from the well has remained the same through time. The Pleistocene to Recent geology of the Caesarea area consists of alternating units of kurkar, sand and clay that unconformably overly the thick Tertiary clay units of the Saqiye. The Pleistocene sequence is up to 100–200 m thick along the coast, becoming thinner inland. Along the coastal zone, there are up to five discontinuous layers of clay dividing the Pleistocene aquifer into sub units. The modern water table occurs within the upper-most sub-unit that is most affected by fluctuations in sea level. Because local sea-level change over the past 2000 years has been small and because there has been little modern ground-water extraction from the immediate area surrounding the near-shore wells, it is assumed that these same aquifers also fed the post Roman-age wells and that the above relationship between well and sea level is valid for the earlier data as well. Thus, an elevation of $+0.8 \pm 0.14$ m for an ancient water table would indicate zero sea-level change throughout the period. The second assumption is that water extraction occurred using jars and that the minimum water table needed for the well to be effective was 30–40 cm. The evidence from the well fill suggests that the wells were used for domestic purposes throughout and archaeological accounts suggest that the methods of extraction changed little during the interval in question. The reductions used, therefore, are:

$$\begin{aligned}&\text{Well bottom} + 30\ \text{cm} = \text{past water table}\\&\text{Past water table} - 80\ \text{cm} = \text{palaeo sea level}\end{aligned} \tag{2}$$

3. Palaeo sea levels

3.1. Archaeological observations from Caesarea

Fig. 2 illustrates the observed base-elevations of the wells with the wells arranged in successive cultural periods. Note that within each period, this is not a time series since we cannot establish the relative ages within each interval. All results for the Byzantine period, for example, have the same nominal age of 480 ± 140 (the mean age for the Byzantine period and half its duration). For each cultural period, the mean base elevation has been estimated as the arithmetic mean of the individual results in the interval. The epoch of observation is taken to be the middle of the interval, half the duration of which is equated to the standard deviation σ_t of the age measurement. Fig. 6 illustrates the inferred time series for the sea-level change, based on relationships (2). In deriving these results, the data from wells 4–6 have been combined because their ages overlap despite corresponding to different but short periods, as have, for the same reason, the data from wells 7–17. The error bars illustrated for the sea-level estimates are based on the spread of values within each interval and they are generally consistent with the expected accuracies inferred from the precisions of the measurements and the assumptions made in relating the water-table level to sea level. Where there are only a few observations within an interval, the expected uncertainty of 0.14 m has been adopted.

Throughout the Byzantine and Moslem periods, the sea levels have been close to the present position, possibly having been somewhat higher for the earlier interval from ~ 1.65–1.3 ka BP than during the Abbasid interval centred on about 1.15 ka BP. These latter wells yield a consistent result that lies below the mean level from Late Roman to Umaid time although this difference is small and within observational uncertainty. The more recent data points show greater oscillations but the number of points are also small and a cautious interpretation is that throughout the first millenium AD, the local sea levels for Caesarea occurred within 20 cm of present day sea level.

The fact that only a single well construction has been identified for the Fatimide period is probably because the Abbaside wells continued to provide adequate water and that the water-table level did not

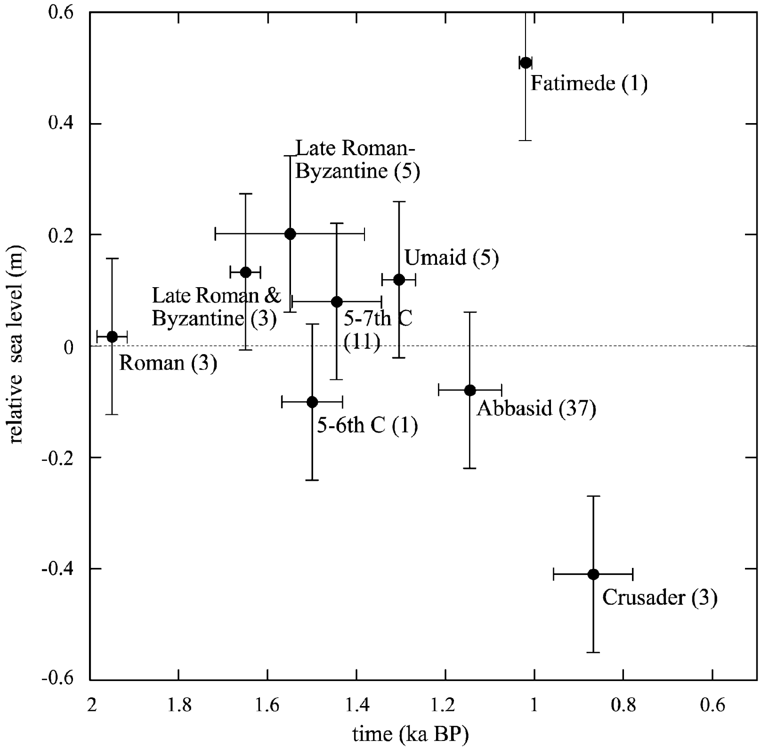

Fig. 6. Estimates of relative sea level from the Caesarean well data. The number in parenthesis indicates the number of data points for each interval. The Late Roman–Byzantine data point is for wells that could not be differentiated between Late Roman and Byzantine construction periods.

change substantially during this time. In contrast, the lower level for the Crusader wells suggests that a lowering of the water table may have occurred. The older wells tend to be narrow at their base such that further deepening, involving the construction of timber walls, would have been difficult and new wells would have been constructed rather than deepening existing wells. The absence of other wells in this interval suggests, therefore, that this period of low stand was of short duration, possibly the result of anomalous weather conditions that suppressed the local water table for a prolonged period. Until substantiated with other well data for this period, we adopt a cautious interpretation and consider this local anomaly rather than a regional trend.

Sea-level oscillations within 20 ± 15 cm of present day sea level, as had been concluded in this research, have great local and regional importance, both for locating sea level at different cultural periods and for understanding the role and rate of the tectonic component in each archaeological site. Previous coastal research (e.g. Ref. [12]) based on archaeological observations from Dor (Fig 1a) argued for higher sea levels during the Byzantine period and lower levels during the Crusader time, of up to 1 m above and below present sea level, respectively. Lower levels of up to -2 m during the Crusader period were presented by Gertwagen [13] based on archaeological observations in ancient Acre (Fig. 1a). Some geologists (e.g. Ref. [14]) suggested oscillatory tectonic movements along the coast of Israel during the last 2000 years while others (e.g. Ref. [15]) insisted that there is no evidence for Holocene tectonic displacements along the coast. Galili and Sharvit [16] also argue, from man-made installations and archaeological structures that can still function in the present-day sea-level environment, for tectonic stability during the last 2500 years, and thus for no changes in relative sea level. The high resolution and accurate data from the wells provide more reliable indicators of local sea-level change than those used in these other arguments and this kind of data can provide important insights into the tectonic movement, for more tectonically active areas such as Lebanon and Syria.

3.2. Glacio-isostatic sea-level change at Caesarea

Sea-level change is measured as the shift in relative position of the land and sea surfaces resulting from changes in ocean volume, changes in the distribution of the water within the deforming ocean basins, and from land movements. The major change during recent geological time results from cyclic global climate change with the concomitant growth and decay of large high-latitude ice sheets and the adjustment of the Earth's surface and gravity field to the changing ice-ocean mass distribution [1]. Because of the Earth's viscosity, these glacially induced changes occur long after melting has ceased and can be expected to contribute to the post-glacial sea-level changes on the eastern Mediterranean coast [11].

Throughout the Mediterranean, the isostatic influence of the melting of the large northern ice sheets is one of crustal subsidence, and hence relative sea-level rise, as the broad bulge that developed around Scandinavia during the glaciation phase slowly subsides. This is the glacio-isostatic contribution to sea-level change. Superimposed on this is the hydro-isostatic effect of the water added into the Mediterranean basin and this results in a subsidence of the sea floor and adjacent land. Based on model parameters that are consistent with the analysis of older data [11], the predicted glacio-isostatic contribution at Caesarea for the post-glacial phase is one of a slowly rising sea level during the post-glacial phase because the site is located on the distal part of the bulge. The hydro-isostatic part in contrast is one of a falling sea level [1,17]. At this location, the two contributions are nearly of the same magnitude for the past 4000–3000 years and the total isostatic signal is small for the post-glacial period. This is in contrast to Mediterranean localities closer to the former ice centers—Italy, Greece and France, for example—where the glacio-isostatic signal dominates and the total isostatic signal is one of a rising sea level up to the present time.

Superimposed on these isostatic contributions, and in the absence of tectonics, is any contribution from changes in ocean volume after the end of the major deglaciation. This could include changes in volumes of the remaining ice sheets of Antarctica and Greenland, changes in high latitude and mountain glacier volume, changes in the water balance between the oceans and the continents, and thermal expansion consequences of changes in ocean temperature. Previous analyses in the Mediterranean [17–19] and elsewhere [20] have concluded that there has been a small increase in ocean volume that continued to increase since the end of the major phase of deglaciation at about 7000 years ago until about 2000 years ago. Generally, the resolution of the geological observations has been inadequate to define precisely the sea-level change for the past 3000–2000 years and it has not been possible to ascertain the validity of the eustatic model for the past few millennia. One of the objectives of the analyses of the well data is to establish whether this is indeed the case. Models for late- and post-glacial sea levels for the Mediterranean sea have been developed for a number of regions including Italy, the French Mediterranean coast, Greece, and Israel [11,17–19,21]. Agreement between observations and predictions is generally satisfactory and the parameters describing the earth response and the ice loads provide a robust model for interpolating and predicting sea-level change across the Mediterranean basin. The model discussed in Lambeck et al. [22] is used here and its accuracy estimates have been derived by perturbing the model earth and ice sheet parameters through an observationally constrained range of values and calculating the range of predicted values at any time for any location [11]. The results for the Israel coast between Haifa and Tel-Aviv are illustrated in Fig. 7a together with the previously discussed observational evidence for the past 9000 years [11]. At Caesarea, the hydro- and glacio-hydrostatic effects for the post-glacial phase are approximately of equal magnitude but of opposite sign and the total isostatic correction is small and positive (Fig. 7b) for the past 6000 years and sea levels in this interval would lie at or above present day values if the eustatic component has remained constant. Fig. 7c compares the new sea levels inferred from the well observations. Agreement between the observed and predicted values is satisfactory and, because the former have been tested against other geological indicators of sea level in the Mediterra-

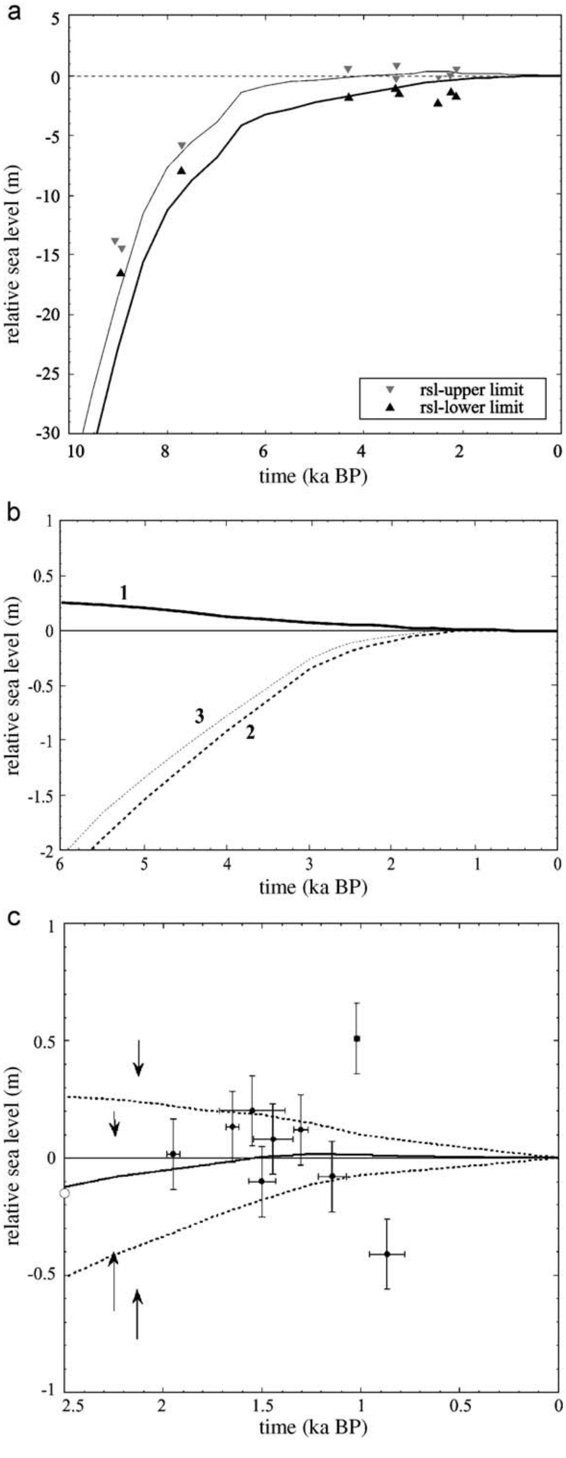

Fig. 7. (a) Predicted sea level change for Caesarea compared with observed values over the past 9000 years. The predicted values are shown by two lines of upper and lower limits of the glacio-hydro-isostatic model based on the model of Lambeck et al. [22] for the central Mediterranean basin. The upper (inverted triangles and lower (upright triangles) limiting observed values are from Sivan et al. [11]. (b) Predicted sea level change at Caesarea based on the above model. Curve 1 is the predicted combined isostatic contribution. Curve 2 is the eustatic sea level change based on other Mediterranean and global analyses. Curve 3 is the predicted relative sea level change for Caesarea for the past 6000 years. (c) Comparison of the predicted sea level (solid line) and upper and lower limits (dashed lines), for Caesarea with the observed values (with error bars) inferred from the well data.

nean, the well data provide a precise measure of sea-level change. Furthermore, the observations are consistent with the eustatic model assumption of constant ocean volume for much of the past two millenia.

3.3. Tectonic contributions to sea-level change

Potentially superimposed upon the eustatic–isostatic changes in sea level are tectonically driven changes in land level, including movements resulting from sedimentation and erosion, changes in crustal stress regimes, and tectonic processes at plate margins and plate interiors. Thus, local sea-level curves may reflect changes in ocean volume as well as tectonic signals. The occurrence of the latter can usually be identified by elevation of shorelines of the successive interglacials (particularly the MIS-5.5 shoreline) with respect to present sea level and first-order corrections can be made. We use the position of the inferred MIS-5.5 sea levels as a measure of average rates of vertical tectonic movement along the Israel coast with the assumption that for tectonically stable areas this shoreline occurs at $\sim 5-7$ m above present sea level in the eastern Mediterranean. According to Gvirtzman et al. [23], the Herzeliyya stratigraphical unit correlates with stage 5.5 and occurs between -55 and -25 m in the Caesarea area, with the lower one-third of the unit interpreted as marine and the upper part as aeolian. Thus, the marine horizon is indicative of a subsidence of about 40–50 m over the last 125,000 years at an average rate of 0.40 ± 0.06 mm/year or about 0.8 m over the past 2000 years. However, the detailed study by Mart and Perecman [24] indicates that the exposed aeolian deposits on the shallow shelf are cut by coast-parallel faults with 1–3 m offsets down throwing the seaward side but leaving the landward side stable. This interpretation is supported by the observation that aquaducts bringing water to Caesarea from the east maintained their gradients during the past 2000 years [24]. Hence, our null hypothesis is that any vertical movement of the land-side of Caesarea is the result of the glacio-hydro-isostatic effect only. This is consistent with the comparisons in Fig. 7c that indicate that the observed sea-level changes are compatible with the null hypothesis.

4. Conclusions

The near-coastal well data from Caesarea appear to provide reliable indicators of sea-level change for a period beyond the reach of the instrumental data and when most geological data is of lower accuracy. It therefore provides an important data set for examining fluctuations in sea level during the last two millenia with an accuracy of about 10–15 cm and additional data should provide a significant improvement for understanding both sea level and tectonic movements. The successful use of the well data rests on the ability to relate the well levels to the nearby sea level and on the assumption that this relationship has remained constant which requires that the wells must be close to the coast such that the water-table level is sea-level controlled. The wells less than 150 m from the coast appear to fulfill this condition but wells further inland do not. For example, two modern wells monitored for nearly 30 years, one about 250 m from the coast (well 55a, Fig. 1c) and well 54/0 at a similar distance from the coast about 1.5 km south of Caesarea (Fig. 1a) and both from locations where ground water has been extracted in modern times, give less satisfactory results (Fig. 8) in that they indicate a secular fall in the water level over thirty years that is much larger than the secular sea-level change over the same period. Thus, further monitoring of the well levels of the near-coastal wells is highly desirable to establish whether there is a secular component to the coastal well levels as well.

The present results indicate that during the Byzantine and Moslem periods, sea levels at Caesarea were at or above present level (Figs. 6 and 7c). The Late Moslem and Crusader data show greater fluctuations

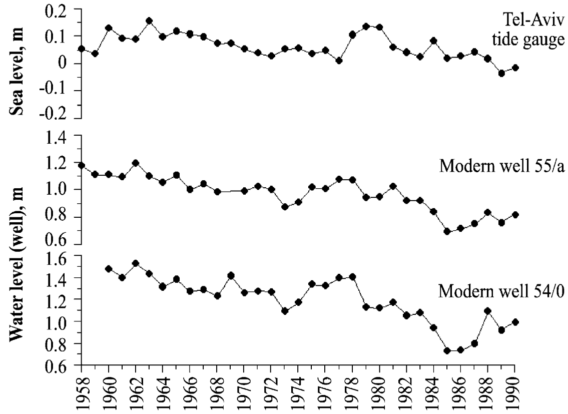

Fig. 8. Monthly water-table data derived from two modern monitoring water wells (for location, see Fig. 1c), representing 32 years, from 1958 to 1990, compared to sea levels during the same period. The wells: 54/0 south of the research area, coord. 209 /139, and 55/a south to the southern Crusader wall, coord. 211/140. The water-table data obtained from the Israel Hydrological Service, and sea level data from the Survey of Israel.

but the data sets are also much smaller than for the earlier periods (possibly during the Crusader period sea level may have been lower than today at about 30 ± 15 cm). These observed results are consistent with the observations for the earlier periods (Fig. 7a) discussed by Sivan et al. [11] and with the evidence from other Mediterranean localities once the differential isostatic effects are considered. In particular, ocean volumes appear to have remained constant for much of the past 2000 years. As indicated by the global tide-gauge data [25], eustatic sea level has risen at a rate of approximately 1.0–1.5 mm/year for the past 100 years but the record for the interval before this is restricted to a few isolated records [25] and the timing of the onset of this rise remains uncertain. However, if it were representative for the last millenium, then predicted sea levels for Crusader time would be about 1–1.5 m lower than today and for Roman time about 2–3 m lower than today. This is precluded by the well data and the onset of the modern sea-level rise must have been a relatively recent phenomenon.

The well data is consistent with an absence of significant vertical tectonic movement of the coast over about 2000 years and the earlier data extends this inference, albeit with less resolution, back to about 9000 years BP. The absence of significant vertical tectonics of the coastal plain is consistent with the preservation of an effective gradient in the Roman aquaduct across the plain [24]. However, the interpretation of the Last Interglacial evidence by Gvirtzman et al. [23] suggests that significant vertical movement has occurred over longer time intervals and that the repeat time between relatively large events may be longer than about 2000 years.

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References

[1] K. Lambeck, J. Chappell, Sea level change through the Last Glacial cycle, Science 292 (2001) 679–686.

[2] N.C. Flemming, Archaeological Evidence for Eustatic Change of Sea Level and Earth Movements in the Western Mediterranean During the Last 2000 Years, Geological Society of America, Colorado, 1969, pp. 1–125.

[3] Y. Porath, The water-supply to Caesarea: a re-assessment, in: D. Amit, Y. Hirschfeld, J. Patrich (Eds.), The Aqueducts of Israel, J. Roman Archaeology Suppl. Series, 46 (2002) 104–129.

[4] G. Le Strange, Library of the Palestine Pilgrim's Text Society XI.

[5] A. Raban, E. Galili, Recent maritime archaeological research in Israel—a preliminary report, Int. J. Naut. Archaeol. Underw. Explor. 14 (1985) 321–356.

[6] E. Galili, Y. Nir, The submerged Pre-Pottery Neolithic water well of Atlit-Yam, Northern Israel, and its paleoenvironmental implications, Holocene 3 (1993) 265–270.

[7] E.S. Marcus, Tel Nami, a study of a Middle Bronze 2a period coastal settlement. MA thesis, Haifa University, Haifa (1991) 259 pp.

[8] A. Raban, Dor-Yam: Marine and coastal installations at Dor in their geomorphological and stratigraphic context, Qedem Reports, Excavations at Dor, Final Report Volume 1A, Areas A and C, Introduction and Stratigraphy, the Institute of Archaeology, The Hebrew University of Jerusalem in cooperation of Israel Exploration Society, 1995, pp. 285–354.

[9] E. Bard, R.G. Fairbanks, B. Hamelin, 230Th–234U and 14C ages obtained by mass spectrometry on corals, Radiocarbon 35 (1993) 191–199.

[10] Y. Nir, I. Eldar, Ancient ground-water table in old wells as an indicator of paleo sea-levels and neotectonic changes along the coastal plain of Israel, Geol. Surv. Israel Rep. GSI/34/86 (1986) 28 pp. (in Hebrew).

[11] D. Sivan, S. Wdowinski, K. Lambeck, E. Galili, A. Raban, Holocene sea-level changes along the Mediterranean coast of Israel, based on archaeological observations and numerical model, Palaeogeogr. Palaeoclimato. Palaeoecol. 167 (2001) 101–117.

[12] Y. Sneh, M. Klein, Holocene sea level changes at the coast of Dor, Southeast Mediterranean, Science 226 (1984) 831–832.

[13] R. Gertwagen, The Crusader port of Acre: layout and problems of maintenance, Autour de la Premiere Croisade, Actes du colloque de la society for the study of the Crusaders and the Latin East, Reunis par Michel Balard, Publication de la Sorbonne, Paris, 1996, pp. 553–581.

[14] D. Neev, N. Bakler, K.O. Emery, Mediterranean Coasts of Israel and North Sinai. Holocene tectonism from geology, Geophysics and Archaeology, Taylor and Francis, New York, 1987. 130 pp.

[15] A. Sneh, Faulting in the coastal plain of Israel during the late Quaternary, reexamined, Isr. J. Earth-Sci. 49 (2000) 21–29.

[16] E. Galili, J. Sharvit, Ancient coastal installations and the tectonic stability of the Israeli coast in historical times, in: I.S. Vita-Finzi, C. Vita-Finzi (Eds.), Coastal Tectonics, Special Publication-Geological Society of London, vol. 146, 1998, pp. 147–163.

[17] K. Lambeck, Sea-level change and shoreline evolution in Aegean Greece since Upper Palaeolithic time, Antiquity 70 (1996) 588–611.

[18] K. Lambeck, E. Bard, Sea level changes along the French Mediterranean coast for the past 30,000 years, Earth Planet. Sci. Lett. 175 (2000) 203–222.

[19] K. Lambeck, Late Pleistocene and Holocene sea level changes in Greece and southwestern Turkey: a separation of eustatic, isostatic and tectonic contributions, Geophys. J. Int. 122 (1995) 1022–1044.

[20] K. Lambeck, Sea-level change from mid-Holocene to recent time: an Australian example with global implications, in: J.X. Mitrovica (Ed.), American Geophysical Union, Monograph (2002) 33–50.

[21] K. Lambeck, F. Antonioli, A. Urcell, S. Silenzi, Sea level change along the Italian coast for the past 10,000 years. Quat. Sci. Rev., in press.

[22] K. Lambeck, A. Purcell, P. Johnson, M. Nakada, Y. Yokoyama, Water-load definition in the glacio-hydro-isostatic sea-level equation, Quat. Sci. Rev. 22 (2003) 309–318.

[23] G. Gvirtzman, E. Schachnai, N. Bakler, S. Illani, Stratigraphy

of the Kurkar group (Quaternary) of the coastal plain of Israel, Geol. Surv. Isr., Curr. Res., (1984) 70–82.
[24] Y. Mart, I. Perecman, Neotectonic activity in Caesarea, the Mediterranean coast of central Israel, Tectonophysics 254 (1996) 139–153.
[25] J.A. Church, J.M. Gregor, P. Huybrechts, M. Kuhn, K. Lambeck, M.T. Nhuan, D. Qin, P.L. Woodworth, Changes in sea level, Intergovernmental Panel on Climate Change, Third Assessment Report, Cambridge Univ. Press, Cambridge, UK, 2001, pp. 641–693, Chapter 11.