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Tectonic and Eustatic Coastal Changes During the last 10,000 Years Derived From Archaeological Data

by

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with 13 figures and 4 tables

Summary. Data for 1053 coastal archaeological sites in the Mediterranean are analysed for age and relative vertical displacement. 335 sites produce accurate data from several periods, creating a reliable data set of 406 records for the last 10,000 years and with a vertical range from −11 m to +8.5 m relative to present sea level. The variance of rate of displacement is closely related to geographical location. The best fit eustatic curves for each region, after removal of the geographical component, are combined into a single best fit curve for the whole Mediterranean. The geographical variations are correlated with modern seismicity, historical seismicity, and sedimentary processes.

The highest rates of uplift or subsidence bear on coastal protection, navigational draught in harbours, and long-term seismic risk.

INDEXED

Introduction

Archaeological remains on the coast of the Mediterranean from which relative changes of land and sea level can be deduced include buildings and structures for the more recent archaeological periods, and caves, bones, middens, and stone tools for the older sites. The time range of the data used in this paper is about 8000 BC to AD 1920. Over 1000 sites have been identified which could produce data, and of these 335 do provide indications of sea level at dates in the past. Some sites produce multiple estimates for several different dates, and the total number of records with valid estimates for both age and displacement is 406 (table 1).

The data for 1053 identified sites were entered onto a Datagem Database operated on a BBC microcomputer. A complete printout of the geophysically relevant data and bibliographic references can be obtained from the authors. The numerical data from the Datagem file were transferred to a Honeywell 66 computer, and analysed using the BMDP statistical package. The precise argument for the deduction of relative change of land/sea level at each site can be obtained from the references, including those for which short codes are listed in Annex 1, and unpublished expedition reports by YORKE & DAVIDSON

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FLEMMING N.C. (1986)
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(1969), YORKE et al. (1973), and CLARIS & COLLINSON (1977). These publications and reports provide data on 300 sites, with numerous references to substantiate each site.

There is a need to reassess the conclusions of all papers prior to about 1965/70, so as to re-interpret the data within the modern structure of geophysical knowledge. The present archaeological data set provides 406 estimates of relative land/sea level throughout the Mediterranean, mostly dating from the last 5000 years. The technique is accurate to approximately 0.2–0.5 m vertically (F2, F5, F7, S1), and to about 100–200 years in age for the last 3000 years. (For assessment of errors see F5.) Previous publications by various authors have been based on different criteria, with different assumptions of eustatic and tectonic theories, and using different statistical methods, if any.

This paper is more nearly complete than previous publications, but inevitably many sites have been omitted. With regard to sites of the classical period (broadly 2500–1600 BP) the site list is more or less finite, since ports and harbours of the Greek, Roman, and Phoenician cultures were comparable in scale and distribution to modern cities. However, even within this period (S1) has shown that numerous individual structures can be identified between major cities. For more recent periods castles, slipways, moles, etc., of Norman, Portuguese, Byzantine, Genoese, Turkish, Armenian, and other civilisations occur in a sporadic, but very useful way, thoughout the Mediterranean area. For older periods, Iron Age, Bronze Age, and Neolithic sites are now being discovered in considerable numbers (FM1), and even some Palaeolithic sites (F7, FM1). Cave sites, Neolithic villages, and Palaeolithic kill sites throughout the area of the continental shelf extend the technique potentially in time and space, and increase the possible number of sites into many thousands.

Methods and accuracy

To construct the MEDSITE database all known sites were identified from the multi-site sources, together with reports and data on single sites from the archaeological literature and atlases. So far as possible all sites were labelled with an ancient name and a modern name, and recorded with their latitude and longitude. Of the 1053 sites, sea level estimates and age were derived at 335 (table 1). Data for over 270 of the present sites are based on field surveys by the principal author. For the majority of the other sites employed in the calculations, the present paper uses the same estimate of relative sea level changes as cited by the original authors. However, the data of other published authors has been used as data only, and the conclusions with regard to eustatic or tectonic change may be different in the present paper. Additionally, the present data base contains estimates of the accuracy of data, defined by a probable error bar on the basis of the type of sea level indicators used, and the inherent limits on accuracy described in the next section.

In general, data earlier than 5000 BP only indicate that an occupation site was dry land at a given date, but the sea level may have been several metres lower, unless geomorphological evidence can be found for linking shoreline features and human artifacts into a contemporaneous assemblage. Sites which can be dated by artifacts, but can only be proven to be above sea level, are termed "one-sided" in the present study. In statistical studies the "one-sided" data points were sometimes included and sometimes excluded in order to test different hypotheses. There are 14 one-sided sites, all older than 5000 BP.

Table 1. Data volumes per region.

Region number	Name	SIT	DTA	NON	A/S %	DDD	MLT	ONE	X km	Y km	AREA km^2	CST km	DSP km	SSP km
1	Spain	64	24	40	38	24	2	2	1780	280	498,400	2200	92	34
2	Balearics	5	2	2	40	4	2	0	310	130	40,300	6500	325	130
3	Morocco	52	24	28	46	26	2	2	1600	280	448,000	2200	92	42
4	Sardinia	16	3	13	19	3	0	0	180	500	90,000	1400	467	88
5	W. Italy	102	42	60	41	45	4	0	1100	270	297,000	1800	43	18
6	Adriatic	71	3	68	4	6	2	0	890	330	293,700	3100	1033	44
7	Sicily	43	9	34	21	9	0	0	470	610	286,700	900	100	21
8	Sirte	13	5	8	38	5	0	0	980	260	254,800	1550	310	119
9	W. Greece	38	1	37	3	1	0	0	360	190	68,400	600	600	16
10	Peloponnese	71	30	41	42	32	2	0	240	300	72,000	1000	33	14
11	Crete	72	43	29	60	47	3	0	330	130	42,900	650	15	9
12	N. Aegean	185	5	180	3	8	1	0	680	420	285,600	–	–	–
13	S. Aegean	36	5	31	14	6	1	3	410	240	98,400	–	–	–
14	S.W. Turkey	66	36	30	55	47	9	0	380	310	117,800	–	–	–
15	Rhodes	25	17	8	68	20	3	0	200	80	16,000	300	18	12
16	Cyrenaica	36	4	32	11	5	1	0	830	120	99,600	950	238	26
17	E. Turkey	32	23	9	72	23	0	0	530	130	68,900	700	30	22
18	Cyprus	36	17	19	47	20	4	0	250	170	42,500	700	41	19
19	Egypt	4	0	4	0	0	0	0	450	110	49,500	500	0	125
20	Syria/Israel	83	42	41	51	75	20	6	710	110	78,100	650	15	8
21	Islands	3	0	3	0	0	0	0	–	–	–	–	–	–
					mn						mn	mn	mn	mn
Total/means		1053	335	718	32	406	56	13			162,430	993	164	36

Distribution of valid and invalid data records by region. Codes as follows: SIT=number of sites; DTA=number of sites with valid data; NON=sites with no data; A/S=percentage of sites with data; DDD=number of valid data records; MLT=number of sites with more than one valid period; ONE=sites with 1-sided records; X and Y=dimension of the region in km; AREA=area of region km^2; CST=length of coastline in km; DSP=mean spacing between sites with valid data; SSP=mean spacing of all sites. Note that regions 12, 13 and 14 have such complex coastlines that the length cannot be measured accurately. mn=mean value.

By observing solution notches and comparing the present notch with higher or lower notches (e.g. SPRATT 1865; GU1, H2, P4, F4). Mean sea level in the open sea can only be determined to an accuracy of about 0.2–0.3 m. Even in sheltered bays, the error is of the order of 0.2 m. Notches occasionally cut across structures, as at the Roman quays in Marseille (32), the harbour entrance at Phalasarna (365), or the Casa degli Spiriti at Posilipo (75).

A rock-cut storage tank or fish tank can act as a stilling pool, with the long entrance channel acting as a filter to remove wave action, as at Dor (199), Lambousa (382), and Caesarea, Israel (203/1058) where the tanks are not submerged below the level of the outer walls. In these circumstances the flat water surface combined with the tidal range of 20–30 cms results in a double solution notch, with a small indentation at mean high tide, and a second at mean low tide. The W-shaped indentation has a profile which can be matched very precisely between ancient and modern notch system, with an accuracy of 0.1 m. Since the notch system records mean sea level averaged over several decades, this observation requires no correction for seasonal or barometric factors, provided that there is a similar double notch at present sea level.

Accuracy

Once the accuracy of individual observation approaches 0.3–0.2 m further limitations occur. Assuming that the tidal cycle is measured or known, the relative change of level can be corrected; but often the state of the tide is not known in relation to the time and date of observation. The Mediterranean tides are of the order of 0.2–0.5 m, and so are not regarded as important for shipping and navigation. The only reliably way to obtain tidal data is to install a tide gauge during the period of measurement, and very few observers have done this. Seasonal and barometric variation of sea level is of the order of 0.3 m (F5, F6, S1, STRIEM 1974; RICKARDS 1985). We know of no case where this factor has been taken fully into account, although FLEMMING (1983, unpublished report) recorded fluctuations of daily mean sea level of 0.4 m during a 6-day study of Tel Qatif (225).

So far as is known to the present authors, the only sites at which observations were corrected by on-site measurement of the state of the tide are the data reported by (S1) and Lambousa (382), Salamis Cyprus (392), Kenchreai (244), Tel Qatif (225), Aghios Petros (964), Tel Nami (195), Dor (199), Caesarea (203/1058), and Pavlo Petri (970).

The most accurately observed data set assembled so far is that published by SCHMIEDT (S1), but as he does not state how mean sea level was established locally, it must be implicit that there are unresolved errors of the order of 0.2 m.

Since many structures were in use for 2 centuries or more, and since expected relative rates of sea level change are of the order of 0.05–0.1 m per century, a time error bar of 2 centuries is equivalent to a vertical error bar of 0.1–0.2 m.

In addition, uncertainty arises from our lack of knowledge about acceptable frequencies of flooding or drying out of structures. In short, good observation and instrumental methods results in an accuracy of the order of ±0.2–0.3 m in the best cases, but refinement beyond this point would require full tidal, storm, barometric, and seasonal correction at every site, combined with subjective estimates of permissible frequency of flooding. No site has yet been observed in such detail.

In addition to those artifacts or structures which produce precise data, many other features can be classified as to whether they must have been dry (e.g. a road surface,

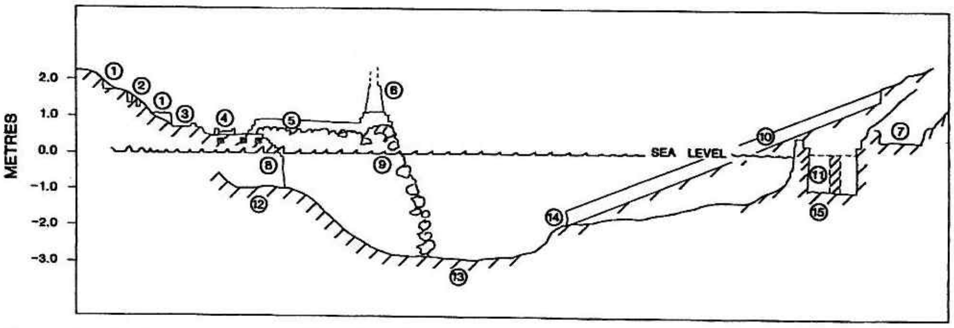

Fig. 1. Synthetic composite profile of a classical harbour site illustrating the architectural features and structures which indicate sea level; (a) above contemporary sea level, 1) house foundations, 2) tombs, 3) road, 4) quay upper surface with buildings; (b) partly above and partly below contemporary sea level, 5) quay and wall on top of breakwater, 6) lighthouse foundations, 7) storage tanks, silos, salt pans, 8) quay wall with steps and mooring bollards, 9) rubble breakwater, 10) working surface of slipways, 11) upper part of fish tanks; (c) below contemporary sea level, 12) base of quay wall, 13) floor of harbour channel, 14) bottom end of slipway, 15) floor of fish tanks. [Horizontal scale arbitrary].

mosaic floor, tomb, etc.); part in the water and part out (e.g. mole, quay, slipway, etc.); or wholly submerged (e.g. floor of an entrance channel to a harbour, floor of a fish tank). If many structures exist at a single site, the assemblage may provide a very accurate bracket. Figure 1 shows an idealised cross-section of a site with structures which indicate sea level. At some sites (e.g. Atlit, 193; Dor, 199) structures from different archaeological periods provide a relative sea level time curve.

In reassessment of early data by the principal author (especially F1, F2, F3) derivations of sea level and error bars have been revised in some cases on the basis of subsequent experience, and further data on the site.

The accuracy of vertical displacement and time estimates may not be symmetrical. For example, a site may have been built at a known date, or destroyed at a known date, but not both. The date error bar is therefore firmly limited on one side, but extends with diminished probability in the other. Similarly, a key structure such as a mole foundation may place a lowest possible level on sea level, but there may be no data to limit the highest estimate. The method for allocating probability histograms to such data is given in (F3, F4). In the present paper, since many of the sites have not been personally visited by the principal author, a more conventional estimate of errors is used, based on symmetrical error bars.

Choice of reference level

The standard reference level for a survey concerned with precise vertical levelling is usually the ordnance survey datum for the country concerned, or the national benchmark for mean sea level. The only site known to the present authors for which this has been done is Marseille (32) which is a standard port with a major tide gauge installation (P3, p. 17).

The alternative choice of reference level is the present observable sea level at the site itself. There is some logical benefit from this, and some disadvantage. The logical benefit arises because the purpose of the study is to find evidence for change of relative sea level at that site.

The disadvantage is that mean sea level still must be determined at each site by direct measurement. Since there are few Mediterranean ports with tide gauges (see PSMSL 1976) and few calculations indicating the relevant time and amplitude of tides in bays and re-entrants, it is not usually possible to make short term measurements, and then use these to compute the tides relative to a principal port. Any measurements made at a site have to be regarded as self-sufficient, so far as they go.

Figure 2 shows the boundaries of the regions within which the data are analysed. The structure of the data set will be described in terms of the total data set and each region separately. Regions 1 and 3 overlap, but in the present analysis data in the overlap zone are counted in Region 3. A valid site is a site where at least one estimate of sea level change and date is recorded. An invalid site is one where no conclusion has been reached on an estimate of sea level change for any date span. A valid site may be described by several valid records, and several invalid records. The invalid records in this case refer to periods in the history of the site for which some data are available but not enough to reach a conclusion for that period.

Table 1 shows that regions 2, 4, 6, 7, 8, 9, 12, 13, 16, 19, and 21 each contain so few valid data sites that full statistical treatment is not feasible. Regions 2, 4 and 7 are small, and the available data can be analysed in simple mathematical terms and by visual inspection. Regions 6, 9, 12, and 13, have a great number of inconclusive sites, and statistical analysis is not justified on the basis of the very small sample available. Regions 8, 16, and 19 are large, but have a low density of settlements per km of coast. These regions will only be analysed in simple terms.

Figure 3 shows the distribution of data in time, with mean age, range, and mean errors for each region. Figure 4 shows a histogram of frequency of occurrence of sites of different ages.

Figure 4 shows that the data are heavily concentrated in the last 4.0 ka with a peak occurrence at 2.0 ka. This peak is a real reflection of the high development of harbour building during the late Roman Republic and early Imperial years. One-sided estimates are all earlier than 5 ka.

Figure 2 shows a dot map of the distribution of valid sites. On this scale it is not possible to insert the site numbers. The spacing of valid sites along the coastline, and the average area containing one site for each region are shown in table 1. The vertical error range of each data point was converted into a weight value, and used in the BMDP statistical tests. See Figure 5 for the frequency of occurrence of errors, and the related weights.

Data analysis

General principles

On theoretical predictions (CLARK & LINGLE 1978: 281, 295 & 296) the eustatic factor in the Mediterranean may either produce a slight rise above present sea level about 2000

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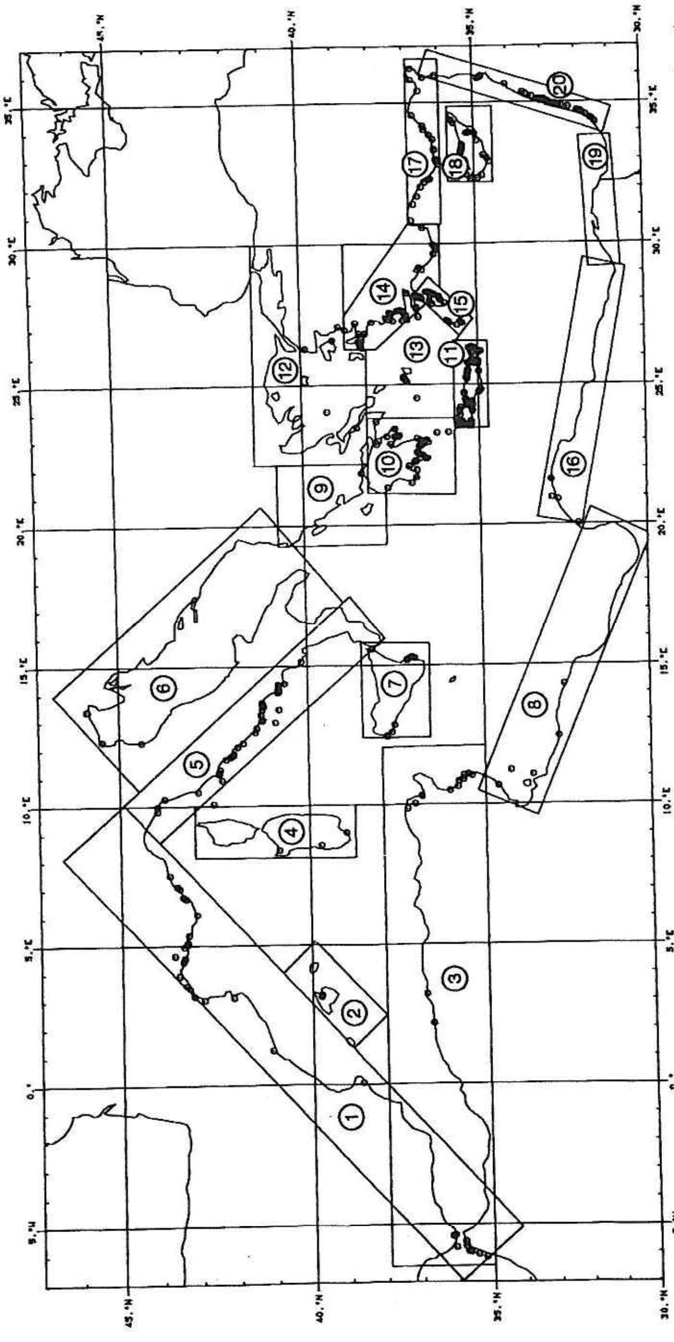


Fig. 2. Dot map shows the distribution of valid data sites included in the analysis. Boundaries of regions for analysis are shown, and region numbers. See table 1 for statistics of sites per region.

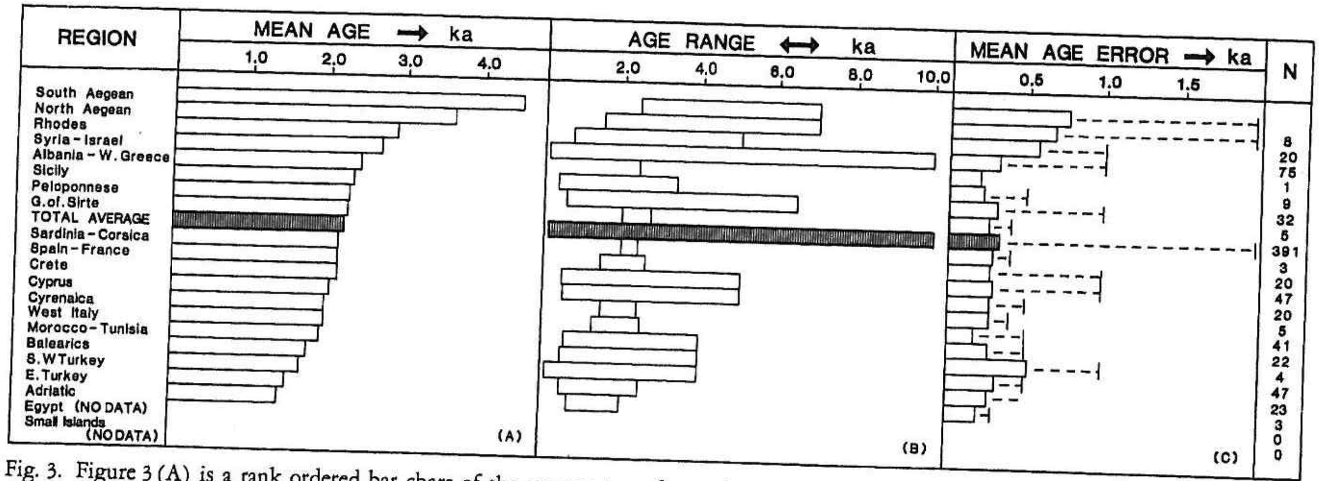


Fig. 3. Figure 3 (A) is a rank ordered bar chart of the average age of records at sites in each region, measured in thousands of years (ka); 3 (B) shows the range of age of records in each region; 3 (C) shows the mean error, and maximum error, for records in each region.

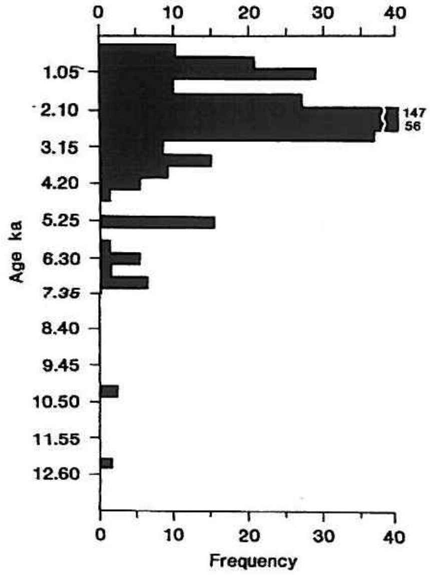


Fig. 4. Histogram of frequency of occurrence of records by age (ka). The age interval is 0.35 ka; records in each interval have an age less than or equal to the label. All sites are included for which age data exist.

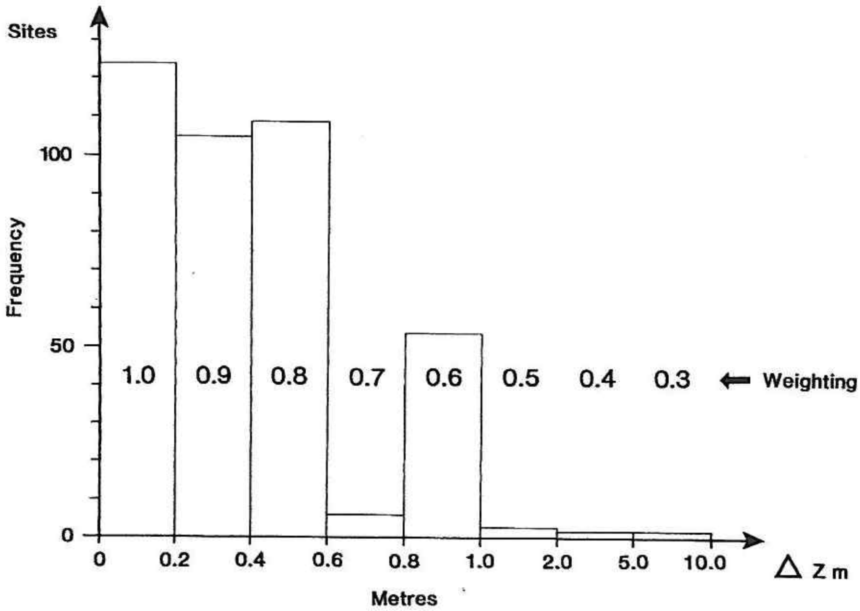


Fig. 5. Histogram of frequency of occurrence of errors in estimates of vertical displacement for each site record. Estimate of error is based on the type of data and accuracy of measurement at each site. For each error range the weighting allocated is shown in bold lettering. The weights are used in the statistical analysis.

years ago, followed by a gradual fall, or it may produce a gradual rise from 1.0 m below present sea level 4000 years ago, steadily up to present sea level. (F5). NEWMAN et al. (1980) and other authors have shown that eustatic sea level fluctuations of the order of 0.5–1.0 m during the last 5000 years are difficult to separate statistically from local tectonic and isostatic deformations of coastal regions. No assumptions can therefore be made about stable and unstable zones, the type of relative sea level curves to be found in each region, or the type of absolute common sea level curve which we may deduce for the whole Mediterranean after removal of tectonic, isostatic, and compaction effects.

A scatter diagram of vertical displacement against age for all valid sites emphasises the problem (fig. 6). The existence of vertical earth movements is manifest.

Ideally the measurement of vertical earth movements and sea level changes would be based on the same number of data points in each vertical interval. Figure 7 shows that the actual distribution of data is far from ideal. The modal frequency, with 204 occurrences, is in the vertical interval 0.0 to –0.60 m. This mode is largely accounted for by Roman and Greek ports of age approximately 2.0 ka. The overall form of the distribution is approxi-

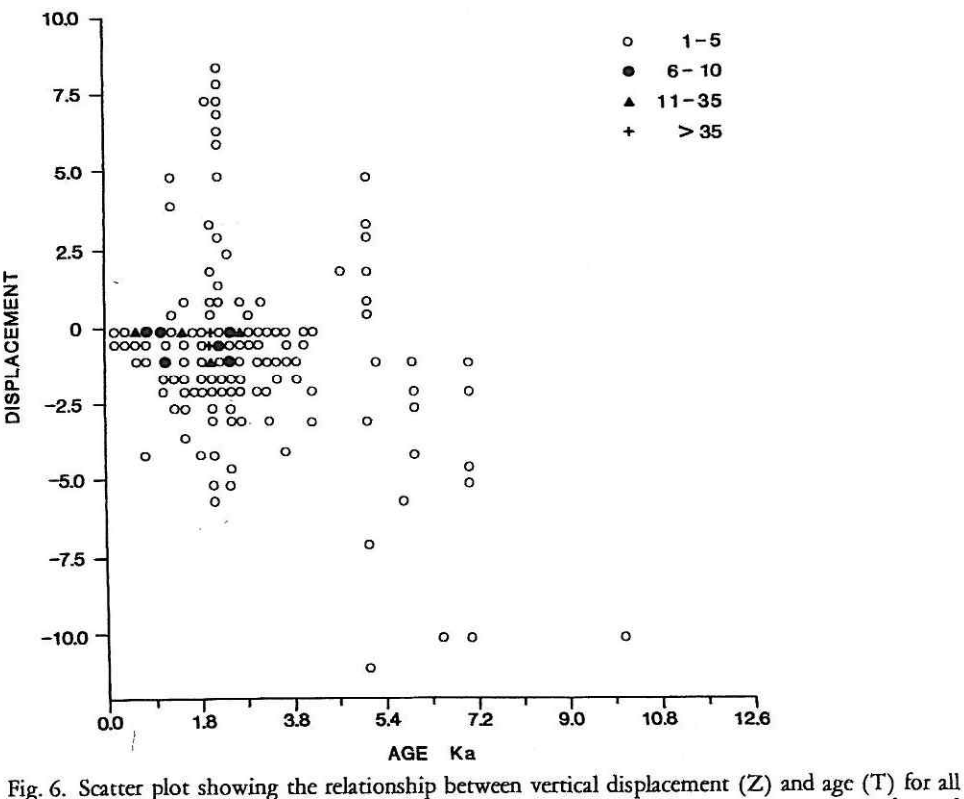


Fig. 6. Scatter plot showing the relationship between vertical displacement (Z) and age (T) for all valid records. Note the massive concentration of data trending slightly below the axis to 2 ka, and the bifurcation of the scatter into relatively uplifted and submerged site records.

mately normal, due to the occurrence of highly uplifted sites in Crete and Rhodes on the one hand, and the occurrence of a small number of deep water Neolithic sites at the opposite end of the scale.

The histogram of frequency of occurrence of rates of vertical change (fig. 8) shows a pronounced peak at the range 0.0 to −0.30 m/ka. The mean rate of submergence is −0.262 m/ka. This implies that a large number of sites have been submerged at this rate for at least 2.0 ka. These simple statistics of the whole data set confirm, and put on a broader basis, the proposals of (S1) and (P2) to the effect that there has probably been a net average relative sea level change in the Mediterranean of about 0.4–0.5 m since 2000 years ago. This rate is also consistent with the regional results for SW Turkey (F3) and Israel (F6). However, fig. 8 also shows that the rate of displacement varies from −5.7 to +4.5 m/ka. Although some of the extreme rates could be rejected as obviously associated with tectonism, more detailed analysis is required to identify the components of relative change which can be attributed to eustatic causes and earth movements in such a way as to explain all the data.

The data for vertical displacement and rates of displacement are grouped by region in fig. 9. Regions show significant differences in mean displacement and mean rates of displacement. The extreme value for the Adriatic is caused by the fact that the only data for the region come from a few sites close to the Po delta. The regions also differ in that some have a narrow range of displacement and rates of displacement, whilst others are more noisy, with wide ranges. Of the regions with a significant number of data points, East Turkey is quietest on every count. Morocco-Tunisia comes second. Crete, West Italy, and the Adriatic have the greatest variety in rates of displacement.

The previous discussion is based on simple bulk statistics on the whole data set and regions. No distinction has been made between one-sided and two-sided sites, and no allowance has been made for the inclusion of a small number of sites older than 5 ka, from a period when eustatic rates of change were probably of the order of 5–10 m/ka. Table 2 shows the effect on the bulk means of including all known data for a given variable, restricting analysis to valid sites only, and to valid 2-sided sites only. Since the 1-sided sites are all older than 5 ka, removal of these from the data set reduces the mean age slightly, mean displacement, and the mean rate of submergence. The changes are small, and explicable, but do not alter the previous generalisations.

It is not possible to apply contoured best fit surfaces to the distribution of earth movements for the whole Mediterranean, since the analysis of site distribution shows that the grouping of sites only justifies extrapolation or interpolation over distances of the order of 50 km. Even that is risky in the Aegean area where tectonic de-coupling and horst-and-graben features may occur over distances of the order of 20 km. NEWMAN et al. (1980) and MARCUS & NEWMAN (1983) have shown that valuable results can be obtained applying a spline technique on a continental basis, but in the context of the present study it is not reasonable to suggest that data on the coastlines measured with an accuracy of 20–40 cm are going to provide predictions of any comparable value which are applicable to the central Mediterranean sea floor, or the central Anatolian Plateau.

Fitting a polynomial surface, or any other analytical surface, to a set of data, is equivalent to testing a physical hypothesis for the explanation of the data. Thus a planar surface fitted to the uplifted sites of western Crete is equivalent to saying that western Crete is tilting as a rigid block (F5, p. 430). An exponential decay fitted to a model of glacial isostatic recovery is stating assumptions about the rheology of the mantle and lithosphere

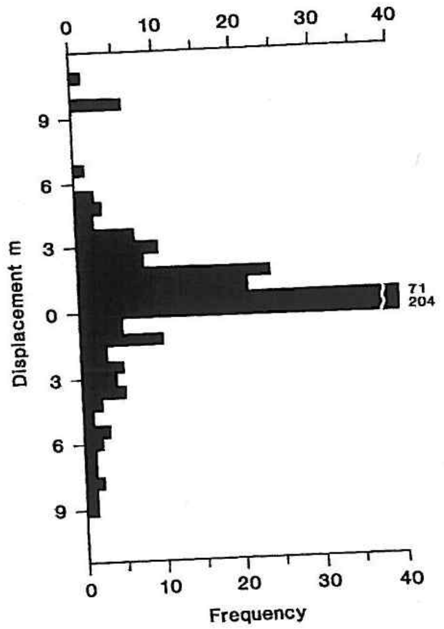


Fig. 7. Histogram of the frequency of occurrence of values of vertical displacement (Z) in metres. The interval width is 0.6 m; records in each interval have a value equal to or less than the label. All valid records are included.

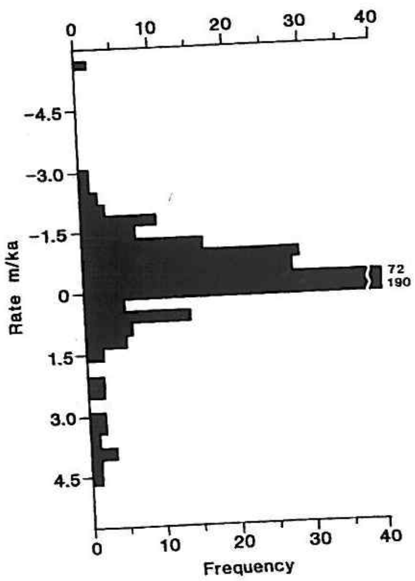


Fig. 8. Histogram of the frequency of occurrence of values of rate of vertical displacement (Z/T) in metres per ka. The interval width is 0.3 m/ka; records in each interval have a value equal to or less than the label. All valid records are included.

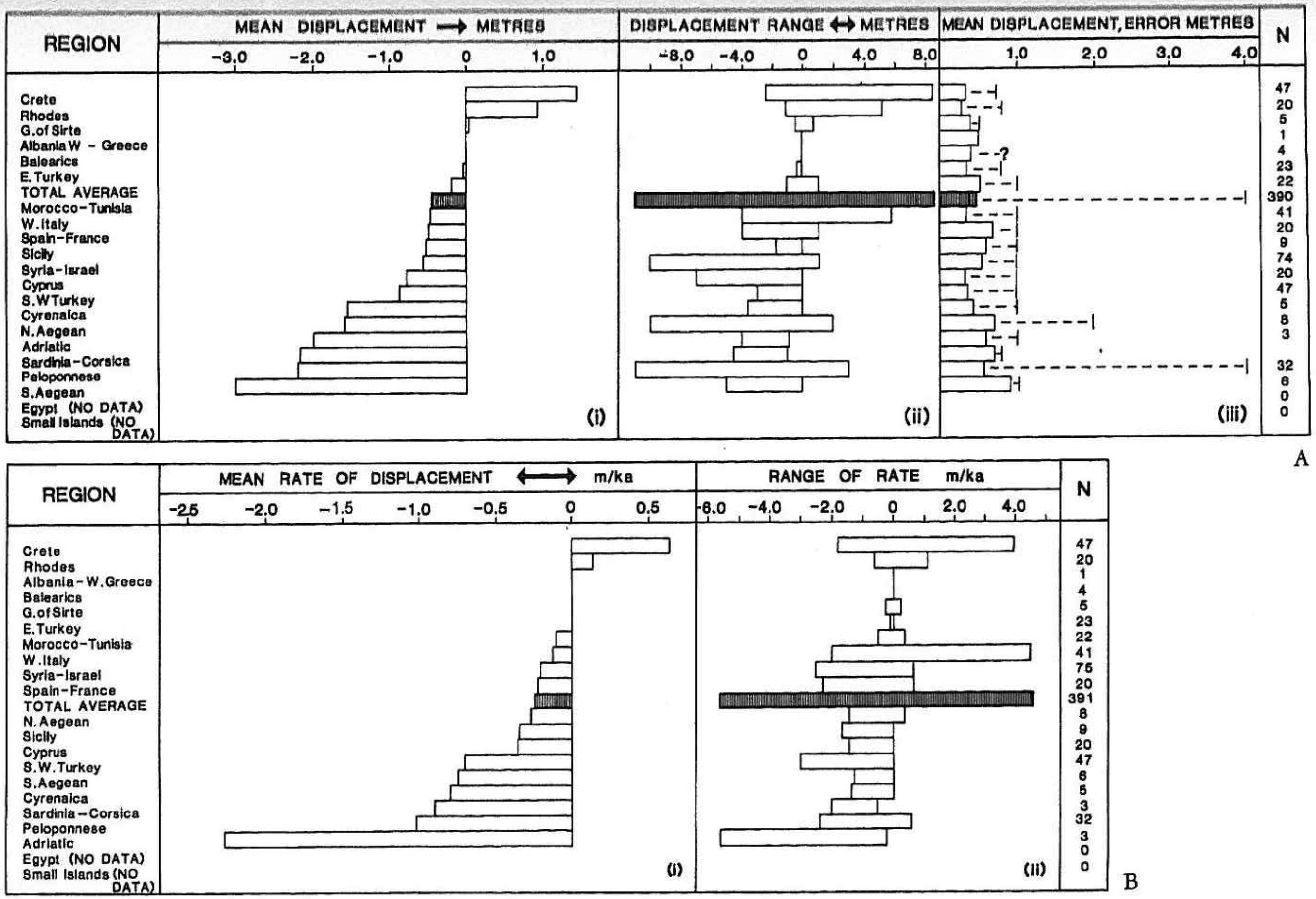


Fig. 9. A (i) Ranked bar chart of the magnitude of mean displacement in metres for each region; A (ii) range of vertical displacement of site records within each region; A (iii) mean error and maximum error of estimates of vertical displacement for records at valid sites. B (i) Ranked bar chart of the mean rate of displacement in m/ka for each region; B (ii) range of rate of vertical displacement for all valid records at sites in each region.

Table 2. Effect of inclusion of different data points on mean values.

	All sites A+B	A – only, 1+2-sided	A, – 2-sided only
Mean Age (ka)	2.381	2.294	2.222
Mean Displacement (m)	–0.555	–0.564	–0.436
Mean Rate (m/ka)	n.a.	–0.262	–0.233
Total no. of Records	1147	–	–
Records of Age	477	406	391
Records of Displacement	409	406	391

Data records are not complete for all sites. Some sites have no data, some have only age data or only displacement data, all classified as (B); some have both age and displacement data (A). Valid (A) sites may contain data records which have displacement indicators providing accurate estimates (2-sided), or only an upper limit (1-sided). The mean values of various parameters are calculated using different sections of the total data set.

(see discussions in MÖRNER 1980). In contrast, a contouring package which joins a series of cubic splines in order to obtain a representation of the data of arbitrary smoothness is not testing a physical hypothesis, it is depicting the data graphically for subsequent analysis. In the present case we have chosen to test a wide range of analytical surfaces and curves on regional subsets of the data. This requires justification.

Firstly, the choice of analytical surfaces is deliberate, since this tests the physical nature of processes at work. Secondly, the choice of long narrow coastal strips for analysis reduces the dimensionality of the problem. Thirdly, the bunching of the data within narrow coastal strips more or less dictates such a choice, since there is no justification for bridging large data gaps over either land or water. (Highly crenelated coastlines and archipelagos such as Yugoslavia and the Aegean require treatment in more equiaxial regions.) Finally, fitting an analytical curve by regression results in an objective measure of the magnitude of residuals in comparison with the explained variance of the data. Different hypotheses and models can thus be compared for goodness of fit, and the simplest model selected which explains most of the data.

The choice of region boundaries is necessarily somewhat subjective. Very small narrow rectangles would be possible, but each one would contain very few data points, and statistical tests would be invalid. To fit analytical surfaces and curves of cubic or quartic degree will require several tens of valid points per region. The larger equiaxial regions were defined first (fig. 2, regions 6, 7, 10, 12, 13, 14, 16). Then the smaller islands were given discrete regions (2, 4, 21).

The final criterion was to make the remaining regions as long and as narrow as possible, and to terminate a region boundary when a change in orientation of the coast would result in a broadening of the region so that site-to-site interpolation would become unjustified across open spaces of land or sea. The most obvious junction of this kind occurs at Genoa, at the junction of Regions 1 and 5.

Within each region the analyis is based on the following principles. The local regional sea level curve common to all sites within the region is assumed to have an analytical form with two or three turning points, expressible as an equation in displacement, Z, and age, T, only. The earth movements at each point are assumed to occur at a constant rate (up or down) averaged over 500–1000 years. Tectonic events are often periodic in nature (AMBRASEYS 1971; (F5); VITA-FINZI & KING 1985) so that one cannot assume a literally constant velocity. Reversals of a stick-slip nature may also occur (F5). Nevertheless, a constant rate over the periods of the order of 500–5000 years is reasonable.

At some sites the assumption of a constant rate and direction is clearly wrong. (F2) decribes major reversals of direction in the Naples region. (F5) describes reversals of movement in southern Crete, and northern Rhodes. (P4) deduces major reversals of direction in Crete. In the present data set there is additional evidence for reversal of direction at least for short periods at Dor (199), Sidon (939), Arvad (931), though the apparent reversal could be due to either tectonic or eustatic factors. At Caesarea (203/1058) there is evidence that tectonic activity or local slumping caused half of the city to subside into the sea. There are thus two data points of identical date, and almost identical location, but with different altitudes. As a first method all the data will be treated at face value, and these anomalies will presumably result in large local residuals. For analysis the location of each site is defined with reference to the corners of the region. Rectangular co-ordinates X, Y, parallel to the boundaries of the region, are measured in kilometers.

Results

Regression of displacement on age only

The regions with sufficient data were tested for the dependence of vertical displacement of sites on age, using a cubic equation. The mean square residuals are shown in table 3. Additionally, the regions with the most data points, 5 and 20, were tested using a quartic equation. Not surprisingly, residuals were highest for the regions with obvious tectonic activity, and lowest for eastern Turkey, which is almost completely stable with respect to present sea level. Mean square residuals are generally in the range 0.2 to 2.4 m.

The curves for each region, and the mean curve for all the data, show extreme diversity (fig. 10). Whilst it may be obvious that some regions are more affected by tectonic activity than others, the diversity of curves in fig. 10 goes at least some way to explain why different authors working in different parts of the Mediterranean have obtained different estimated eustatic curves. The curve for the whole data set is generally plausible as an estimate of the eustatic curve for the Mediterranean, suggesting that, with the very large data sample, the range of tectonic and sediment-subsidence factors are distributed normally, and partially cancel out. The form of the curve for the whole data set, and the scale of the residuals, indicates that curves of 3rd or 4th degree may be adequate models for the eustatic component of relative change of land/sea level.

Regression of displacement on location

To model the spatial variation it is desirable to allow for doming, tilting, and saddle-point topographic deformations, requiring cubic or quartic equations in X and Y. A quartic equation would have 14 terms, which together with the terms (cubic or quartic) relating

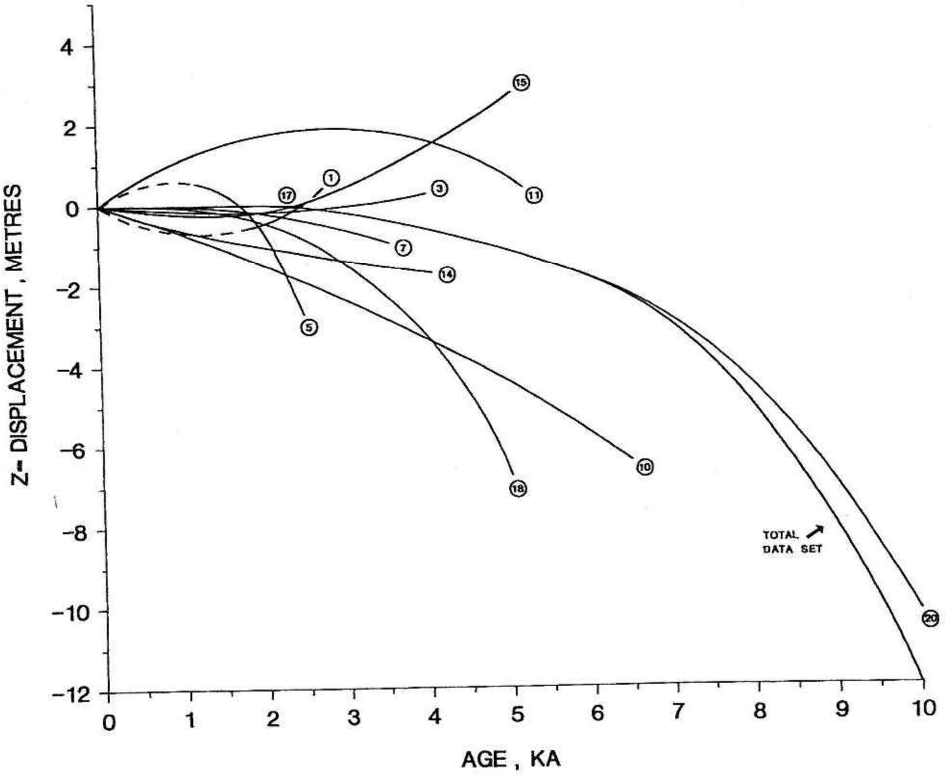


Fig. 10. Best fit curves showing the relationship $Z=f(T^n)$, for site records for each region and the whole data set, where Z=vertical displacement in metres; T=age of each site record in ka. Equations are 3rd or 4th degree depending upon the number of valid records. Valid 2-sided records are included. Geographically dependent earth movements have not been subtracted from the data. Numbers indicate regions.

to age, would make the equation too large to be correlated with any but the largest regional data sets. In order to reduce the number of terms, the long narrow regions (1, 3, 5, 17 and 20) are analysed principally in terms of the along coast distance, X, using a cubic or quartic equation. They were then tested for an onshore-offshore component by including a linear term in Y. The more equiaxial regions (7, 10, 14, 15, and 18) were analysed in terms of quadratic and cubic expressions in X and Y, and Crete (11), quartic.

Since rate of displacement by earth movement is assumed to be constant at each location, the observed displacement at a point is the product of that rate, and the age of the site. It is therefore the rate of displacement which must be correlated with location. Since the mean age of sites is 2.2 ka, residuals based on rate should be approximately doubled for comparison with the residuals of displacement from the regression on age. The residuals obtained for narrow regions by a regression of rate of displacement on distance along the coast, using a cubic equation, and on geographical location in terms of X and Y for the more equiaxial regions, suggest that the variability of the observed data is explained at least as much by location as by age.

Regression on age and location combined

The previous analyses suggest that a combined equation should be at least cubic in age, and cubic or quartic in locational co-ordinates, provided that there are sufficient data. The general equation is of the form:

$$Z = T \times f(XY) + f'T$$

where f and f′ are unknown polynomials of degree 2, 3, or 4. In order to reduce the correlation between terms, and improve the efficiency of the regression analysis, it is desirable to remove the common factor of T from the right hand side of the equation, which then becomes:

$$\text{Rate} = Z/T = f(XY) + f'T.$$

For each region variations of this equation were tested, until minimum square residuals were achieved (Table 3). For the linear regions Spain–France shows a reduction of

Table 3. Mean Square Residuals.

	A	B	C	D
Region	$Z \propto T^n$ (1)	$Z/T \propto X^3$	$Z/T \propto X^4, T^3$	$Z/T \propto X^4, Y, T^3$
Whole	3.54	–	–	–
Linear				
1	0.7123	0.2196	0.2048	0.1536
3	0.1814	0.0295	0.0344	0.0371
5	2.3508	1.288	0.1522	0.1608
17	0.0008	0.0002	0.0001	0.0001
20	0.6407	0.2141	0.1947	0.1938
	$Z \propto T^n$	$Z/T \propto X^n, Y^n$ (2)		$Z/T \propto X^nY^nT^3$ (2)
Equiaxial				
7	0.4375	0.0456		n.a.
10	4.4280	0.2741		0.2769
11	9.281	0.2042		0.1879
14	0.4832	0.3315		0.2476
15	1.6247	0.1708		0.1356
18	0.5290	0.1490		0.1284

Notes: (1) $n=3$ or 4; (2) $n=2, 3, 4$ depending on number of data points.
The table shows the mean square residuals for each data region, and for each type of polynomial equation tested. The upper part of the table refers to the linear narrow regions; the lower part to the more equi-axial regions. All data sets utilised valid A data, 2-sided only. For discussion see text.

23% when a factor for offshore tilt is included, and Syria–Israel shows a reduction of 0.5%. The other linear regions are not improved by including a tilt component. Of the equiaxial regions, Sicily does not have enough valid points to make a useful test. The Peloponnese fit remains almost unchanged by inclusion of the eustatic term. For Crete, the highly complex tectonics are well-modelled by the combined equation, and the final residual is very low. SW Turkey, Rhodes, and Cyprus, all show minimum residuals with the combined equations.

Eustatic curve in last 5 ka, after removal of earth movements

The regression coefficients of the terms in T, and the constant term, from the best fit equations, were used to generate polynomial equations for displacement in terms of age only for each region.

The attempt to solve the equations simultaneously for sea level changes and earth movements has failed for Regions 1 and 5. For both regions the reason is a lack of data in the last 1 ka from relatively stable areas (see fig. 11 A).

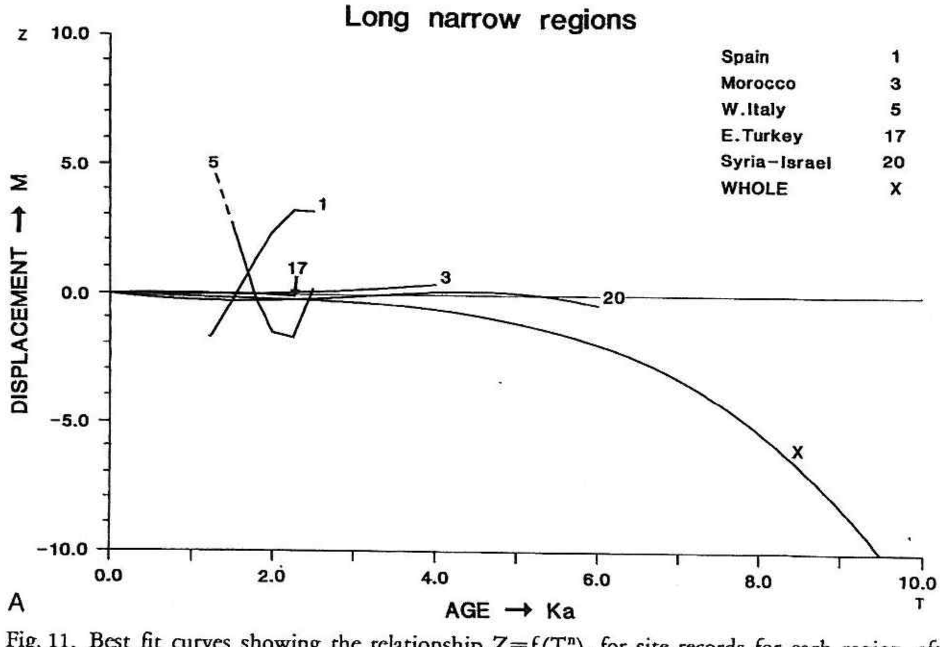
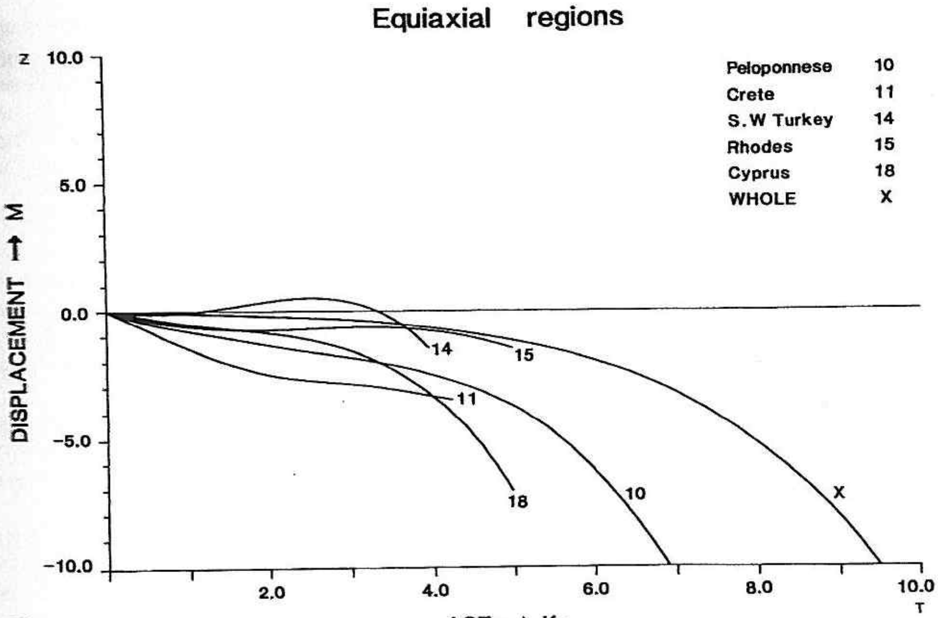
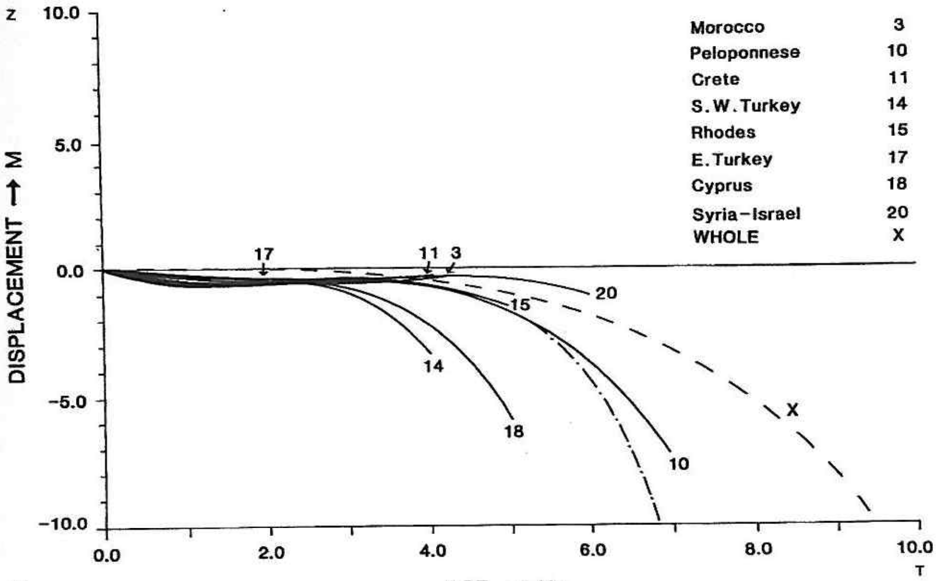


Fig. 11. Best fit curves showing the relationship $Z=f(T^n)$, for site records for each region, after removal of geographically dependent components representing earth movements. Z=vertical displacement in metres; T=age in ka. A=curves for long narrow regions, uncorrected for transfer of linear component of rate of change between eustatic factor and earth movements; B=equi-axial regions, uncorrected for transfer of linear component of rate of change between eustatic factor and earth movement; C=all curves from A and B after correction by transfer of linear components of rate of change to or from earth movements. Numbers indicate regions. In each plot the original mean plot of Z against T for the whole data set is reproduced for comparison. The dotted section of the final curve in C is based on the inclusion of 1-sided data.


Equiaxial regions
Peloponnese 10
Crete 11
S.W Turkey 14
Rhodes 15
Cyprus 18
WHOLE X
Z
DISPLACEMENT → M
10.0
5.0
0.0
-5.0
-10.0
2.0
4.0
6.0
8.0
10.0
T
AGE → Ka
14
15
11
18
10
X

B


Morocco 3
Peloponnese 10
Crete 11
S.W.Turkey 14
Rhodes 15
E.Turkey 17
Cyprus 18
Syria-Israel 20
WHOLE X
Z
DISPLACEMENT → M
10.0
5.0
0.0
-5.0
-10.0
0.0
2.0
4.0
6.0
8.0
10.0
T
AGE → Ka
17
11 3
20
15
14
18
10
X

C

The curves for Morocco, E. Turkey, and Syria-Israel show similar form, including a slight oscillation which is lacking from the broad average curve. Morocco shows a slight low in the last few centuries, and then an apparent rise to + 0.4 m at 4.0 ka. E. Turkey shows a low of a few mm during the last few centuries, levelling out around 2 ka, and then dropping to −0.1 m at 2.25 ka. Syria–Israel shows a low of −0.22 m at 1.5 ka, a high of +0.15 m at 4.5 ka, and then dropping to −0.3 m at 0.6 ka, with a progressive drop for earlier dates.

The curves for the equiaxial regions have the following characteristics. For the Peloponnese the curve drops fairly steeply, with a point of inflection around 1−2 ka. For Crete, the curve appears to drop steeply with very little sinuosity. For SW Turkey the curve is quite sinuous, with a point of inflection at 1−2 ka, but the whole curve rising more steeply than the average. The curve for Rhodes and Karpathos shows a low at 1−2 ka, and a slight high at 4−5 ka. For Cyprus, the curve drops more steeply than average.

In the regional curves shown in fig. 11 a and 11 b all the linear component of the type $Z=kT$ from the combined equations has been included as eustatic. (It would have been equally logical, as a first assumption, to class the linear component as purely earth movement.)

The regional curves can logically be made more like each other by transferring a linear component in age to or from the earth movement equations. The resulting curves are shown in fig. 11 c. The curve for SW Turkey is very similar to that obtained in (F5), and that for Israel is similar to the curve obtained by cruder methods in (F6).

The analysis suggest that mean sea level relative to the coast of the Mediterranean has been very nearly stable for the last 5 ka to within 0.2−0.4 m. The first estimate curves for Regions 1 and 20 suggest a possibility of a high sea level of the order of +0.2−0.4 m at around 4 ka, which would be compatible with a climatic optimum, or a relative high sea level predicted by CLARK & LINGLE (1978) curve type III.

All the acceptable curves suggest a shallow S-form, with a relative low within the last 2 ka, a slight high at 3−4 ka, and then low levels at earlier dates. These variations may appear only as inflection points on an otherwise rising sea level.

The predicted curve of earth movement for Region 3 (fig. 12) shows a slight subsidence throughout most of the length of the coast with uplift at the eastern end in Tunisia. If the correction factor of 0.22 m/ka is applied, the average tectonic displacement is brought very close to zero, which is acceptable. The correction for E. Turkey would imply an earth movement in the same sense, since the net rate of relative change of level is zero (see fig. 12). It is not unreasonable to suggest an aseismic uplift of this coast at 0.18 m/ka, in view of its location in an area of convergence behind subduction zones, but it is equally reasonable to suggest that, since none of the sites on this coast is older than 2.5 ka, and many are much younger, the submergence due to an eustatic rise of the order of 0.1 to 0.2 m during the last millenium has not been detected. The first estimate of earth movements along the Israel–Syria coast suggests subsidence of −0.2 m/ka in the

Fig. 12. Plots of regional earth movements, after removal of the eustatic component. For the long narrow regions the mean rate of displacement in m/ka is plotted along the coast as a function of distance in hundreds of km. Distance is measured along the X-axis of the Region. For the equi-axial regions, plots are shown as contours of rates of vertical movements in m/ka.

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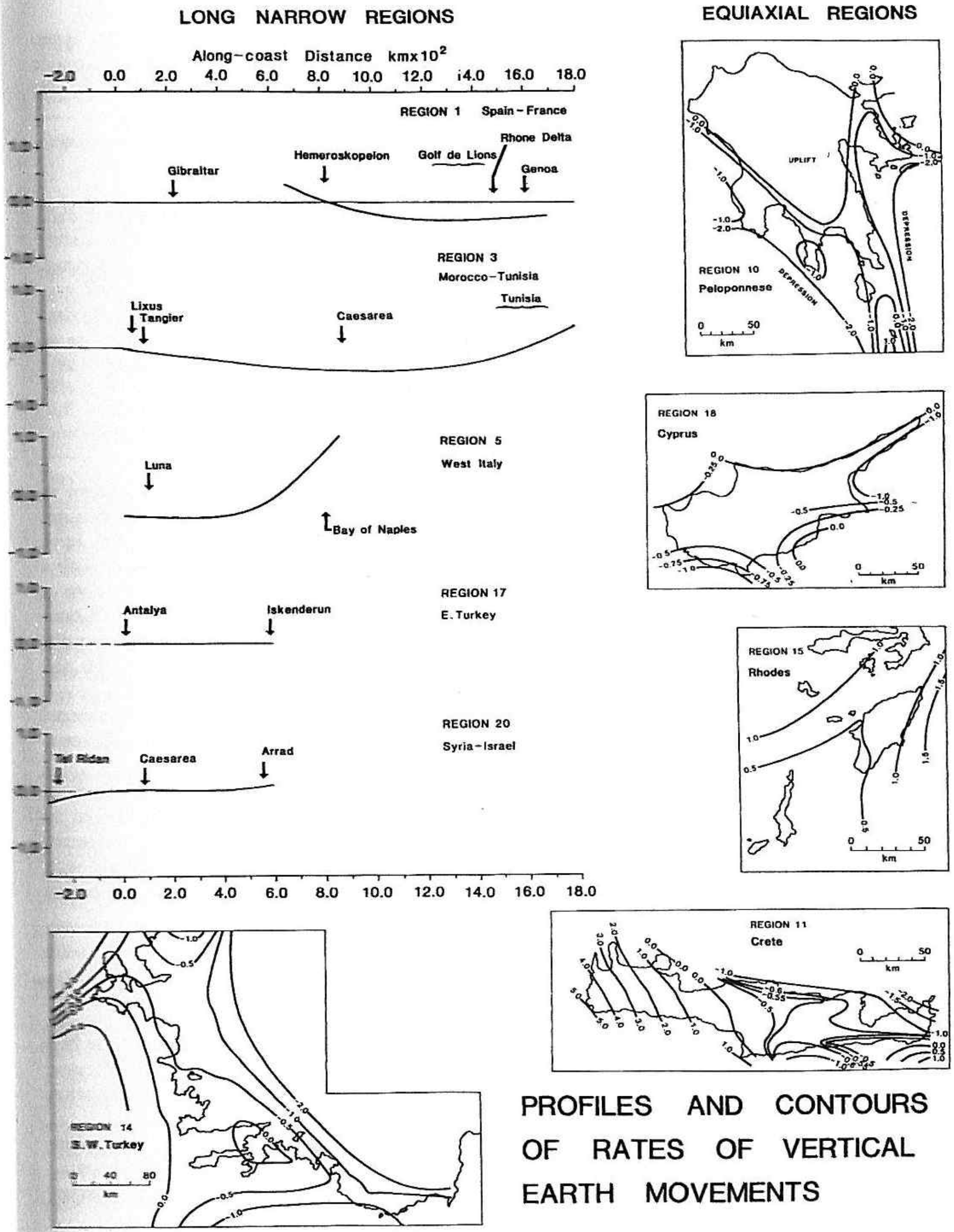

PROFILES AND CONTOURS OF RATES OF VERTICAL EARTH MOVEMENTS south, most of the coast very nearly stable, and uplift of the order of 0.1 m/ka in Syria. The suggested correction would reduce the subsidence in the south and increase the uplift in the north.

Eustatic curve before 5 ka

Most data older than 5 ka is 1-sided. The mean curve in fig. 10 is based on 2-sided data, and the one-sided points suggest that the curve should be considerably lower. The scatter at this age is considerable, and the number of points very few, scattered between Israel, the Aegean, and the Straits of Gibraltar. Whilst the mean curve in fig. 10 does not suggest a steep enough curve based on other evidence (MARCUS & NEWMAN 1983) the data set, including the 1-sided points, is compatible with a much steeper curve, dropping to about −10 m at 7 ka. This section of the curve has been added as a dotted line in fig. 11 c.

Earth movements

For the long narrow regions the predicted pattern of mean earth movements is shown in fig. 12 a. There are no data south of Naples so that the data from this volcanic region severely distorts the plot for West Italy. The most probable corrections to be applied have been discussed in the context of the eustatic curves. At this highly smoothed level, with a wavelength of 100s of km, the effects of local faulting are concealed, and these show up as high residuals. The most obvious effects are the broad subsidence of the Golfe de Lions-Rhône Delta region, the uplift in Tunisia, and the slight uplift in Syria. These phenomena are not altered, relatively speaking, by the application of the small corrections from the eustatic curves.

The highest residuals, and/or rates of earth movement, are concentrated around Caesarea in Algeria, Naples, SW Crete, the Cesme Peninsula of west Turkey, the Kekova-Kas region in south Turkey, and Caesarea-Acco in Israel.

Regional patterns of earth movement have been plotted previously for the equiaxial Regions 10, 11, 14 and 15, (F5). The techniques used in the present study are similar to those used previously for these regions, although the computer software was different. Plots from the present study have been compared with the earlier results, and are very consistent. Since the earlier work contained more detailed considerations than can be set out in the present work, the curves from (F5) are reproduced in fig. 12 b.

Discussion

The vertical relative displacements identified in the present study are relevant to the history of earth movements in the Mediterranean, and to the regional eustatic sea level curve for the area. The curve is described as regional because of the continental-scale variation predicted by CLARK *et al.* (1978).

The number of data points used in the present survey is 406, located at 335 separate locations. The spatial distribution has already been discussed. Previous authors using archaeological methods have studied the numbers of sites shown in table 4. Each author

Table 4.

Region	Sea level estimates and accuracy stated by authors			
Aegean only	NEGRIS	1904	18 sites	−3.0 m at 2000 BP −3.5 m at 2500 BP −5.0 m at 4000 BP
Whole Mediterranean	GNIRS	1908	67 sites	−1.75 m ± 0.3 m at 2000 BP
Whole Mediterranean	HAFEMANN	1960	57 sites	−2.0 m ± 0.3 m at 2000 BP; −2.6 m ± 0.2 m at 2500 BP
Whole Mediterranean	FAIRBRIDGE	1961		−2.0 m at 2000 BP
West Mediterranean	FLEMMING	1969	54 sites	0.0 m ± 0.5 m at 2000 BP
W. Italy coast	SCHMIEDT	1970	19 sites	−0.65 m ± 0.25 at 2000 BP and rising at 1.4 m/ka.
S.W. Turkey	FLEMMING	1972	32 sites	−0.3 m ± 0.3 m at 2000 BP
Whole Mediterranean	PIRAZZOLI	1976	121 sites	−0.4 m ± 0.1 m at 2000 BP
N.E. Mediterranean	FLEMMING	1978	202 sites	−0.3 m ± 0.3 m at 2000 BP
Israel coast	FLEMMING et al.	1978	54 sites	−0.5 m ± 0.3 m at 2000 BP

Previous authors have usually stated their results with upper and lower bounds, rather than estimates of errors at individual sites. These estimates have been taken at face value and listed in Table 4. Sources of errors in the early works are discussed in the text. The estimated eustatic change of sea level in the Mediterranean in the last 2000 Years has changed from 3.0 m at the turn of the century to about 0.4 m in recent years.

has tended to use the data of previous authors in each region. The present survey has used data from almost twice as many sites as any other analysis. Of the 335 locations cited, over 270 have been surveyed in the field by the principal author.

Comparison of eustatic curves

The best fit eustatic curve for all regions (fig. 11 c) in the present survey shows a low of −0.2–0.7 m at 1000 BP; a point of inflection or a high of −0.2–0.5 m at 3000–4000 BP; and a steady rise from 7000 to 5000 BP. At no time did the sea level rise above present sea level to within the accuracy of the present study. That is, no eustatic oscillation occurred above present sea level with an amplitude greater than 30 cms, and a duration greater than about 400 years, in the Mediterranean area. The curve therefore conforms to CLARK & LINGLE type IV, which is consistent with their predictions.

The present results, with quantified error estimates, are consistent with those of other authors published since 1969, fill in the curve with a great deal more detail through the last 2000 years, and extend it with considerable reliability to 5000 BP, and some probability to about 7000 BP. At that age other methods begin to take over. The evidence of the present data provides a more accurate estimate of the eustatic curve for the area, separated from the contamination of earth movements, and makes it extremely unlikely that there have been eustatic fluctuations of the order of 0.5 m or more.

(P1, P2) based in part on the data of (S1) suggests that there is evidence for a progressive rise of sea level by 30 cms between 2300 BP and 1900 BP. The evidence of the present analysis shows that the curve for West Italy based on age only (fig. 10) confirms this trend in the Italian data. The trend is apparent independently of the extreme values around Naples. This curve stands out as an anomaly in fig. 10, and is not typical for the whole Mediterranean.

GORNITZ et al. (1982) use tide gauge data from 193 stations worldwide to deduce that global eustatic sea level has risen 0.1 m during the last 100 years. This is deduced as being the consequence of the heating of the upper layer of the ocean above the thermocline, with consequent expansion of that water mass. The computed sea level-time curve is highly correlated with the mean air temperature with a time lag of 18 years. This model of cause and effect is more responsive to short term temperature changes and climatic fluctuations than a model based on glacial eustatic control. However, the total magnitude of the effect can only amount to a few tens of cms. On the assumption that the climate has been fluctuating about a constant temperature for the last 5000 years the thermal expansion factor should not have contributed to any net rise of sea level since 5000 BP. On the other hand, medium term fluctuations such as the "Little Ice Age" would have resulted in both a small glacial eustatic drop and a thermal drop in sea level. The results of the present analysis show a low at about 0.5–1.0 ka for several regions, although this may only be manifested as a reduction in the gradual rise of sea level. The magnitude of the fluctuation is of the order of 10–20 cms over 1000 years.

The rate of change of sea level indicated by GORNITZ et al. (1982) of 0.1 m per 100 years is not sufficient to introduce any detectable alteration in the observations due to the earliest and latest date of fieldwork cited, largely because errors in the early work were of the order of 0.5 m in most cases. However, if the results of the present survey were to be compared with field data in 50 years time, a change might be detected.

Correlation with plate boundaries

Figure 13 is a simplified diagram representing the location of plate boundaries in the Mediterranean, derived from various authors.

The most extensive quiet zones revealed by the present study, Gibraltar to Genoa (Region 1) and Antalya to Iskenderun (Region 17) are both far from active plate boundaries. In general there is a broad correlation between proximity of a plate boundary, and degree of vertical tectonic motion averaged over several thousand years.

The Hellenic Arc is associated with consistent evidence for rapid uplift on the outermost islands (Antikythera, Crete, Karpathos, and Rhodes), with the most rapid rates of movement observed anywhere in the Mediterranean (9.5 m in 2000 years, SW Crete). (P4) proposes that the notches observed in these locations were formed during a progressive descent, followed by a single massive uplift. Whilst the present authors doubt this model, it may be confirmed, and this would establish the association of arc tectonics and rapid vertical movement even more clearly. (F5) tested computer fitted regression surfaces to the data for Crete and Antikythera considered both as a continuous unit, or as separate units. The residuals are much lower when the islands are considered separately, and it is therefore logical to consider them as de-coupled by the active faulting in the Antikythera Channel (see MCKENZIE (1972) for evidence of recent seismicity).

One concludes that the islands of the Hellenic Arc are broken into coherent slabs of typical dimension 50–100 km, which are tilting as monolithic de-coupled units in re-

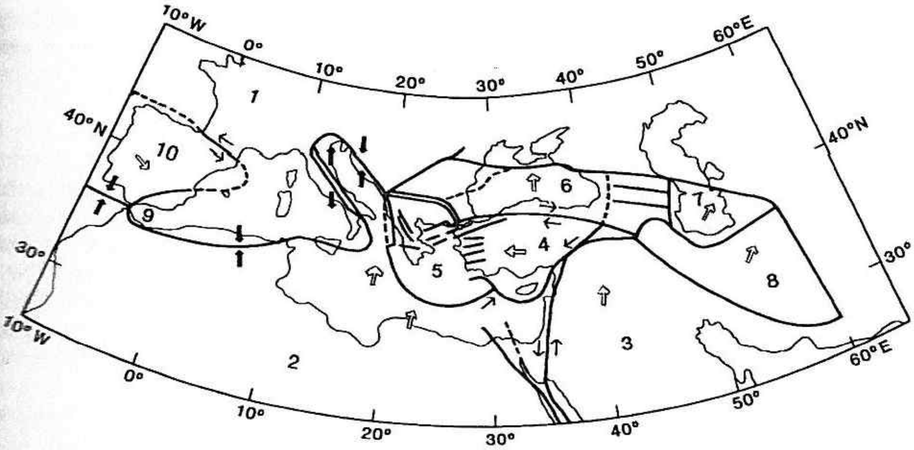

Fig. 13. Plate boundaries, simplified from PETERS (1985).

response to the underthrusting of the subduction zone. PETERS (1985: 208) reports similar tilting on the Quaternary timescale for the eastern region of Crete.

The evidence for the Calabrian Arc is less clear. Apart from the Messina earthquake of 1908, and the obvious volcanism of the Lipari Islands and the Bay of Naples, the majority of archaeological sites in the area fail to produce data. The Bay of Naples shows the greatest range of vertical movement, after SW Crete, but this is associated with volcanism rather than the immediate effects of subduction (GU1; F2).

The incidences of most rapid upward movement of the Mediterranean coast are thus from the arc areas, with rates of the order of 5 m/ka. The coast of Israel is moderately active with vertical movements of 5 m at Caesarea (203/1058) and possibly 2 m at Dor (199) and 1.0 m at Acco (182). But these movements seem to be localised around the Carmel-Qishon Graben, rather than being direct effects of the plate boundary. The existing data do show a correlation of submergence with local faulting, although this may require further interpretation.

Correlation with modern and historical seismicity

In the eastern Mediterranean southern Turkey and northern Cyprus are aseismic, and correlate with vertical stability. The Levant coast and Cyrenaica are moderate on both counts. The Hellenic Arc shows dramatically high rates of seismicity, with the greatest concentrations of large events in Rhodes and SW Crete, where the highest rates of vertical movement are measured. We do not have data for the Ionian islands and Achaia, where similar seismicity is recorded. The vertical activity of the Gulf of Corinth correlates with that of high current seismicity.

Although the present data set is not complete in some of the most interesting areas, there is strong indication that observed relative vertical displacements are correlated with local seismicity during recent years. (F5, p. 444) showed that the data for the NE Mediterranean correlate with the evidence from AMBRASEYS (1971) for historic seismicity. Historical seismicity for France (VOGT 1979; GAGNEPAIN-BEYNEIX et. al. 1982: 274), and Italy (ENEL 1977) provide source material for further historical comparisons.

Conclusions

1. The best estimate of the eustatic sea level curve which can be derived from archaeological data in the Mediterranean is shown in fig. 11c. The curve is probably accurate to ±0.3 m up to 2.0 ka; and ±0.5 m at 5 ka. For ages from 5.0–10.0 ka the curve is based on too few data points to be reliable, and should probably be considerably lower. The evidence of 1-sided data points confirms this, but does not generate an accurate curve.

2. The 10 regions discussed in this paper with sufficient valid data can be categorised in terms of their pattern of tectonic activity and subsidence due to sedimentary accumulations, isostasy, or compaction. These characteristics are summarised in fig. 12.

3. Vertical tectonic movements in the 10 regions over several ka correlate closely with plate boundaries, seismicity, volcanism, and active faulting.

4. Aseismic subsidence occurs in the Golfe de Lions area, emphasised by isostatic loading of sediments on the continental shelf from the various rivers, especially the Rhône.

5. The Straits of Gibraltar have been vertically stable to within ±0.3 m for the last 2.5 ka, and there is no evidence for vertical activity in the previous period back to 10 ka.

6. Previous published estimates of eustatic curves for the Mediterranean have been based on partial or regional data sets. Some have, by judicious sampling, produced estimates of specific sea levels at given dates which are close to the present results. Others have chosen regions or samples which have produced estimates of eustatic curves which differ from the present results. These differences can be accounted for largely by the tectonic patterns of each region, and by the comparative regression curves shown in fig. 10.

7. Ten regions produced insufficient data for full analysis. The existing data from these regions does not conflict with the present models, but further data would add to the understanding of Mediterranean tectonics. In particular, data would be very useful for the Adriatic, North and South Aegean, and the coast of Egypt. There are ample potential data sites in these regions (see table 1).

8. The present estimated sea level curve is reliable to within the limits stated, for the Mediterranean, for the last 5 ka. It can therefore be used to derive earth movements at new sites at which displaced sea level indicators are discovered, to within these limits, in the Mediterranean.

9. The best estimate eustatic curve conforms to Type IV according to the classification proposed by CLARK et al. (1978) and CLARK & LINGLE (1978). Although the maps published by these authors are not precise about the type of curve to be expected in the Mediterranean, the present result is consistent with the prediction that the curve should be of Type III or IV.

10. The regional curves, and the best composite curve, suggest a rapid rise of sea level up to about 5–6 ka, with a maximum or point of inflexion at about 4 ka, followed by a slight lowering of sea level or a reduction in the rate of rise between 2 ka and 1 ka, followed by a rise to present sea level. The low, or reduced rate of rise, around 1–2 ka may possibly be correlated with climatic fluctuation, superimposed on the CLARK & LINGLE (1978) Type IV curve, or may be a component of Type III.

11. The present methods identify long-term trends with temporal periodicity of the order of 500 years, and spatial periodicity of the order of 100 km. Features with shorter wavelengths appear as high residuals. Local studies with reliable time series in a small area may reveal relatively short-term on-lap and off-lap sequences, or may indicate more oscillations in the relative sea level curve, and these can be genuine features. However, it is not possible to detect whether they are earth movements or eustatic oscillations. Ultimately the resolution of smaller features can only be obtained by time series of 20 or more reliable dates and depths for the last 5 ka at each of hundreds of locations, implying a data set of many thousands of data points.

12. The regional contour patterns of rates of vertical displacement represent smoothed models of the net effects of tectonic and isostatic processes. Local faulting, discontinuities, grabens, etc., are not modelled individually by this process. These can be analysed at least in part by study of residuals. There has been no space to analyse residuals in the present paper, but in future work these will be correlated with local geophysical and sedimentary factors.

13. The method could be extended more effectively into the time range 6 ka–10 ka by gathering data from the large number of Neolithic sites which probably exist on the Mediterranean continental shelf. RENFREW (1972) and MELLAART (1975) plot large numbers of coastal and island sites of this period, and sufficient discoveries underwater have been made in the last decade to suggest that many more will be made.

14. The extensional normal faulting of the Aegean may be associated with complex patterns of rotation on listric faults. The data potentially available in the Aegean from archaeological sites not yet measured for vertical change could be used to check this model.

15. The distribution of earth movements derived from the present data can be used in the planning of coastal defences and coastal construction projects with a time span of 50 years or more in the Mediterranean.

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Annex 1: Abbreviations for references used in text.

B1, BLACKMAN 1973	FM1, MASTERS & FLEMMING 1983	P1, PIRAZZOLI 1976a
B2, BLACKMAN 1982, a, b.	FR1, FROST 1972	P2, PIRAZZOLI 1976b
F1, FLEMMING 1968	GN1, GNIRS 1908	P3, GUERY et al. 1981
F2, FLEMMING 1969	GU1, GÜNTHER 1903	P4, PIRAZZOLI et al. 1981
F3, FLEMMING 1972	H1, HAFEMANN 1960	PA1, PASKOFF & SANLAVILLE 1983
F4, FLEMMING et al. 1973	H2, HAFEMANN 1965	PA2, PASKOFF et al. 1981
F5, FLEMMING 1978	LG1, LE GALL 1981	R1, RABAN 1981
F6, FLEMMING et al. 1978	LH1, LEHMAN-HARTLEBEN 1923	R2, RABAN 1983
F7, FLEMMING 1979	N1, NEGRIS 1904	S1, SCHMIEDT 1972

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