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PREDICTIONS OF RELATIVE COASTAL SEA-LEVEL CHANGE IN THE MEDITERRANEAN BASED ON ARCHAEOLOGICAL, HISTORICAL AND TIDE GAUGE DATA

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ABSTRACT

Prediction of relative sea level change at each point on the Mediterranean coast over the next 50-100 years requires an estimate of the global change of absolute sea level which may be caused by climate change, and the local vertical displacement of the level of the land at each point on the coast relative to absolute co-ordinates. This paper is concerned with the vertical land movements. Two methods of prediction are discussed, firstly archaeological data for past earth movements over 100 to 2000 years; secondly tide gauge data for vertical earth movements over 10-100 years. Good archaeological data are available from 335 archaeological sites, but only 32 tide gauge records. The tide gauge data are the most accurate, and refer to the appropriate timescale for extrapolation into the future. However, data on earth movements can only be interpolated laterally for a few tens of km between data sites, and thus the tide gauge data can only be used to indicate expected earth movements in very limited regions along a total coast of 45,000km length. By comparing known tide-gauge and archaeological data at those sites where they coincide, or can be applied to averages of groups of sites, a correction rule is derived to compensate for the aliasing which occurs when averaging over periods of various lengths. As a result it is possible to suggest statistically probable estimates for the rate of vertical movement to be expected in the next 50-100 years for most sectors of the Mediterranean coast.

In order to obtain the most probable net change of sea level at each site, the data given in this paper should be added, with correct regard to sign, to predicted changes of sea level from climatic causes.

Field data from archaeological sites suggest that many sites are experiencing rapid erosion. Submerged ruins represent a unique record of ancient maritime technology, and are being destroyed by wave action and human activities, with marked collapse and scattering of structures observable over

1-10 years. Assuming that most sites cannot be protected, they should at least be surveyed and photographed as accurately as possible before it is too late. Older sites from the Neolithic and Palaeolithic are usually in deeper water, 8-30m, and so are protected from wave action.

NOTE

This paper is designed to be read in conjunction with the two annex papers, Flemming and Webb (1986), and Flemming and Woodworth (1988). Both papers are attached and reproduced by permission of the respective publishers. Reference should also be made to the documentation and summary print-out of the MEDSITE database, (available on request to the Author).

INTRODUCTION

The tidal amplitude throughout most of the Mediterranean is of the order of 20-30cms, with the exception of the immediate region of Gibraltar, where it is approximately 1.0m. Wind forcing and variations in barometric pressure cause fluctuations in level of the order of 30cms over periods of several days, and 10-12cms during the year (Striem 1974, Rickards 1985). Structures built close to the water such as jetties, landing docks, boat slipways, etc., are naturally designed to resist the local wave conditions, but are not designed to resist a sea level change of more than 50cms extreme, and in practice the expected annual change is of the order of 30cms. Similarly, natural coastal processes, the formation of stable beach gradients, marshes and wetlands, deltaic alluviation, etc., are adjusted to a near constant sea level which fluctuates by only 30-50cms.

Anthropogenic climate change caused by the release of so-called greenhouse gases is at present predicted to cause a global rise in sea level of the order of 20-140cms in the next 50 years. Even at the lower estimate, such a change would bring wave action consistently into contact each year with structures or natural shoreline features which had never previously been exposed to wave forces. The upper estimate would cause massive inundation of low-lying structures and coastal landforms in many parts of the Mediterranean. However, no general prediction can be made for the Mediterranean coast because local vertical earth movements are of approximately the same magnitude, 10-50cm/century (Flemming 1978; Flemming and Webb 1986; Pirazzoli 1976a; 1976b; 1987; Flemming and Woodworth 1988). Tectonic earth movements may be vertically up or down, and thus in some places the relative rise of sea level over the next 100 years may be almost twice the absolute rise of sea level, whereas in others it may be much less, or the local relative sea level may even drop. From the point of view of planning defensive action, it is important to know where the areas of maximum and minimum relative rises of sea level are likely to be.

METHOD

The Mediterranean lies across a major global plate tectonic boundary (Le Pichon and Angelier 1981; Dewey et. al. 1973; McKenzie 1972; 1978) and many parts of the coast are subject to regular earthquake activity. Volcanism is also active in south west Italy, the Lipari Islands, Sicily, and the central Aegean. These processes cause sections of the coast to be displaced vertically at varying rates (Vita Finzi and King 1985; Schmiedt 1972; Flemming 1969; 1972; 1978; Flemming and Webb 1986, Pirazzoli 1976.a, b,; 1987; Flemming and Woodworth 1988). Although parts of the Pacific rim, Indonesia, Japan, and Alaska, have higher rates of movement, it is reasonable to say that the Mediterranean coast is amongst the most active in the world.

In addition to the up-and-down displacements due to tectonism and volcanism, the coast is liable to downwards movement due to the accumulation of alluvium in coastal plains, and on deltas. The net subsidence may be caused both by the isostatic response to the weight of the alluvium, and by compaction within the sediment column. Several areas of such subsidence have been documented both by identification of archaeological remains, and through coring (Venice, Pirazzoli 1877a; Messenia, Kraft et. al. 1975, Kraft and Aschenbrenner 1977; Larnaca, Gifford 1978).

In the most active regions of the Mediterranean sites separated by only 10-20km can show different directions and rates of vertical movement. In the western Mediterraean, the variability is less pronounced. Nevertheless, the mechanisms which are being proposed for the tectonic movements in the crust suggest that spatial variability on the scale of 10km-20km would be expected. A description of the vertical movements to be expected in the future on the coast of the Mediterranean would ideally therefore be based on a data set which provided reliable data at 10km-20km intervals along the whole coast length of 45,000km.

Such a data set is plainly unobtainable. Possible sources of data include tide gauges, erosional and solution formations, biological formations such as vermetid terraces or lithodomus borings, sedimentary accumulations with layers containing organic carbon which can be dated by radiocarbon methods, or archaeological structures on the coast (van der Plaasche 1986).

All the above types of data can be obtained for the last 2,000 years in some parts of the Mediterranean coast, but the most widely spread data type is the archaeological, which provides sea level estimates at 335 locations, (Flemming and Webb 1986). Other data sources could be integrated with the archaeological data over the same time scale of 100-2000 years, but the present author does not have experience of the errors and corrections which would need to be applied to create a homogeneous data set. For the moment it seems better to rely on the internally consistent archaeological data for the timespan longer than that of tide guages.

For periods of a few decades, tide gauges are extremely accurate, provided that the calibration and reference datum of the instrument is properly maintained. Standards for this procedure are maintained by the Permanent Service for Mean Sea Level (PSMSL), and the data referred to in this study have been obtained by various authors from the PSMSL. Pirazzoli (1987b) studied 22 tide gauge records within the MAP area of which 16 provide reliable records; Flemming and Woodworth (1988) studied 16 sites in Greece. Emery and Aubrey (1985, p.250) deduce rates of earth movement for northern and north west Europe adjacent to the present study area.

Tide gauge accuracy is of the order of mm (Pugh 1987; Rossiter 1967; Emery et. al 1988; and others). The principal source of errors arises from undocumented changes in datum, or corrections or adjustments to the instrument calibration. Additionally, data may be 'corrected' by authors before they are published to allow for presumed local earth movements. If this has occurred it is pointless to try and detect earth movements by studying the differences between adjacent tide gauges, which is the principal method. Various methods have been used to separate global or regional sea level change from earth movements on the basis of statistical treatment of large numbers of tide gauge records (Graaf 1980; Pirazzoli 1987b; Emery and Aubrey 1985; Gornitz et al 1982; Emery et. al. 1988) including regression analysis and eigenanalysis. It is not the purpose of this paper to discuss the virtues of the different methods. Suffice it to say that there is no reservation about the capability of modern well-maintained tide gauges to produce excellent records: the problem is simply that there are not sufficient instruments in the Mediterranean to give an accurate picture of the tectonic variability of the complex coastline. Furthermore, in the absence of existing records of a decade or more at a desired location, an instrument installed now will only provide a suitable time series in 10-20 years time. Several hundred tide gauges would be needed to show the true land movement at a sufficient number of sites.

Archaeological methods

Site selection

The deduction of relative land/sea level changes at a number of archaeological sites, was attempted by several 18th and 19th century authors (Flemming 1969). Gnirs was the first author to attempt a complete synthesis for the whole Mediterranean, (Gnirs 1908). He used field data from 8 sites; referenced data on a further 34 sites; and made very rough generalisations for a further 25 sites based only on inspection of charts. The total data set was 67 sites. Observations and deductions were based on the assumption that there were no earth movements. Very little attempt was made to estimate errors, and the probable errors at the sites where data were observed were of the order of 0.5-1.0m or more. There was a strong tendency to force data into the simple model of constant rate of eustatic change. Data were concentrated in the Adriatic and Aegean.

A problem with early works is that the authors searched for "submerged ruins", and found them. It is a simple matter to list over 100 sites in the Mediterranean where masonry can be found to a depth of 1.0m or more. The masonry may be part of a harbour wall built at that depth, but before the invention of cheap diving equipment, that was difficult to ascertain. On the principle of "no smoke without a fire", authors naturally assumed that the only question at stake was the measurement of the size of the sea level change since Roman times, which was assumed to be at least 2m. Hafemann (1960) lists well known submerged sites, and makes calculations accordingly.

Lehman-Hartleben (1923) provides an inventory of 303 sites in the Mediterranean, with descriptions of harbours derived from classical literature and archaeological sources. There is no estimate of sea level change, but some useful site maps. In some studies the authors have tried to separate stable and unstable coastal areas, and use the 'stable' areas to measure eustatic sea level change. Schmiedt (1972) in a series of brilliant observations on fish tanks on the west Italian coast deliberately avoids the areas around Naples and Mount Etna. And yet most of the Italian coast is liable to some seismic activity, and it is arbitrary as to what level of low seismicity can be classified as stable.

The present study is designed to measure earth movements, and therefore all possible sites with good data are included. The data set includes all valid sites, whether the data show relative submergence, constant relative sea level, or relative uplift. When this method is used (Flemming 1968; 1969; 1972; 1978; Flemming et al. 1973; 1978) it is apparent that a large number of sites are relatively stable or uplifted, and that the samples used in the papers prior to 1969 were biased towards selection of submerged sites.

Pre-1969 studies also assumed that the objective was to measure the sea level at a specific time in the past, namely 2000 BP. This assumption was also made by Flemming (1969). This results in a partial data set, since many sites will provide data for the Mediaeval, Norman, Arab, Byzantine, Minoan, and other periods, but not the classical Roman. Given the limitations of computer statistics available to most researchers in the mid-1960s, earlier workers did not attempt to analyse the general problem assuming random earth movements, and eustatic sea level change, utilising a data set dispersed in space and time. However, by the early 1970s suitable statistical packages were available and this generalised method has been used by the author since 1972 (Flemming 1972).

To construct the MEDSITE database all known sites were identified from the multi-site sources already quoted, 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. A mid-19th Century folio of Admiralty Mediterranean charts was used to locate many of the ruins which have not been visited, since early chart-surveyors were well-versed in classical geography, and noted the existence of ruins with accuracy and detail. Of the sites listed by Lehman-Hartleben (1923) 18 named sites could not be located on any chart, and there has not been time to check the early German archaeological references which would be needed to locate the sites. Some discrepancy may be due to variations in spelling.

Of the 1053 sites, sea level estimates and age were derived at 335,

(Table 1) and Annex 3. The sites for which data were not obtained constitute an unexploited reservoir of data which could be utilised to extend or improve the present study.

Large scale site maps exist for most sites with data, and most sites are documented with land and underwater photographs. These files can be accessed separately from the MEDSITE database.

Observational methods

Field observations use echo sounding, snorkel diving, scuba diving, wading, aerial photography, underwater photography, and a wide range of simple and sophisticated survey methods depending upon time and budget available. Methods and accuracy are discussed fully by Flemming 1969; 1978; 1979; Blackman 1973; Schmiedt 1972; and Guery et al. 1981). During the preparation of Flemming (1969) it became clear that certain ancient structures such as ship slipways, mooring bollards and mooring rings, fish cultivation tanks, salt pans, docks, quays, sluice gates, etc., could provide a link to the sea level at the time of construction with greater accuracy than previously obtained.

Data for over 270 of the present sites with conclusive data 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. The error bar has been defined on the basis of the type of sea level indicators used, and the inherent limits on accuracy described in the next section.

In the Bronze Age, (5,000-3,000 BP), and later archaeological periods, specialised structures were built in relation to the contemporary sea levels. In earlier periods there do not appear to be identifiable waterline structures, although Aghios Petros (964) (site number in Table 2 and MEDSITE database) is a neolithic village facing directly onto a small estuary which was probably a harbour, and the data from the submerged site at Franchthi Cave (965) also suggest a waterside dwelling area. In general, data earlier than 5,000 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.

The method of observing solution notches and comparing the present notch with higher or lower notches, has been used by many authors (e.g. Spratt 1865; Günther 1903a; 1903b; Hafemann 1965; Pirazzoli et al. 1981; Flemming et al. 1973). In the open sea a solution notch is often 0.5-1.0m in height, and the mean sea level point can only be determined to an accuracy of about 0.2-0.3m. Even in sheltered bays, the error is of the order of 0.2m. 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). Because of wave exposure and unevenness of the substrate the width of the notch is such as to leave uncertainty of exact mean sea level of the order of 0.2m, (Guery et al. 1981).

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. This occurs 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 20-30cms 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 as between ancient and modern notch system, with an accuracy of 0.1m. 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.

Limits to Accuracy

Once the accuracy of individual observation approaches 0.3-0.2m 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 0.2-0.5m, and so are not regarded as important for shipping and navigation. The only reliable 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 0.3m (Flemming 1978, Flemming et al. 1978, Schmiedt 1972; 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 0.4m during a 6-day study of Tel Qatif (225).

So far as is known to the present author, the only sites at which observations were corrected by on-site measurement of the state of the tide are the data reported by Schmiedt (1972), 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 (1972). Schmiedt (1972) observed numerous fish tanks along the west coast of Italy, and made hundreds of measurements at each tank, defining the height of the boundary walls, depth of floor, height of internal dividing walls, level of sills and sluice gates, level of channels, etc. He refers all measurements to mean sea level, but does not state how mean sea level was established locally. If it was the true annual mean sea level, then correction factors should have been introduced to allow for the season with the highest or lowest monthly mean sea level. Conversely, if the mean sea level used as a reference was the mean level at the time of observation, then there is an uncorrected factor for barometric effects at that time, and the seasonal difference between that season and the highest and lowest monthly mean sea levels. The need for these corrections is acknowledged in Schmiedt (1972), and analysed in the appendices to Schmiedt (1972), but the application of the corrections to the data is not shown.

The previous paragraph does not detract from the brilliant observational detail of Schmiedt's work. However, the table of measured sea level changes (Schmiedt 1972, p.213) lists the estimates to the nearest 0.01m, with no estimate of errors. From the present analysis it must be implicit that there are unresolved errors of the order of 0.2m.

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 0.05-0.1m per century, a time error bar of 2 centuries is equivalent to a vertical error bar of 0.1-0.2m.

Granted the seasonal, interannual, storm, and barometric changes of sea level which may endure for days or months, or result in mean sea level being on average higher one year than the previous year, uncertainty arises from our lack of knowledge about acceptable frequencies of flooding or drying out of structures. When a particularly useful type of building-stone can be obtained conveniently by quarrying on the shore directly into a cliff, would the quarry-master find it acceptable to have the quarry floor flooded once a year? for the whole of one month during each year? or never? It is an observable fact that quarries were cut down in almost every case very close to sea level: but were they cut to highest spring high tide, mean spring high tide, mean sea level, or what? Even if we add a constant wave exposure factor, the uncertain range remains.

Good observation and instrumental methods result in an accuracy of the order of ±0.2-0.3m 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, 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. Flemming and Webb (1986, Figure 1.) show 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 present author (especially Flemming 1968; 1969; 1972) 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 dat_ i_ given in Flemming (1972); Flemming et al. (1973). In the present paper, since many of the sites have not been personally visited by the author, a more conventional estimate of errors is used, based on symmetrical error bars.

INTERPRETATION OF ARCHAEOLOGICAL RESULTS

The present author has been most directly concerned with the analysis of archaeological data, and these will be described before the tide gauge data. The principal results have been summarised by Flemming and Webb (1986) which is attached as an annex to this report. (Annex 1)

The principal result which can be deduced from the archaeological sea level indicators after statistical analysis is that the mean sea level for each 200 year period has varied by less than 30cms during the last 2000 years, and that each coastal region has a characteristic mean rate of vertical displacement, combined with very different local variability. The mean and standard deviation of vertical earth movement for each region in the study are shown in Fig. 1. These are the statistics of the raw data, (not after separation of eustatic factors, and computation of smoothed cotoured surfaces showing rates of earth movement as functio of location).

The following discussion refers to Figures 11 and 12 taken from Flemming and Webb (1986) and reproduced here as Figures 2 and 3.

For the long narrow regions in Fig. 1 the predicted pattern of mean earth movements is shown in Fig. 3. There are no data south of Naples in Italy so that the data from this volcanic region severely distorts the plot for West Italy. 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 small corrections from the eustatic curves, (see Flemming and Webb 1986 for details of the corrections).

The highest residuals, and/or rates of earth movement, are concentrated around Caesarea in Algeria, Naples, SW Crete, the Çesme Peninsula of west Turkey, the Kekova-Kaş 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 in Fig. 1, (Flemming 1978). 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 Flemming (1978) are reproduced in Fig. 3.

The pattern of earth movements may be correlated with any of the following factors: plate boundaries in general; subduction zones; strike-slip faults; shallow seismicity; deep seismicity; volcanism; continental shelf width/narrowness; continental marginal tilting; sedimentary isostatic loading; sediment compaction; aseismic warping. The factors listed above will be discussed briefly after the methods and results have been compared with those of other researchers.

Other Methodologies

Other field methods reveal sea level data for the same time span as archaeological data. These include study of alluvial sediments (Kraft et al. 1975; Kraft et al. 1980; Gifford 1978; for example); study of solution notches (e.g. Hafemann 1965; Guery et al. 1981; Pirazzoli et al. 1981; Flemming 1978; Higgins 1980); vermettus reefs and trottoir (Sanlaville 1977; Paskoff et al. 1981; Paskoff and Sanlaville 1983) and the study of organic materials dateable by C14 (Richards and Vita-Finzi 1982); and the study of low level raised erosion terraces (e.g. Peters 1985; Angelier 1976; Le Pichon and Angelier 1981).

Even if each of these methods is perfectable, and produces internally consistent results, there is no reason why all the methodologies should calibrate identically with each other until proven. In the present study the only non-archaeological data used are when solution notches can be traced on cliffs between archaeological sites, and can be identified at some point intersecting archaeological structures with a before/after indication. All other types of indicator have been omitted. This may seem to be an arbitrary rejection of valid data: but in the present circumstances it is preferable to demonstrate that the restricted archaeological data set produces consistent results with a measurable error, and the merging of different data types can be carried out later when calibration is sure.

The different data types each have a bias towards certain sites of occurrence. Solution notches only occur on massive calcareous rocks; vermettus shelves only occur in the south east Mediterranean; alluvial accumulations are strictly local forms. As an example of the relative bias which this can produce, one can cite the differences between most of the data reported in this paper, and that cited by Kraft and Aschenbrenner (1977). The present data set is restricted almost entirely to archaeological remains which can be seen with the naked eye, whether above or below present sea level, and without excavation. This tends to exclude material buried in recent sediments, or even visible data separated from the present shoreline by prograding sediments, since there is seldom opportunity to level accurately across miles of marsh. The present data set is therefore biased slightly by the omission of such data, probably amounting to a few percent of the total number of sites (e.g. Oeniadae, (541) and Ephesus (270) etc).

Conversely, Kraft et al. (1975), Kraft and Aschenbrenner (1977) and Rapp and Kraft (1978) gather data almost exclusively from sites in alluvial and prograding areas. These zones in the Mediterranean are likely to occur in structural depressions which are themselves active grabens; the sediment may be liable to compaction. Data from these areas would be expected to plot consistently below the data observed by (Flemming 1968, 1978, Flemming et al. 1973), and this is indeed the case. With regard to their own data, Kraft and Aschenbrenner (1977, p.39) state "Note the problem of the overwhelming variable tectonic effect". The purpose of this comparison is not to show that one or other method is incorrect, but to draw attention to systematic bias inherent in most sampling procedures which are dictated by methodology.

Correlation with plate boundaries

Figure 4 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. The Gulf of Sirte (Region 8) is probably also quiet, but there is insufficient data to be sure. Cyrenaica (Region 16) appears to be anomalous in view of its active depression, reversal of direction at Apollonia (949) and distance from the Hellenic subduction zone. However, it is probable that the compressive forces caused by the Mediterranean Ridge, and the subduction process, extend to the African foreland, causing tectonic activity, (Biju Duval, 1974).

Plate boundaries extend through northern Algeria, central Italy, and the Jugoslav coast, all of which show some vertical activity. In general there is a broad correlation between proximity of a plate boundary, and degree of vertical tectonic motion averaged over several thousand years.

Correlation with subduction zones

There are two major arcuate subduction zones in the Mediterranean, the Calabrian Arc (Caputo 1983; Ghisetti and Vezzani 1982), and the Hellenic Arc (Le Pichon and Angelier 1981; Angelier 1976; 1977; Galanopoulos 1973; Dewey and Sengör 1979; Peters 1985). Neither arc is a simple subduction zone in the Pacific sense, since the radius of curvature is too sharp to allow for a coherent descending slab of lithosphere, and the proximity of approaching continents forces the back-arc area to develop anomalously (Dewey and Sengör 1979; McKenzie 1978). Notwithstanding these anomalies, the two areas do appear to be the principal zones of recent crustal consumption, and will be discussed as such.

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, (9.5m in 2000 years, SW Crete). Pirazzoli et al. (1981) proposes that the notches observed in these locations were formed during a progressive descent, followed by a single massive uplift. Whilst the present author doubts this model, it may be confirmed, and this would establish the association of arc tectonics and rapid vertical movement even more clearly. Flemming (1978) 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 50-100km, which are tilting as monolithic de-coupled units in response to the underthrusting of the subduction zone. Peters (1985, p.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 (Günther 1903a; Flemming 1969).

The incidences of most rapid upward movement of the Mediterranean coast are thus from the arc areas, with rates of the order of 5m/ka.

Correlation with strike slip plate boundaries

The two major strike-slip plate boundaries are the Anatolian fault, running east-west across northern Turkey, and the Dead Sea fault running N-S through the Gulf of Eilat/Aqaba and the Dead Sea. Neither fault is immediately adjacent to the Mediterranean coast, and the present survey has not included data from the Black Sea which might be helpful. The coast of Israel is moderately active with vertical movements of 5m at Caesarea (203/1058) and possibly 2m at Dor (199) and 1.0m at Acco (182). But these movements seem to be localised around the Carmel-Qishon Graben, rather than being direct effects of the plate boundary.

Correlation with local faulting

The southern and central Aegean should probably be regarded as an intensely faulted region, criss-crossed with normal extensional faults forming multiple horst-and-graben features, (Le Pichon and Angelier 1981; Dewey and Sengör 1979; Flemming 1978; Rotstein 1985). The same model, in very broad terms, extends into the Gulf of Corinth, (Vita-Finzi and King 1985; Brooks and Ferentinos 1984), where vertical movements at rates of 1-3m per 1000 years are recorded for upward motion within 10km of sites which are submerging at similar rates. Unfortunately the present survey has revealed insufficient reliable data for the Aegean area to construct a good model, and such data would be valuable. One would expect to find upward and downward vertical displacement on adjacent islands, or on adjacent blocks separated by normal faults within an island. Flemming (unpublished field report) noted a fault in the cliff at Vurgunda, Karpathos (site 426) with a throw of 1m, dislocating solution notches which were post-Roman. Similar but smaller faults can be seen in cliffs on Crete.

Other locations where vertical site displacement is associated with known faulting are Caesarea (203/1058), Dor (199) and Acco (182) near the Qishon Graben; probably Apollonia in Cyrenaica (949); Ruspina (127); south Turkey, Fethiye (289) to Kekova (302); Nora (160) southern Sardinia. King and Vita-Finzi (1981) analyse the fault structure associated with a modern seismic event near the coast of Algeria, just inland from Caesarea (151), which has the highest rate of subsidence in Region 3. In all cases the observed data indicate submergence, with the exception of one period at Dor. Vita-Finzi and King (1985, p.383) note that submergence is more easily detected than emergence even by contemporary observers of an earthquake event, and the same phenomenon is true of historical and archaeological data. Except for gross examples of uplifted harbour-works, uplift can go unreported. Nevertheless, the existing data do show a correlation of submergence with local faulting, although this may require further interpretation.

Correlation with modern and historical seismicity

Seismicity is associated with active faulting, plate boundaries, and volcanism, so is not independent of the other factors under discussion. The association is not exact in terms of the surface expression of these phenomena, and so direct evidence of seismicity should be reviewed.

The British Geological Survey provided a computer print-out map of modern seismicity of the Mediterranean showing earthquake events classified in terms of depth and magnitude. It is theoretically possible to compute the total number of large and small earthquakes expected over a prolonged period on the basis of recorded events over a few decades (Main and Burton 1984), and hence to typify areas in terms of total energy release. Similar generalisation can be obtained from assessment of slip rates (North 1974). For the present analysis, correlation was made subjectively with the BGS plots. It should be borne in mind that the seismicity refers only to the recent decades, and the distribution is not necessarily identical with the average over several thousand years.

Subjectively the correlation is evident. 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 sea level 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.

As noted above, the data for the Calabrian Arc are not good enough to provide sure correlation, though this may be partly due to the occurrence of most epicentres offshore between the Lipari Islands and Naples. A belt of seismicity cuts across Tunisia and Algeria, intersecting the coast in the neighbourhood of the submerged sites of Sullectum (1027) and Caesarea (151). There is no recorded seismicity relating to the faults in southern Sardinia close to Nora (160), whilst the seismicity of south east Spain is not correlated by data for vertical movement.

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. Flemming (1978, p.444) showed that the data for the NE Mediterranean correlate with the evidence from Ambraseys (1970) for historic seismicity. Historical seismicity for France (Vogt 1979; Gagnepain-Beyneix et al. 1982; p.274), and Italy (ENEL 1977) provide source material for further historical comparisons.

Correlation with modern volcanism

Active volcanoes exist at Lipari Islands, Naples, Etna, and Santorini. There are other extinct or dormant volcanoes, including submarine locations. No adequate data have been obtained from the Lipari Islands, or Santorini, in spite of efforts on site. Naples correlates with one of the highest observed rates of vertical movement, and this is directly related to the eruption of Monte Nuovo in 1538 (see references cited in (Flemming 1969)). No displaced site has been recorded close to Etna, but there is submergence both at Messina (93) and Thapsus (97) to north and south.

Correlation with continental shelf characteristics

The Mediterranean continental shelf is in general very narrow, with the exception of the Golfe du Lions, the northern Adriatic, and the Gulf of Sirte. The narrowest shelf and deepest water are associated with the Hellenic Arc on the south side, and, in this location, with high rates of vertical movements. In contrast, the very steep shelf off the French Côte d'Azur is associated with vertical stability.

The wide shelf of the Golfe du Lions is apparently subsiding; the Gulf of Sirte, at least in the region of Gabes, is associated with uplift; whilst the Adriatic is associated with submergence. Thus there is no general correlation.

The possibility that continental shelves and margins are tilting about an axis parallel to the shore introduces serious problems in interpretation of data. There is evidence that the relief of the Mediterranean area is increasing, and so such tilting, down-warping, or down-faulting of the shelf relative to the hinterland is, on average, probable. The result is that high sea level data indicators inland of the present shoreline will tend to show greater rates of uplift than the present data set; indicators for low sea levels will occur offshore relative to the present shoreline, and will tend to show greater rates of submergence than the present data set. On crenelated coastlines, such as the west coast of Cyprus, the headlands will tend to show submergence (or at least lower rates of uplift) relative to the backs of the bays, (Richards, 1984, field report). Contamination of the data due to coastal and shelf tilting is liable to introduce an average bias into sea level studies, especially over periods longer than 5000 years. Many of the present data values may be determined by their location landward or seaward relative to a near-coastal axis of tilt.

The possible bias towards tilting of the continental margin is shown in some regions by the rapid subsidence of the outer end of the Cesme peninsula (sites 262 and 266); the subsidence of the headlands of western Cyprus (Richards, field report); subsidence and tilting of the shelf off Atlit (193) Adler (1985); and the general doming pattern of the Peloponnese (Fig. 3).

Correlation with sedimentary isostatic loading

Sedimentary isostasy and sediment compaction would both tend to occur on large deltas, and the large alluvial infilling of re-entrant bays and graben valleys. In locations where valid sites occur the correlation is confirmed, with depression below average eustatic curve in the Rhône Delta (sites 30, 31, 971, 978), Po Delta (sites 588, 773, 1125, 1128). It is difficult to separate isostasy from compaction, but the data exist in some cases. For example, some Roman quarries in the Rhône area are on bedrock, where an isostatic factor might be detected independently of compaction. Sites in the Golfe de Lions (25, 969, 1006) are also submerged more than the adjacent coasts, which is compatible with long term sediment accumulation and aseismic subsidence.

ANALYSIS OF TIDE GAUGE DATA

Tide gauge data has been used to estimate earth movements in Europe and the Mediterranean by Emery and Aubrey (1985), Pirazzoli (1987G) and Flemming and Woodworth (1988). The last-mentioned paper is attached to this report as an annex (2).

Tide gauge data provided by the Hellenic Navy (Flemming and Woodworth 1988) show that the residual trend of earth movements, after removal of seasonal and interannual variability, is of the order of 5-20mm/year at 15 Greek ports, with movement of the coast as likely to be up as down. Pirazzoli (1987, Table 5.1) provides data for 16 tide gauges in the Western Mediterranean and Adriatic, showing rates of sea level change over 50-100 years averaging 0.3 to 2.3mm/year, all showing relative subsidence of the coast, with one exception. These data have not been corrected to separate earth movements from eustatic sea level change.

Pirazzoli (1987b, p.175) points out that the rate of rise indicated by the tide gauge at Marseille is much higher than the average over the last 2000 years, and that similarly the rate of rise indicated by two closely dated archaeological features at Marseille approximately 2000 years ago is also higher than the average.

This effect is probably caused by aliasing, and was studied explicitly by Flemming and Woodworth (1988). The problem is illustrated diagramatically in Fig. 5. If the observed relative time series of sea level change at a point on the coast consists of an irregular series of oscillations, with many different frequencies present, the average rate of movement measured over different time-spans will tend to decrease with increased time of averaging, but will usually be of the same sign. Fig. 5 shows that the apparent direction of average movement may reverse without in any way indicating that the general nature of the movements has changed over time.

Flemming and Woodworth (op cit) show that, in general, rates of vertical earth movement in the Aegean averaged over 2000 years are 1/6 x the rate of those measured at the same sites by tide gauges over 10-20 years. From this a general equation can be deduced for the region. A table showing this correlation is shown in Table 3.

Emery and Aubrey (1985) deduce a rate of vertical movement from tide gauges on the Scottish coast which is twice that based on Carbon-14 dating of beach deposits over several thousand years (Flemming 1981). This suggests that the spectrum of variability of earth movements is much less noisy, and has fewer high-frequency components for this region which is dominated by isostatic recovery. The process of isostatic post-glacial rebound is also probably slowing down.

The aliasing ratio for different regions gives a general indication of the reliability of trying to extrapolate from short records to longer periods. The more high frequency components present, the higher the ratio. Large tectonic events separated by time spans of the order of 500-1000 years would be very difficult to detect or predict.

Table 3A shows the ratios which would be expected by comparing tide gauge records of several decades with archaeological periods of 1000 years or 2000 years, if the equation for the Aegean were applied to all data. The ratios range from a minimum of 2.5 when 100 year tide gauge data is compared to 1000 year archaeological data, through to 4.36 when 50 year data is compared with 2000 year data; and a maximum of 8.3 when 10 year data is compared with 2000 year data.

There is no region outside the Aegean where so many tide gauges can be accurately compared with co-located archaeological sea level data. We are therefore reduced to comparing the average rate of displacement of regions over two time periods.

Region (1) from Flemming and Webb (1986) contains 7 tide gauges listed by Pirazzoli (1987). The average length of tide gauge records is 76 years, and the average relative displacement is 0.685mm/year relative rise of sea level. The archaeological data is based on an average age of about 2000 years, and shows a relative subsidence of 0.23mm/year. The ratio is 2.978, or almost exactly 3.0. Table 3 shows that the aliasing ratio from 80 years to 2000 years would be 3.61 if the area were as active as the Aegean, which it is not.

Examination of the data from Pirazzoli (1987b) show that there are no other regions in which even this crude average comparison can be made with confidence. Region 5 contains only two reliable tide gauge records, and region 3 contains 4. None of the available tide gauges co-locates exactly with an archaeological sea level indicator site, and the distances of approximation become unacceptable.

The paper by Emery et. al. (1988) on Mediterranean tide gauge data appeared as the present report was being completed. The data suggest that the analysis discussed above could be extended to show similar correlations for parts of the coasts of Israel, Turkey, and Italy.

PREDICTIONS OF FUTURE COASTAL EARTH MOVEMENTS

The concept of a spectrum of rates of earth movement, with the nature of the spectrum varying from region to region, suggests a way of predicting the probable rate of earth movements in the next 50-100 years. Where there is a tide gauge record itself extending over 50-100 years, then that record is the most accurate basis on which to make a prediction of local earth movements, with the justification of extending that estimate prediction for 10-20km along the coast on either side.

The method of prediction, and the certainty, depends upon the type of data available locally, and the known characteristics of the spectrum of earth movements in time and space. The different conditions of data availability are as follows:

i) Tide gauge data with 50-100 years of accurate well-calibrated data at the study site.

ii) Tide gauge data with 50-100 years of accurate well-calibrated data available at a site within 10-20km of the study site.

iii) Tide gauge data with 10-20 years of well-calibrated data at the study site.

iv) Tide gauge data with 10-20 years of modern well-calibrated data within 10-20km of the study site.

v) Archaeological estimate of relative sea level change and deduced earth movements over 1000-2000 years available at the study site.

vi) Archaeological estimate of relative sea level change and deduced earth movements over 1000-2000 years within 10-20km of the study site.

vii) No tide gauge or archaeological data within 10-20km of the study site.

Each condition above will be considered in turn:

i) A typical tide gauge record of annual mean sea level shows fluctuations which may be due to inter-annual variations in absolute mean sea level, or faster and slower changes of land level. In order to determine the earth movement component, the global mean sea level change over the same time scale should be subtracted. The best estimate of this is subject to some debate (Gornitz et al. 1982; Barnet 1984). In this paper I do not intend to recommend a best estimate, and in any case, the estimate will probably be revised slightly in future years. The residual earth movement can then, with reasonable confidence, be extrapolated for the same period into the future.

Various cross-checks should be applied. If the area is tectonically active, and if archaeological data suggests that the long term rate of change is faster than would be suggested by the general $1/T^{0.4}$ aliasing relationship, then some allowance should be made for the probability that rapid rates of movement may occur from time to time which have not manifested themselves in the last 100 years, but may occur in the next 100.

In all cases of tectonic movement it is possible for the direction of movement to reverse for periods of decades to centuries. Flemming and Woodworth (1988) show that for co-occurring pairs of tide gauges and archaeological data sites the direction of movement is the same in every case. However, this is a small sample, and reversal manifestly could occur. The probability of reversal would be increased if the archaeological record provides clear evidence of reversals in the past (eg. Matala (347), Caesarea (203/1051), Zimbule (416), or if the average rate of movement is significantly less over the archaeological timescale than would be suggested by applying the aliasing factor to the tide gauge data.

If the cause of earth movement at a site is sediment compaction or isostatic subsidence under sediment loading, this will probably proceed at a more even and steady rate than tectonic subsidence. On the other hand, deltaic sediments may actually slump on rare occasions.

ii) If there is no long tide gauge record at a site, but one exists within 10-20km, then the prediction can be extended laterally with reasonable confidence, but some caveats. The lack of coherence between nearby sites is of course more marked in areas of extreme tectonism, than in areas which are aseismic. The data provided by Flemming (1969), Pirazzoli (1976b), Flemming (1978) and Flemming and Webb (1986) show that there are regions of the Mediterranean coast which are stable and laterally coherent (eg. southern Turkey from Antalya to Iskenderun); regions which are moderately stable and coherent, (eg. Spain and southern France); regions which are inherently noisy and laterally incoherent, (eg. much of Greece and the Aegean coast); and finally regions which are unstable, but tilting or warping in coherent blocks, which can be contoured for trends in rate of vertical movement, (eg. Crete).

The factors mentioned above, together with knowledge of local geology, should be used to see if it is justifiable to extrapolate the predicted rate of earth movements from the site of a known tide gauge for a distance of 10, 20 or 30km along the coast. Knowledge of local faulting, presence of alluvium, settlement of sediments in deltas etc., should be taken into account on the basis of immediately local geological data.

iii) A tide gauge record of less than 20 years is relevant, but prediction from such a record for 50-100 years into the future is statistically less certain than with a longer record. The short record may exaggerate the rate of movement through aliasing, or fail to reveal movement if it is periodic with a period longer than the record. If a consistent rate of movement of the earth is detected over a period of the order of 10 years, it is likely to be an over-estimate of the rate of movement to be expected over 50 years by a factor of 2, and an over-estimate of the rate to be expected over 100 years by a factor of 2.5. (see table 3B). These ratios apply to tectonically active areas such as the Aegean, and probably the coast of Jugoslavia and Albania, and parts of Italy, and Algeria. In areas of subsidence and sediment loading, the over-estimate from short tide gauge records is probably less exaggerated.

A short tide gauge record should be cross checked against co-located or nearby archaeological data if possible. (see below).

iv) If there is neither short term nor long term tide gauge records available on site, but a short term tide gauge record within 10-20km, then further approximations must be adopted. Archaeological and geological data permits the region to be characterised in terms of local lateral coherence as in (ii) above. The short term tide gauge estimate of the vertical rate of movement of the coast should be corrected for the extrapolation in time on site, and then for the extrapolation laterally along the coast. Archaeological data should be used wherever possible to cross check the tide gauge prediction, using appropriate correction factors from table 3.

v) If there is archaeological data on site, then a fairly accurate assessment should be available of the vertical rate of earth movement averaged over 1000-2000 years. This average figure will, in some cases, be accurate to better than 0.2mm per year. The problem is that the average can be a severe underestimate of possible short term movements, and therefore the archaeologically indicated rate should be increased by a conversion factor, as shown in table 3. The conversion factor is derived from the Aegean, and should therefore be conservatively safe for other areas.

vi) If there is no archaeological data available at the site, but such data exist within 10-20km, then the regional pattern should be studied, as in (ii) above. Flemming (1972; 1978) and Flemming and Webb (1986) show pronounced regional patterns in crustal tilting, so that the rates of vertical movement can be interpolated with some confidence between sites in some areas. The interpolated values should then be corrected for aliasing, as in (v) above.

vii) If there are no tide gauge data and no archaeological indicators of sea level within 10-20km of a site, the prediction becomes much more subjective, and less certain. This is however the most general case. Examination of regional geological data, seismicity, faults, alluvium, etc, provides a general view of the expected level of vertical movement in the region within say 100-200km of the site. Archaeological sea level data within the region, cross-checked with tide-gauge data where possible, will confirm the general picture. Publications by Vita Finzi and King (1985); Le Pichon and Angelier (1981); Flemming and Webb (1986); Sanlaville (1977); Paskoff and Sanlaville (1981) and others provide general information on the regional rates of crustal deformation, tilt, faulting, etc.

CONCLUSIONS AND RECOMMENDATIONS

1) Tide gauge data are the most accurate source of information on vertical coastal land movements, but a record of at least 10-20 years is needed before a reasonable prediction on the 50-100 year timescale can be made, and the record should preferably be of the order of 50-100 years. There are only 16 published long records in the MAP area, and 15 short records, with adequate quality control.

2) Because of the lateral variability in coastal earth movements, data at one site can only be interpolated or extrapolated laterally for a distance of the order of 10-20km. If a large number of data sites are available for a region, then deduction of trends, tilts, general stability, etc., enables more certain prediction between data points, but even then, local anomalies cannot be ruled out.

3) There are 335 good estimates of sea level change based on archaeological data over the 1000-2000 year timescale, with an average spacing for the whole MAP area of 134km. In practice the regions with archaeological data are much more densely sampled with good data, and some regions are almost totally without data. If the coasts of Jugoslavia, Albania, Egypt, and the North and Central Aegean are excluded, the published archaeological data provides a sampling density of one site per 75km of coast. This is getting quite close to an adequate sample.

4) If a predictive study is needed urgently to cover the whole coast of the MAP area, the following steps are recommended:

5) Obtain further tide gauge data from ports where records exist, but where they have not been published, e.g. Ashdod, Haifa, and others.

6) Calculate the ratios of rates of movement for co-located tide gauge and archaeological data for other regions than Greece, so as to find the correction ratios to be applied in different regions.

7) Obtain archaeological-historical data for the poorly documented regions. A regional study of a national coastline several hundred km long can be conducted in one or two years, and is not expensive. Although the data are not as accurate as tide gauge data, they are available almost immediately, whereas a tide gauge installed now will have to be maintained for at least ten years before it provides valid data on coastal earth movements.

8) The methodology suggested in this paper has been worked out rather quickly, and could be considerably refined. The data sets available for each region should be carefully assessed, and the best regional principles derived for prediction of the vertical rate of movement predicted over the next 50-100 years, with confidence limits.

9) The precise gradient of the shore at each point should be recorded in a database so that the extent of land flooded can be calculated for each additional 10cm rise of relative sea level, summed for eustatic and earth movement causes.

GENERAL NOTE

The present author has worked personally on over 300 coastal archaeological sites during the last 30 years. Several sites have been revisited at intervals during that period. The rate of destruction of coastal and submerged archaeological sites from both natural and human causes is considerable. Whilst some sites are probably well protected for natural reasons, and have remained unchanged for centuries, others have been seriously damaged in 1-10 years. The submerged classical city of Apollonia in Libya was severely damaged by one winter of storms between 1958 and 1959; the Bronze Age walls and Classical Theatre at Plitra-Asopos in Greece were destroyed by wave action between 1968 and 1979. Neolithic remains near Atlit, Israel, are exposed by natural sand movements each year on the sea bed, and organic materials are damaged whilst exposed. In other areas, classical slipways, harbour works, and buildings in shallow water have been damaged or destroyed by the construction of coastal roads, yacht marinas, and land reclamation.

If the unique record of the origins of marine technology in the Mediterranean is to be preserved for humanity, it is recommended that those sites which are most threatened should be identified, and a decision taken as to whether they should be protected, or whether detailed surveys and records should be made.

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RATE OF DISPLACEMENT

MEAN TOTAL: −0.23m/ka (S.D.TOTAL: 0.93)

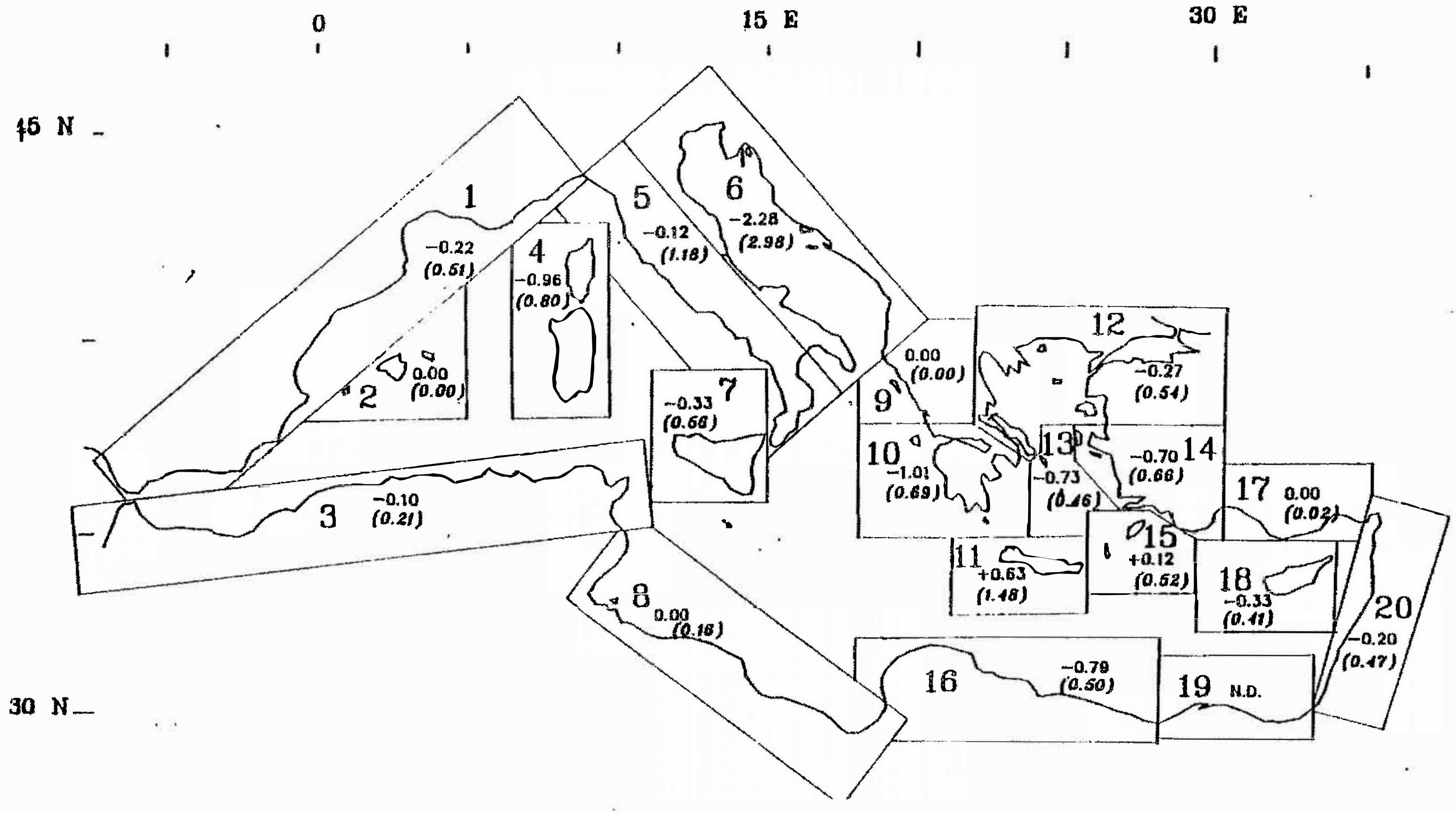
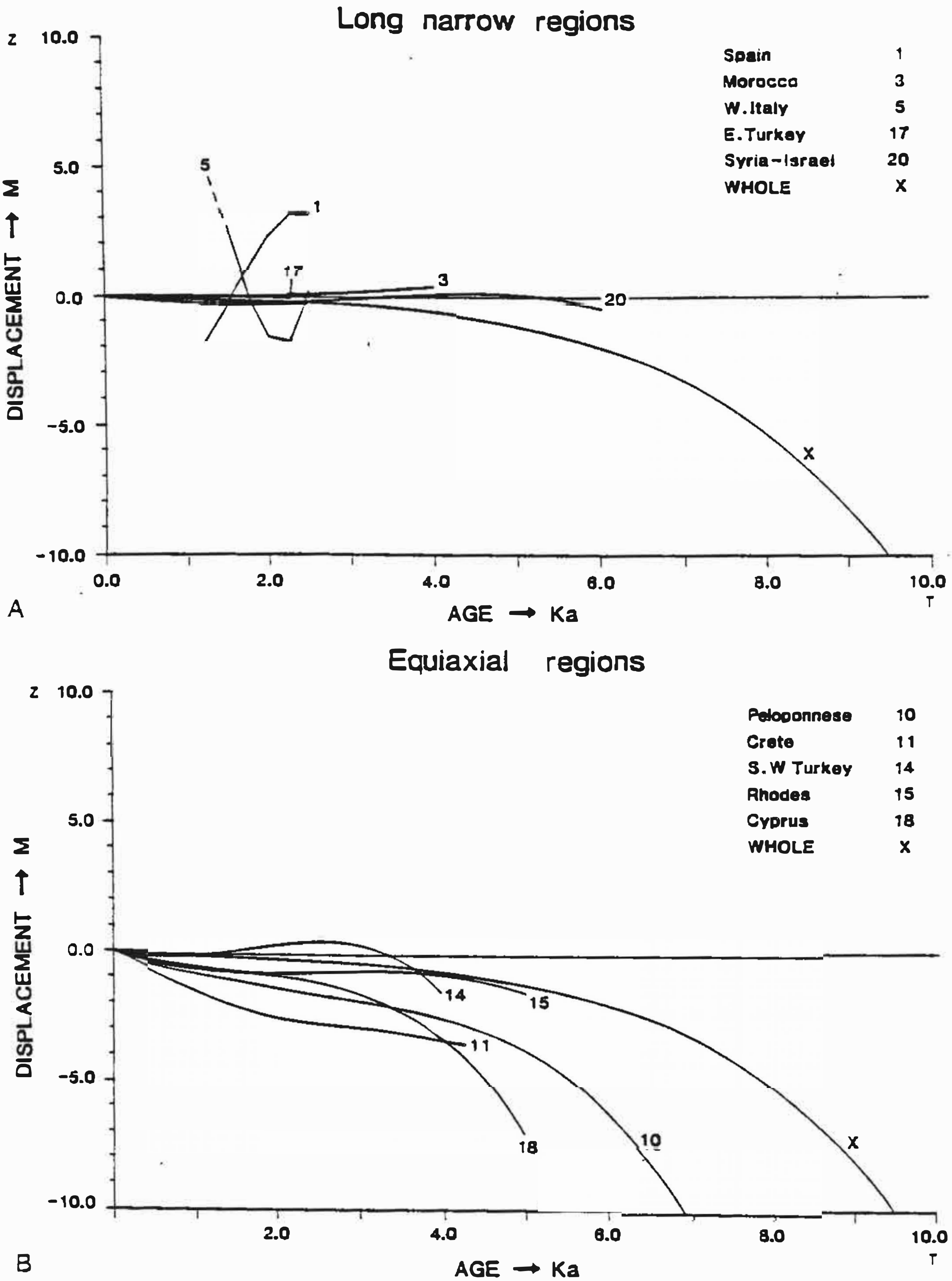
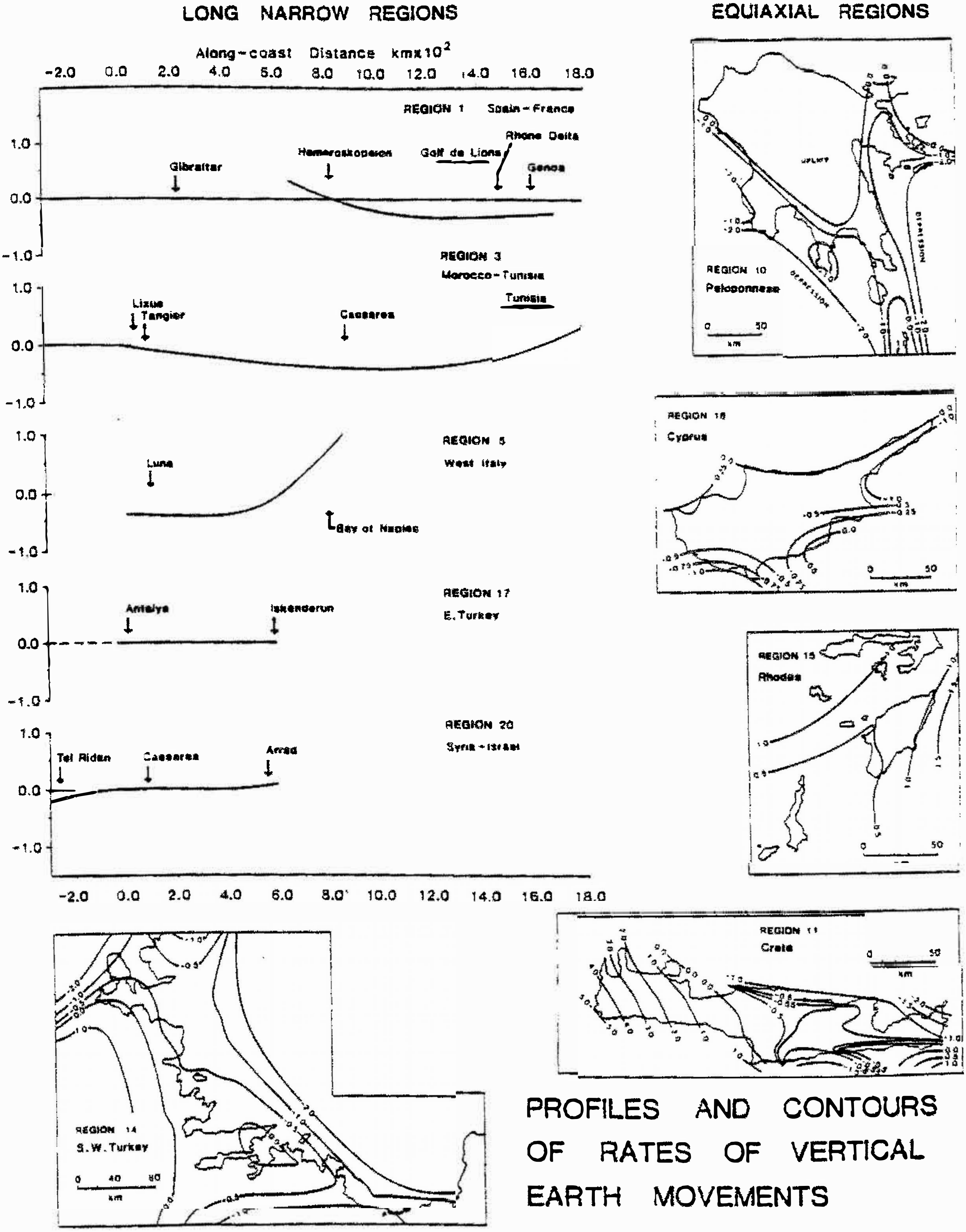


FIG. 1



Best fit curves showing the relationship Z=f(Tⁿ), 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.



PROFILES AND CONTOURS OF RATES OF VERTICAL EARTH MOVEMENTS

Fig 4

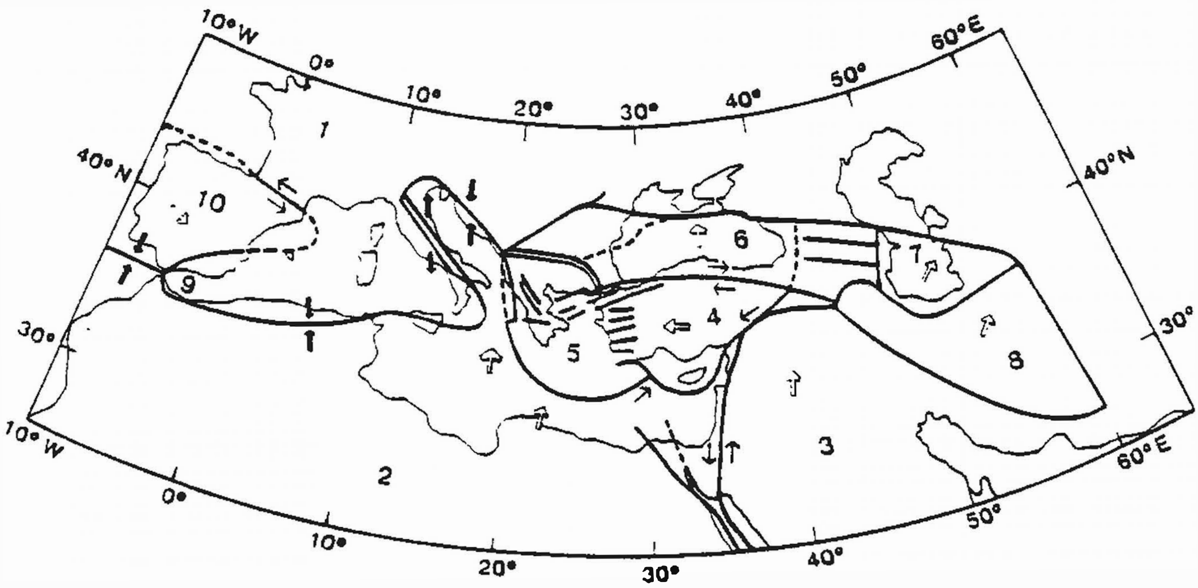


Plate boundaries, simplified from PETERS (1985).

Hypothetical Sea Level Curve

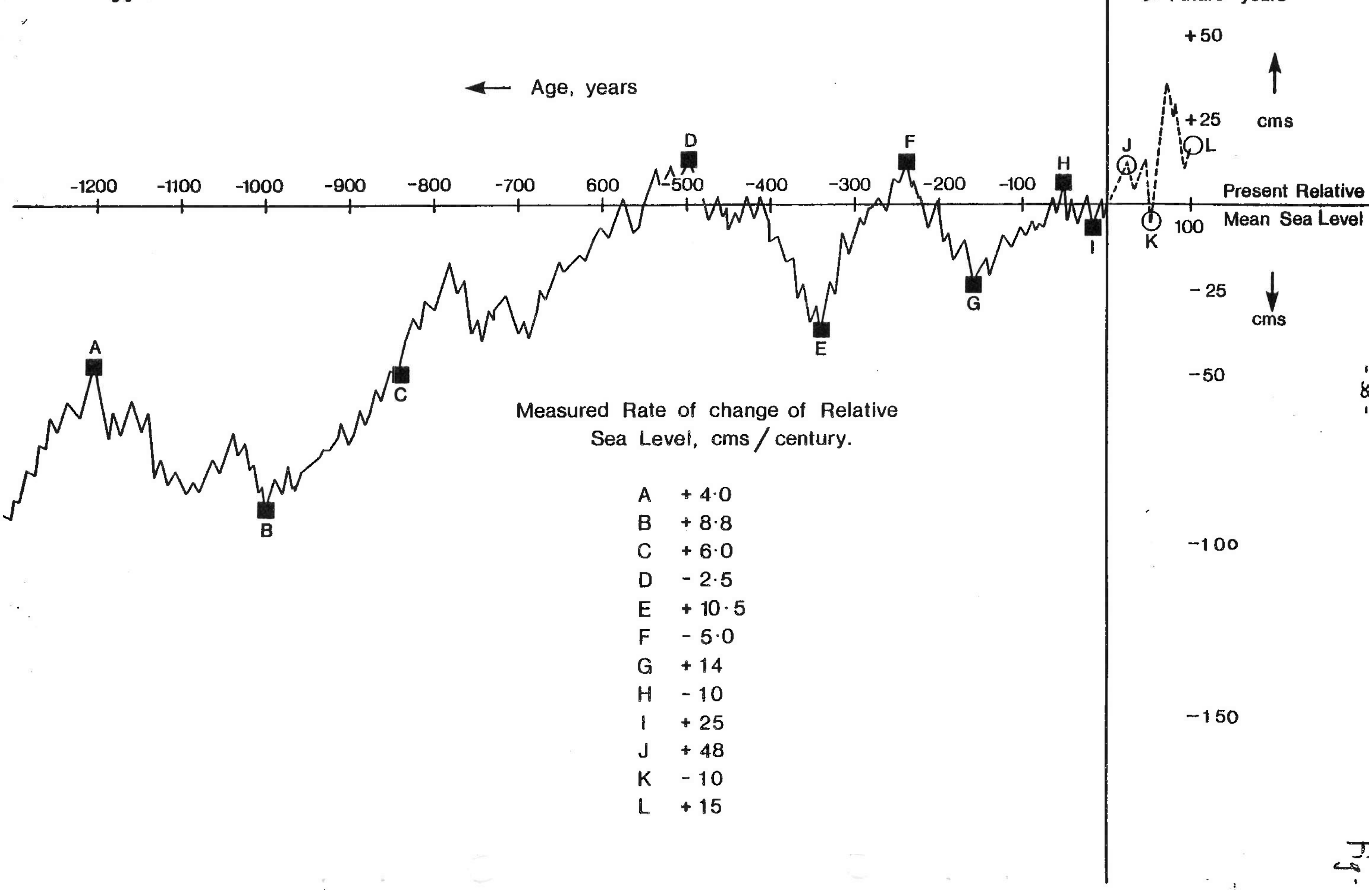


Table 1. Data volumes per region.

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.

Table 3

Assume equation

$$\frac{\text{Rate-T}}{\text{Rate-O}} = \left(\frac{T_o}{T}\right)^{0.4}$$

Where T = period of time over which rate of vertical movement is averaged, many tens to thousands of years; T_o = short period of years over which rate is measured by tide-gauge; Rate-T = rate of vertical movement averaged over time T; Rate-O = rate of vertical movement averaged over a short period of years.

3A. Ratios linking Tide-gauge timescales to Archaeological timescales

T_o years	T years	Ratio = Rate-O/Rate-T
100	1000	2.51
100	2000	3.31
80	1000	2.73
80	2000	3.61
50	1000	3.31
50	2000	4.36
10	1000	6.3
10	2000	8.3

3B. Ratios linking short Tide-gauge timescales to future multi-decade sea level changes

T_o years	T years	Ratio = Rate-O/Rate-T
10	40	1.74
10	50	1.90
10	60	2.04
10	70	2.18
10	80	2.30
10	90	2.41
10	100	2.51

Z. Geomorph. N. F.	Suppl.-Bd. 62	1-29	Berlin · Stuttgart	Dezember 1986

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

by

N. C. FLEMMING and C. O. WEBB, Godalming, England

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.

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 aurhors. 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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(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 abour 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, bur 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 km²	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
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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 km²; 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 our 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,

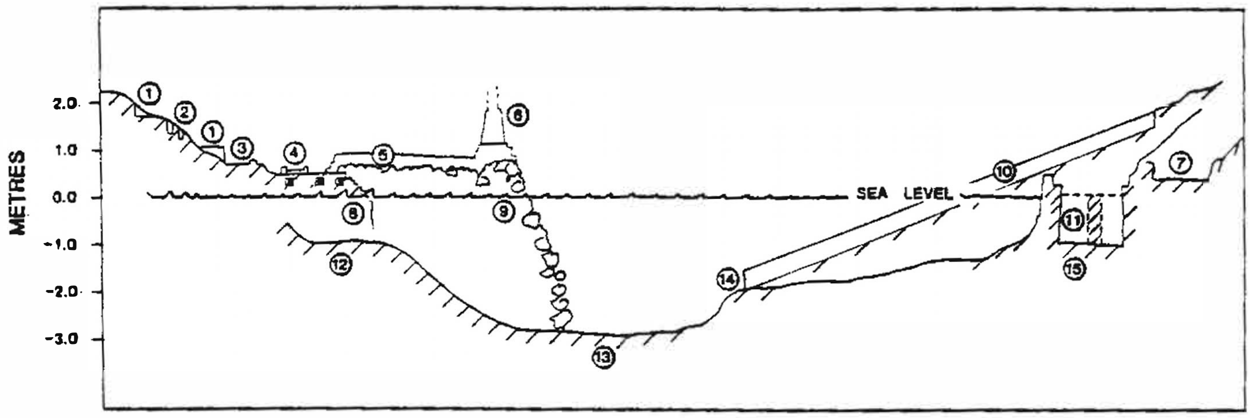


Fig. 1. Synthetic composite profile of a classical harbour site illustrating the architectural features and structures which indicate sea level: (a) above contemporary sea level, 1) house foundations, 2) tombs, 3) road, 4) quay upper surface with buildings; (b) partly above and partly below contemporary 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

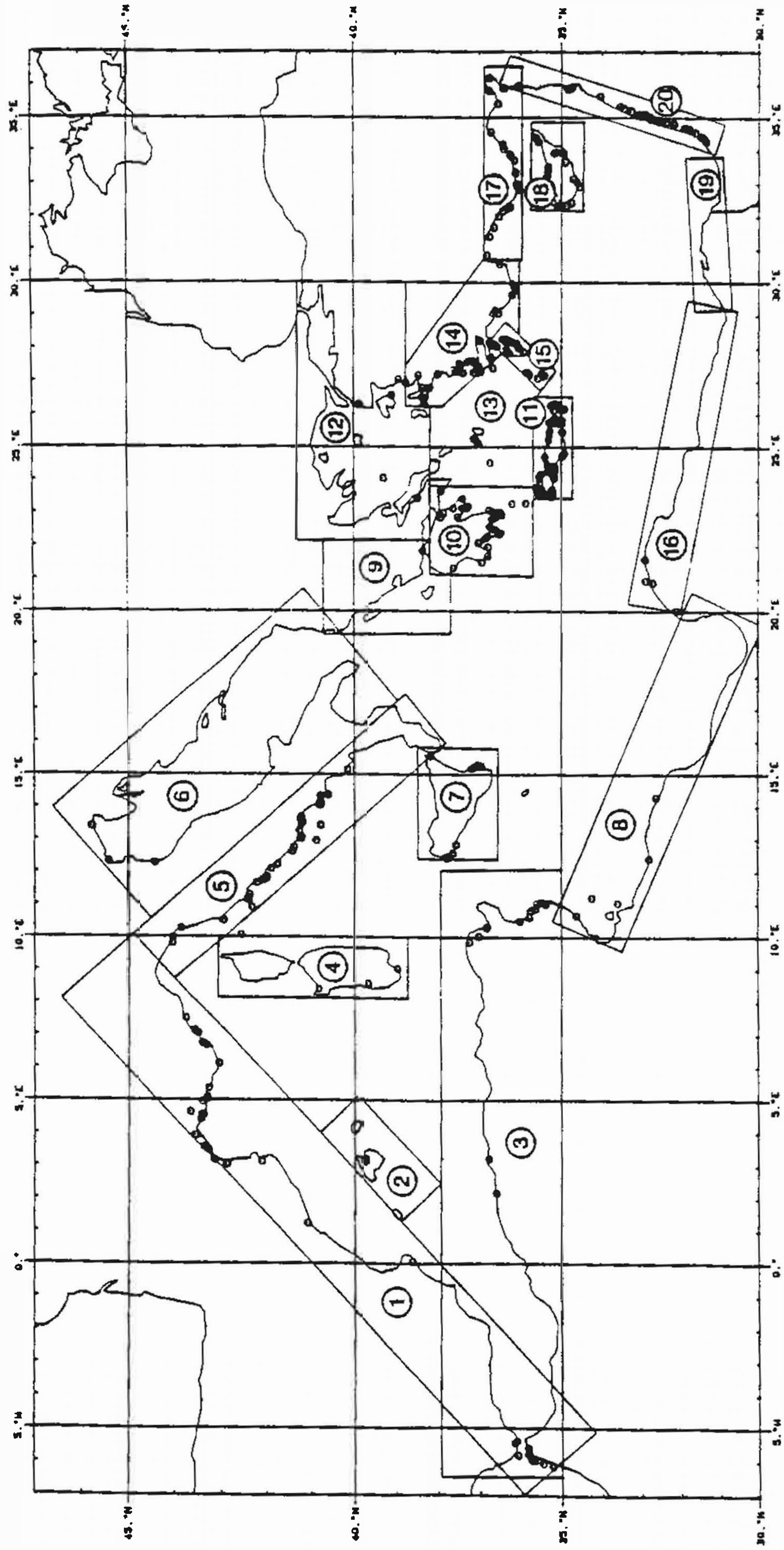


Fig. 2. Dot map shows the distribution of valid data sites included in the analysis. Boundaries of regions for analysis are shown, and region numbers. See table 1 for statistics of sites per region.

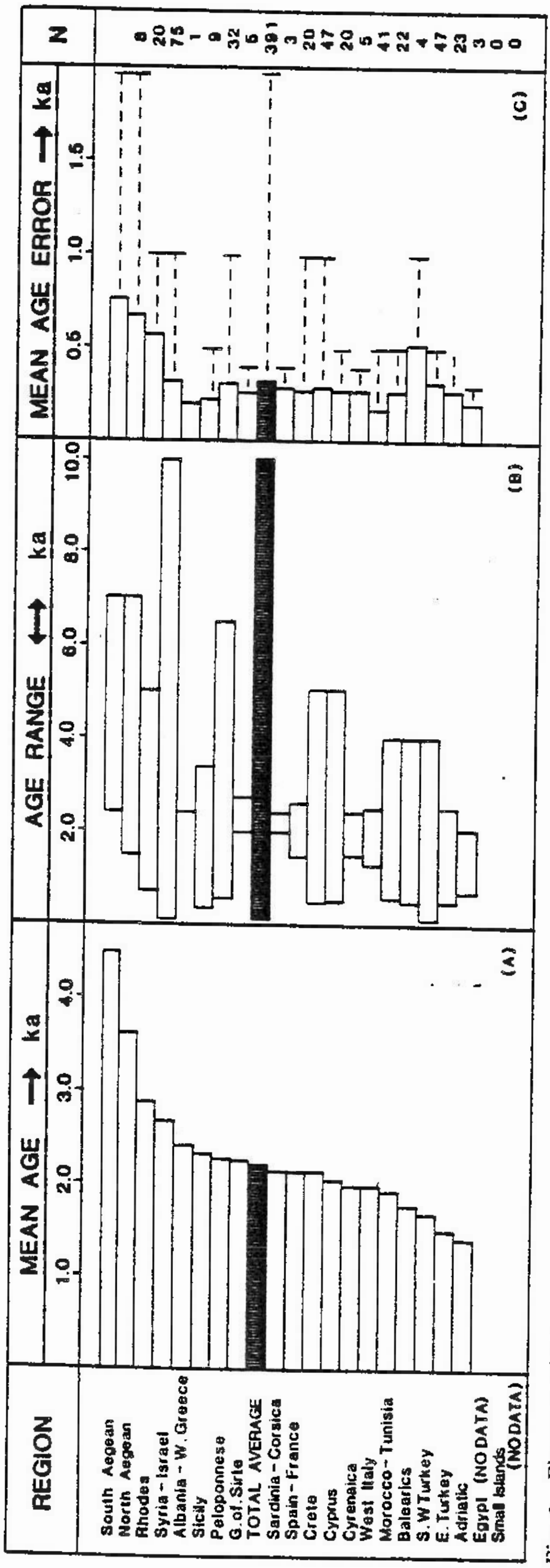


Fig. 3. Figure 3 (A) is a rank ordered bar chart of the average age of records at sites in each region, measured in thousands of years (ka); 3 (B) shows the range of age of records in each region; 3 (C) shows the mean error, and maximum error, for records in each region.

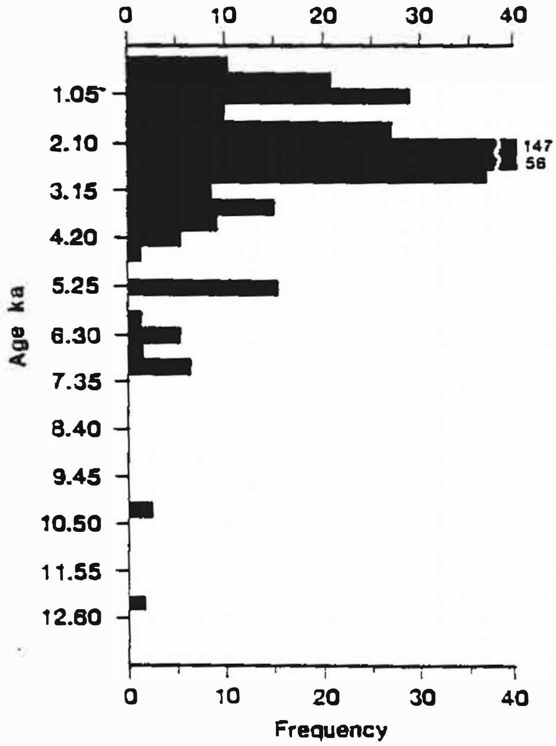


Fig. 4. Histogram of frequency of occurrence of records by age (ka). The age interval is 0.35 ka: records in each interval have an age less than or equal to the label. All sites are included for which age data exist.

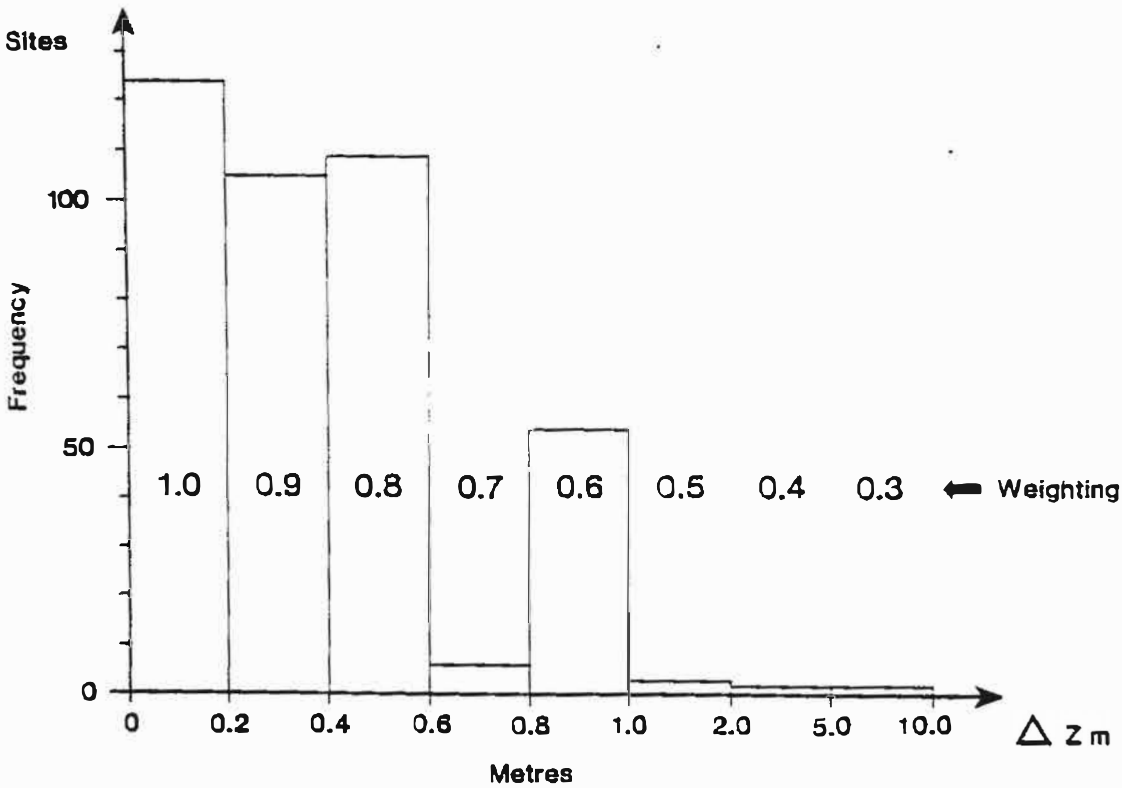


Fig. 5. Histogram of frequency of occurrence of errors in estimates of vertical displacement for each site record. Estimate of error is based on the type of data and accuracy of measurement at each site. For each error range the weighting allocated is shown in bold lettering. The weights are used in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

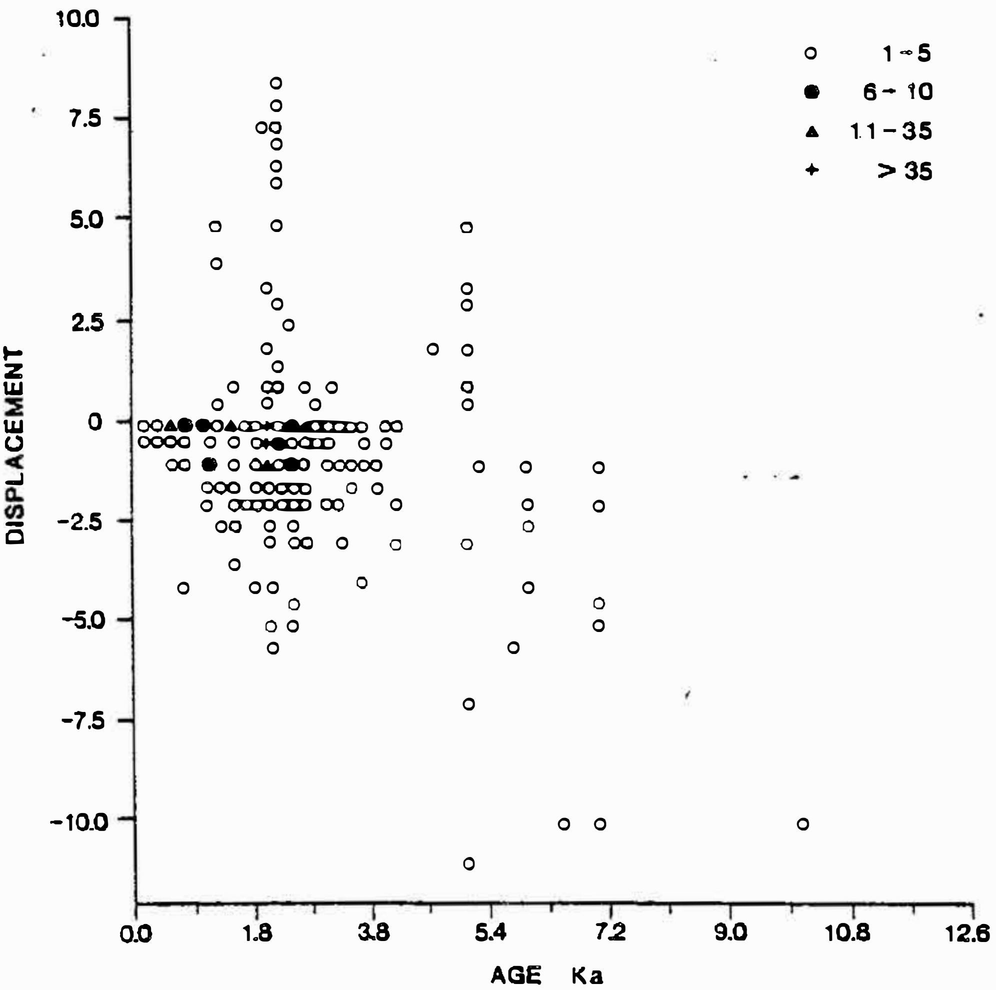


Fig. 6. Scatter plot showing the relationship between vertical displacement (Z) and age (T) for all valid records. Note the massive concentration of data trending slightly below the axis to 2 ka, and the bifurcation of the scatter into relatively uplifted and submerged site records.

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 (S 1) and (P 2) 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 (F 3) and Israel (F 6). 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 (F 5, p. 430). An exponential decay fitted to a model of glacial isostatic recovery is stating assumptions about the rheology of the mantle and lithosphere

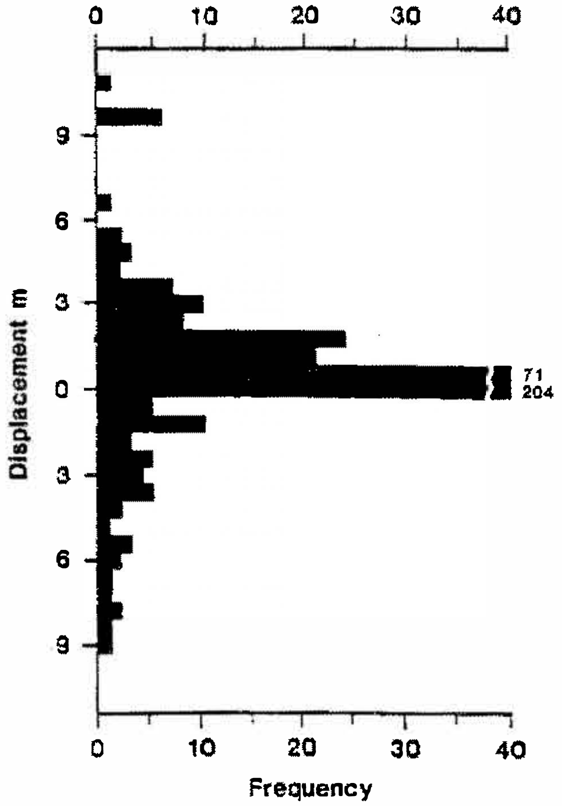


Fig. 7. Histogram of the frequency of occurrence of values of vertical displacement (Z) in metres. The interval width is 0.6 m; records in each interval have a value equal to or less than the label. All valid records are included.

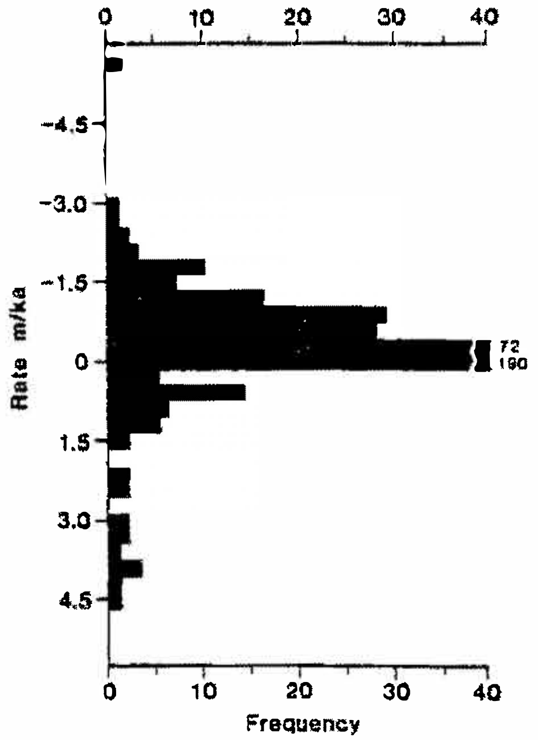


Fig. 8. Histogram of the frequency of occurrence of values of rate of vertical displacement (Z/T) in metres per ka. The interval width is 0.3 m/ka; records in each interval have a value equal to or less than the label. All valid records are included.

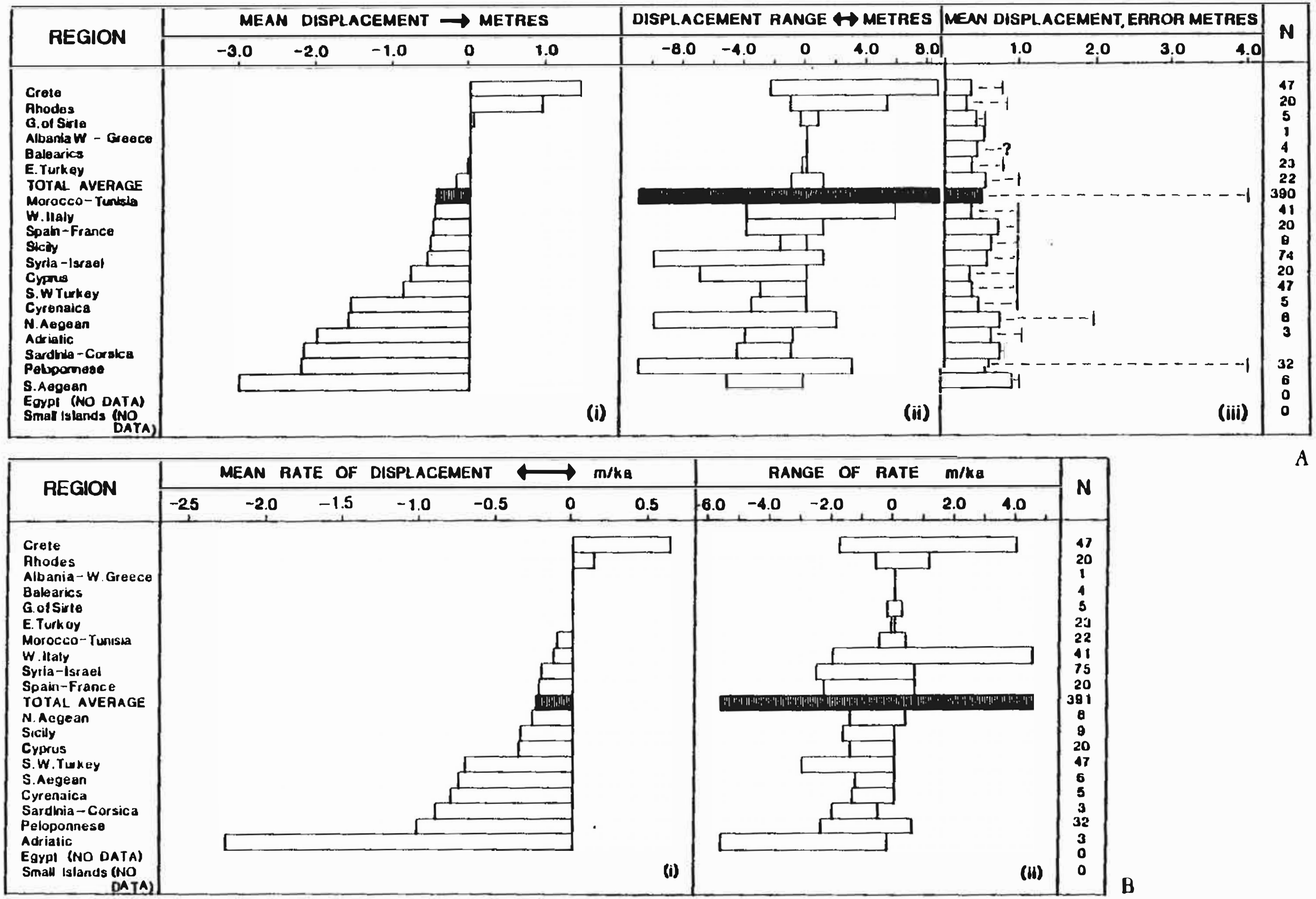


Fig. 9. A (i) Ranked bar chart of the magnitude of mean displacement in metres for each region; A (ii) range of vertical displacement of site records within each region; A (iii) mean error and maximum error of estimates of vertical displacement for records at valid sites. B (i) Ranked bar chart of the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

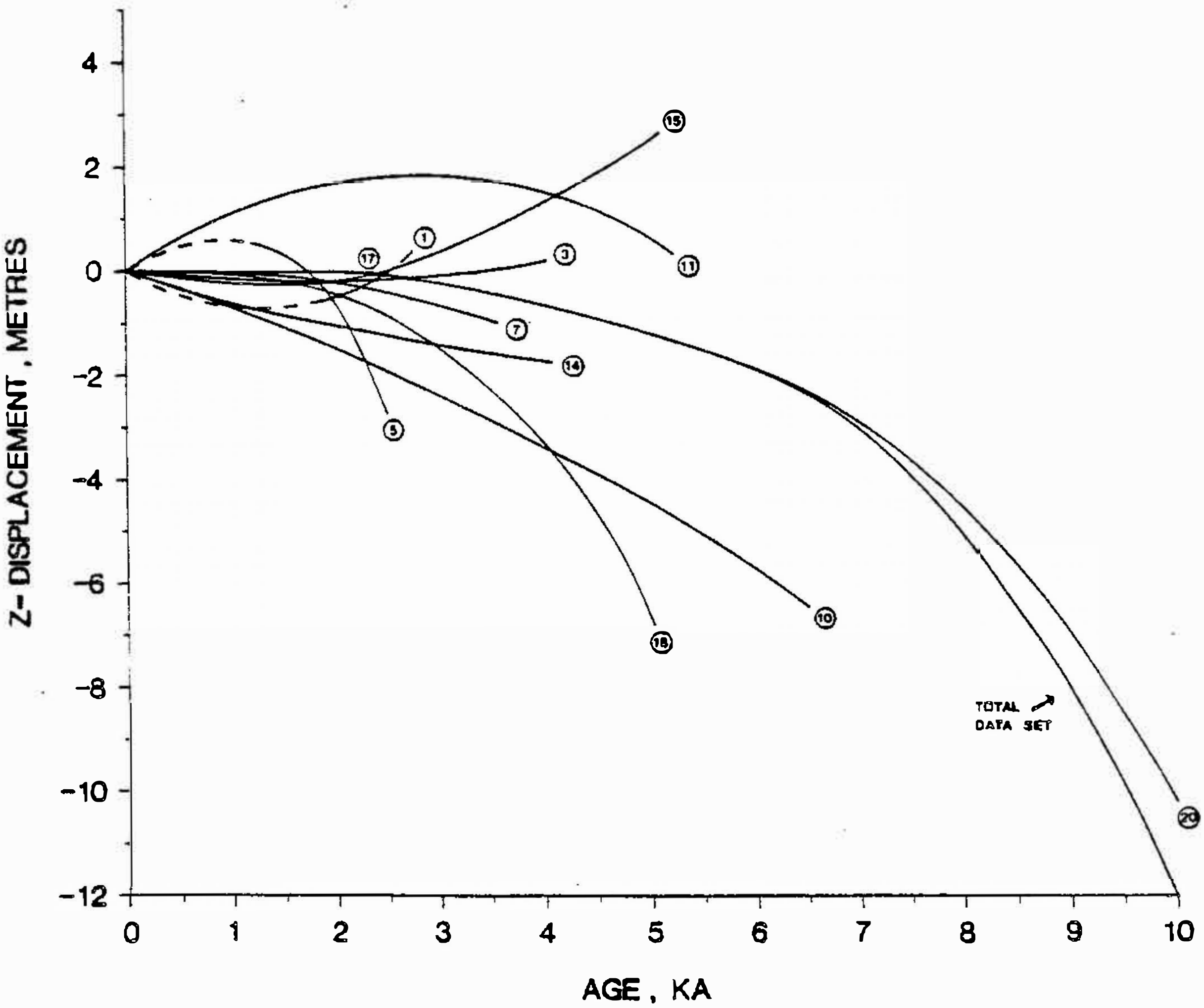


Fig. 10. Best fit curves showing the relationship $Z=f(T^n)$, for site records for each region and the whole data set, where Z=vertical displacement in metres; T=age of each site record in ka. Equations are 3rd or 4th degree depending upon the number of valid records. Valid 2-sided records are included. 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:

$$Z = T \times f(X\,Y) + f'T$$

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:

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

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).

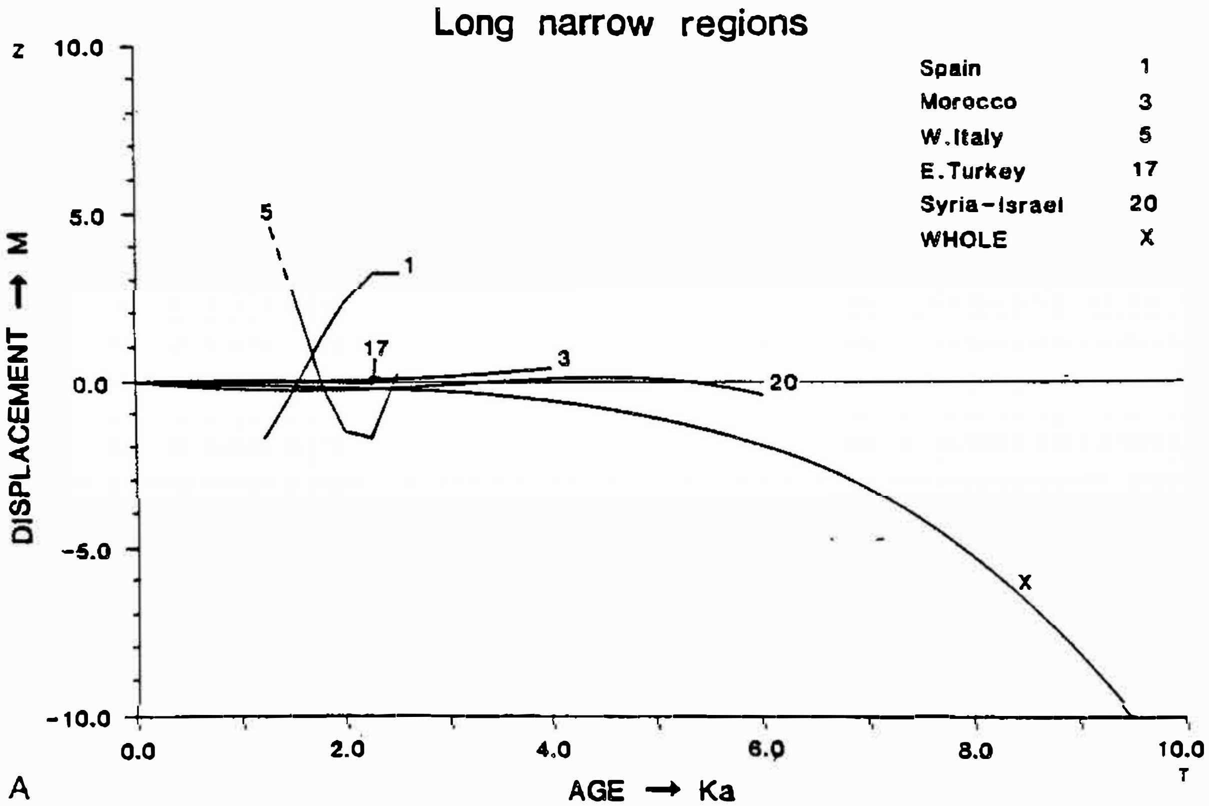
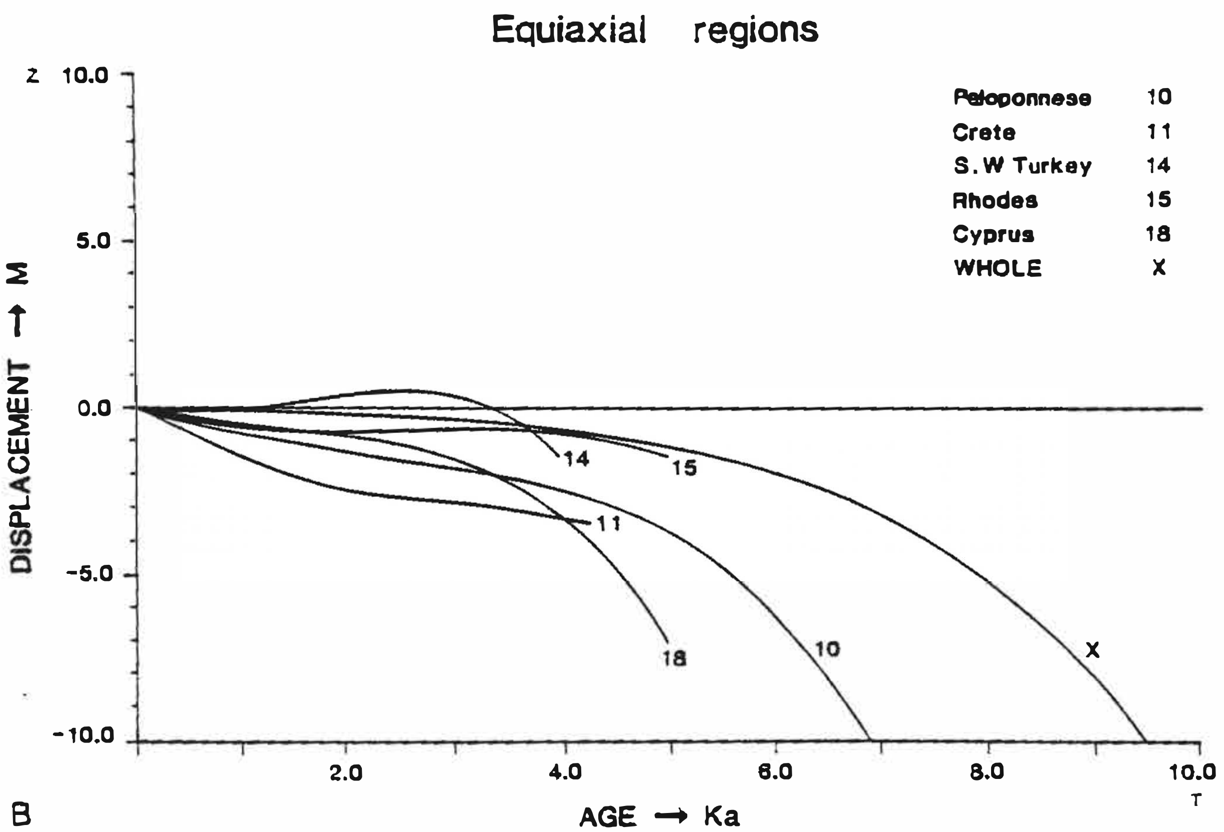
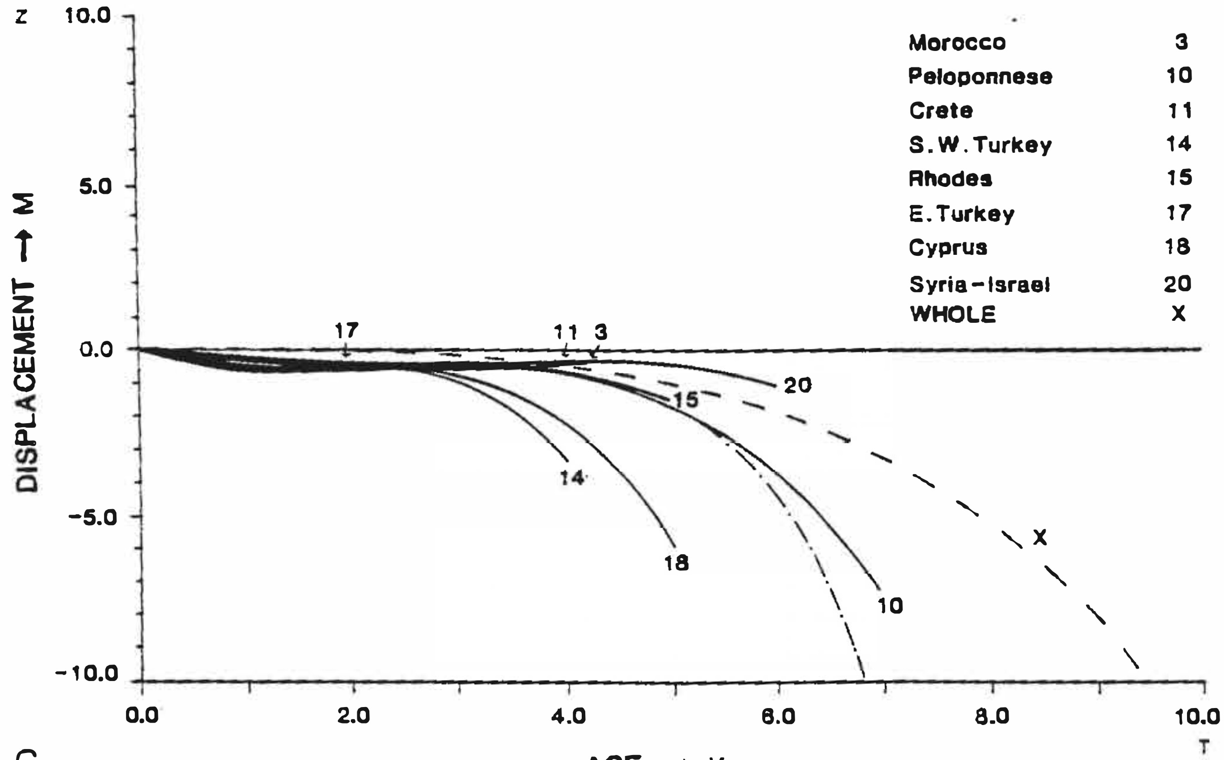


Fig. 11. Best fit curves showing the relationship $Z=f(T^n)$, for site records for each region, after removal of geographically dependent components representing earth movements. Z=vertical displacement in metres: T=age in ka. A=curves for long narrow regions, uncorrected for transfer of linear component 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
10.0
5.0
0.0
-5.0
-10.0
DISPLACEMENT → M
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
10.0
5.0
0.0
-5.0
-10.0
DISPLACEMENT → M
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.)

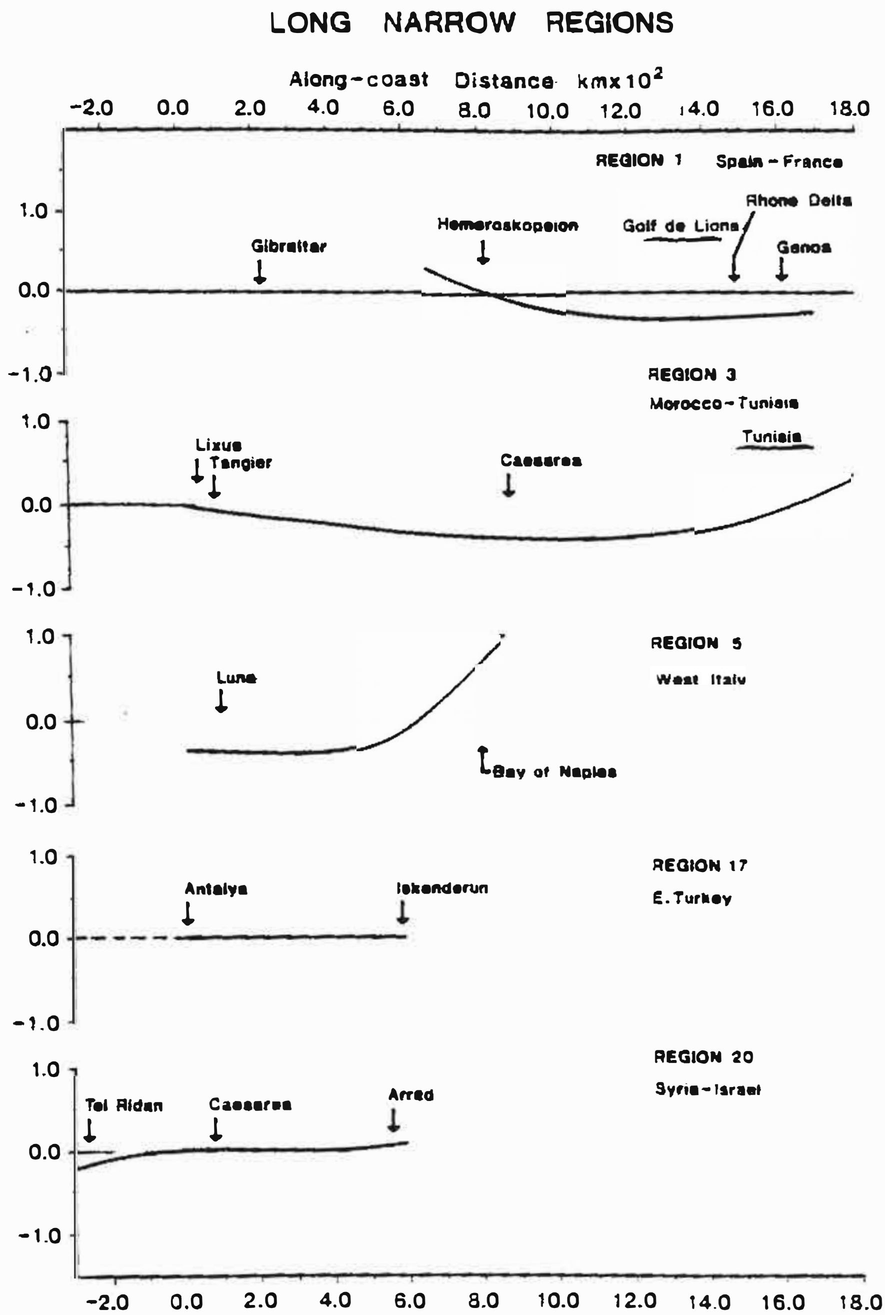
The regional curves can logically be made more like each other by transferring a linear component in age to or from the earth movement equations. The resulting curves are shown in fig. 11 c. The curve for SW Turkey is very similar to that obtained in (F5), and that for Israel is similar to the curve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

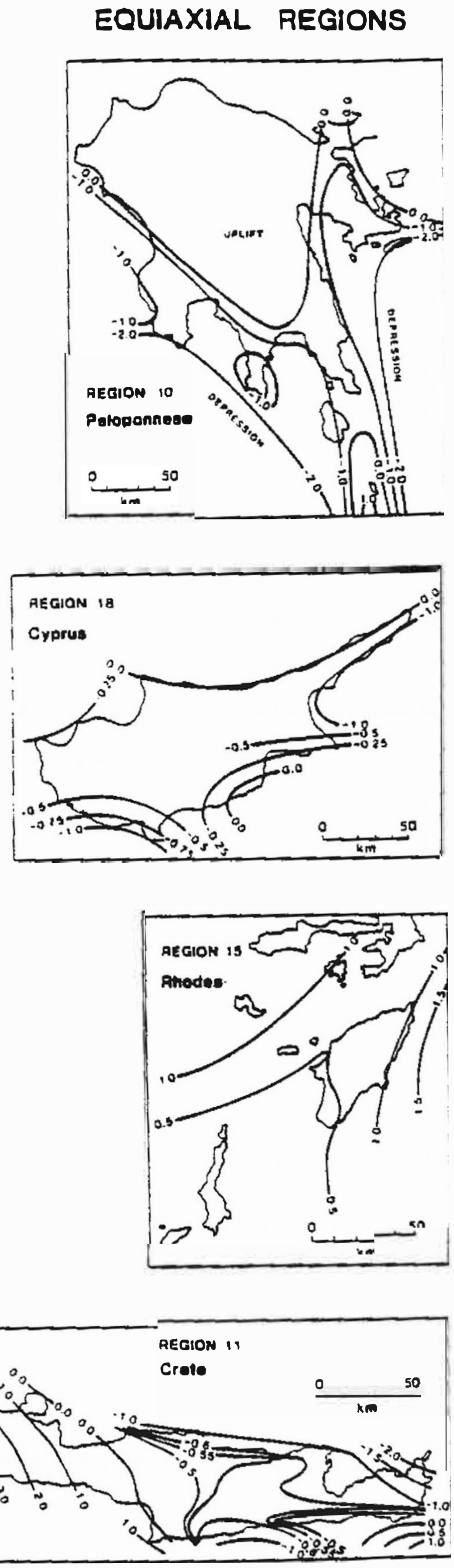
The analysis suggest that mean sea level relative to the coast of the Mediterranean has been very nearly stable for the last 5 ka to within 0.2−0.4 m. The first estimate curves for Regions 1 and 20 suggest a possibility of a high sea level of the order of +0.2−0.4 m at around 4 ka, which would be compatible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

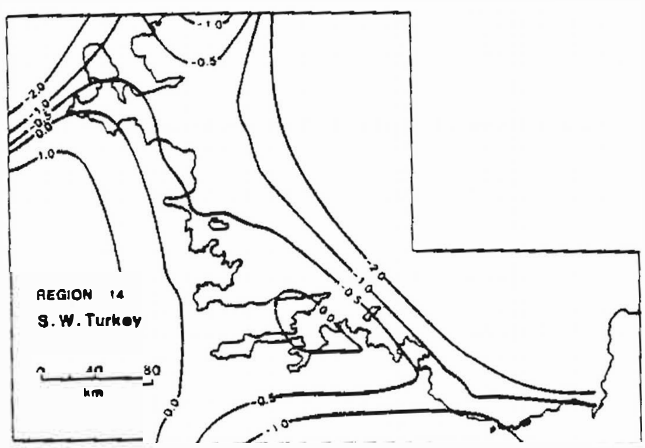
All the acceptable curves suggest a shallow S-form, with a relative low within the last 2 ka, a slight high at 3−4 ka, and then low levels at earlier dates. These variations may appear only as inflection points on an otherwise rising sea level.

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.







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-

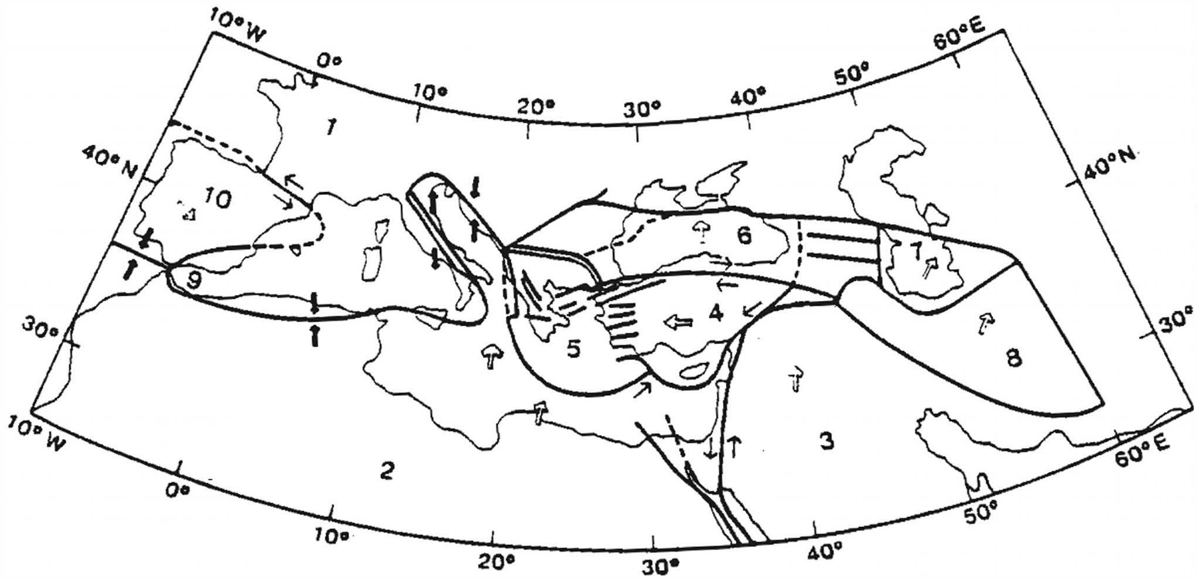


Fig. 13. Plate boundaries, simplified from PETERS (1985).

sponse 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 (GU 1; F 2).

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. (F 5, 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	
F5, FLEMMING 1978	LG1, LE GALL 1981	PA2, PASKOFF et al. 1981
F6, FLEMMING et al. 1978	LH1, LEHMAN-HARTLEBEN 1923	R1, RABAN 1981
F7, FLEMMING 1979	N1, NEGRIS 1904	R2, RABAN 1983
		S1, SCHMIEDT 1972

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ANNEX 2

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Monthly mean sea levels in Greece during 1969–1983 compared to relative vertical land movements measured over different timescales

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Abstract

Flemming, N.C. and Woodworth, P.L., 1988. Monthly mean sea levels in Greece during 1969–1983 compared to relative vertical land movements measured over different timescales. *Tectonophysics*, 148:59–72.

Sea level data from 16 tide gauge stations in Greece have been used in an analysis of the seasonal cycle of mean sea level in Greek waters together with an investigation of the interannual variability of sea level in the region for the period 1969–1983. The recorded seasonal cycle is found to vary considerably across the area and to agree well with sea level observations from neighbouring coastlines. The Greek data result in knowledge of the mean sea level seasonal cycle being now available from throughout the northeastern Mediterranean. An overall drop of sea levels is observed during the mid-1970's, while the larger peaks and dips in the records are found to be coherent over the whole area and, on several occasions, to be general to the entire northern Mediterranean.

The tide gauge data set has also provided measurements of the secular trends in relative mean sea levels over the same 15-year period. A wide geographical variation of sea level trends is observed spanning a range from +21 to −11 mm/yr (measured relative to sea levels at Katakolon). After inversion, these measurements provide estimates of relative vertical land movements of the present epoch which can be compared to those obtained from archaeological and geological sources, i.e. changes over timescales of thousands, tens of thousands and tens of millions of years. Differences in the sign and magnitude of the relative vertical land movements of this geologically complicated region obtained from the different data sets are discussed in detail. It is shown that the direction of vertical movement recorded by the tide gauges correlates well with that observed over longer periods and that, with relatively few exceptions, sites which are uplifting (submerging) relatively rapidly over one timescale are uplifting (submerging) relatively rapidly at all timescales. While the rate of vertical movement throughout the Aegean and southern Greece usually preserves the same sign at a given site over timescales of 10^1–10^7 yrs, its magnitude decreases approximately by a factor $(1/T)^{0.4}$, where T is the measurement averaging period.

Introduction

The measurement of sea levels at sixteen sites in Greece over the period 1969–1983 by the Hellenic Navy has enabled a determination of the average seasonal cycle of mean sea level in Greek waters, a description of the interannual variability of sea levels over the 15-year period and an investigation of the current rates of relative vertical land movements between sites. The latter, a measure of movements over decadal timescales, has been included in a comparison to measurements of vertical land movements observed over time scales of 10^3 to 10^7 years from archaeological and geological sources.

In this article we first present the results of the analysis of the seasonal and interannual variations in Greek sea levels, as a demonstration of the quality of the data and its regional coherence. There then follows a comparison of the rates of

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relative sea level trends and vertical land movements determined from the data sets of sea level changes over different timescales.

The Greek tide gauge data set

Monthly and annual mean values of sea level from sixteen stations in Greece over the period 1969–1983 were obtained from the Permanent Service for Mean Sea Level (PSMSL), Bidston Observatory, U.K. These data had in turn been supplied to the PSMSL by the Hydrographer of the Hellenic Navy. Short records of sea level measurements also exist for Greece prior to 1969 (Pugh et al., 1987) but the earlier records in the main do not contain controlled benchmark datum stability and are, therefore, not suitable for studies of sea level trends. The sixteen 15-year records provide a unique data set of sea level changes across the largest network of gauges in the eastern Mediterranean (Fig. 1).

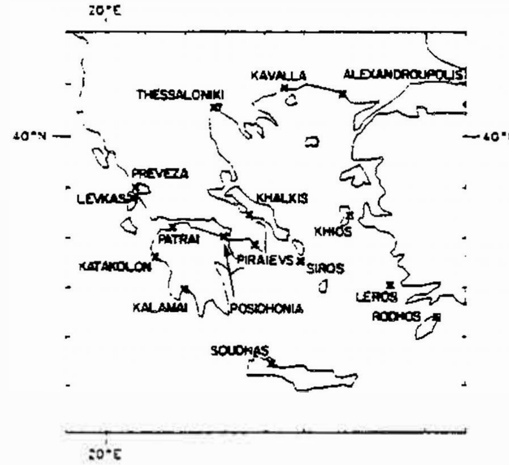

Fig. 1. Locations of the Greek tide gauges.

Sea levels at each site were measured with respect to a single fixed local benchmark on land; no information is available from geodetic methods

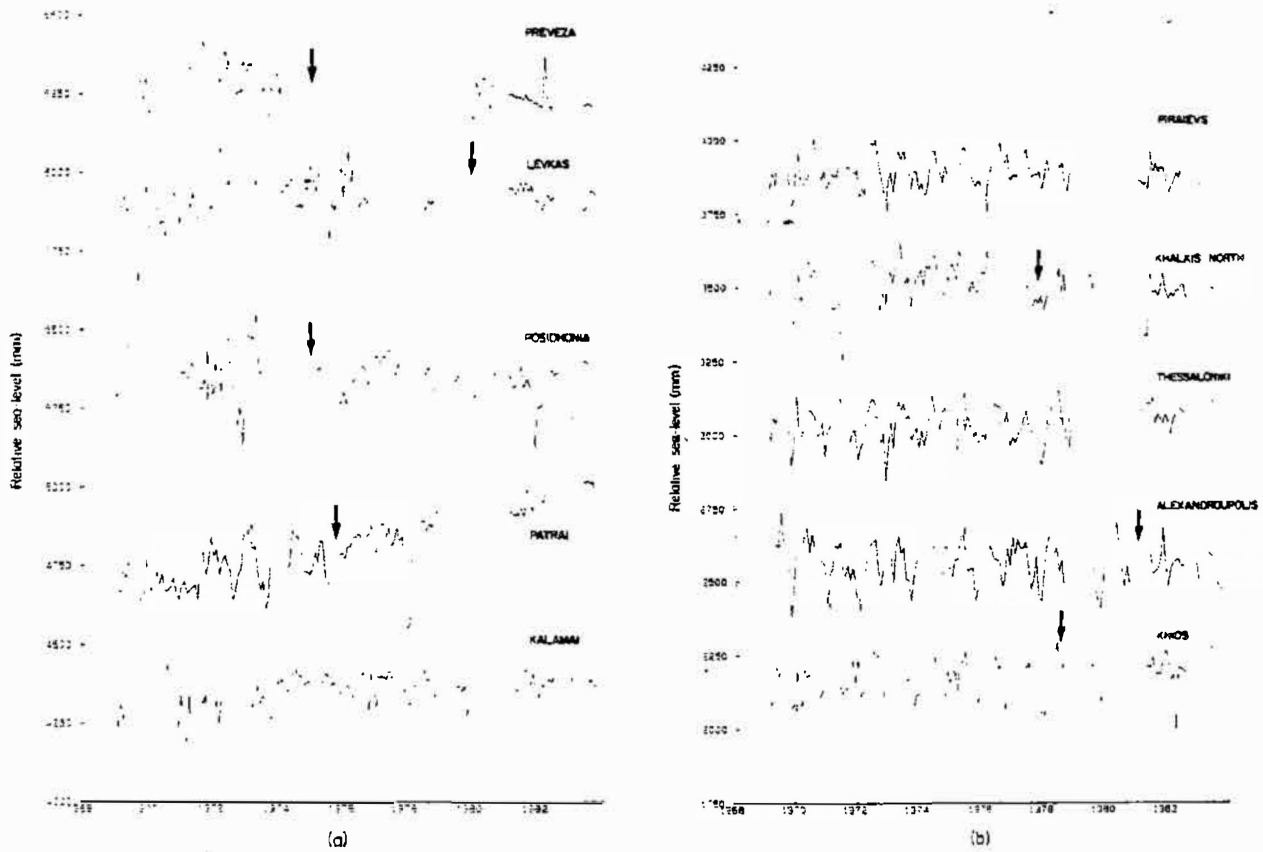

Fig. 2. Monthly values of sea level at each station relative to that at Katakolon. Note that an arbitrary vertical offset has been applied to each time series for plotting purposes. The arrows indicate the changeover from tide pole to stilling well gauges (no arrow implies continuous stilling well operation). Katakolon itself switched over in November 1979.

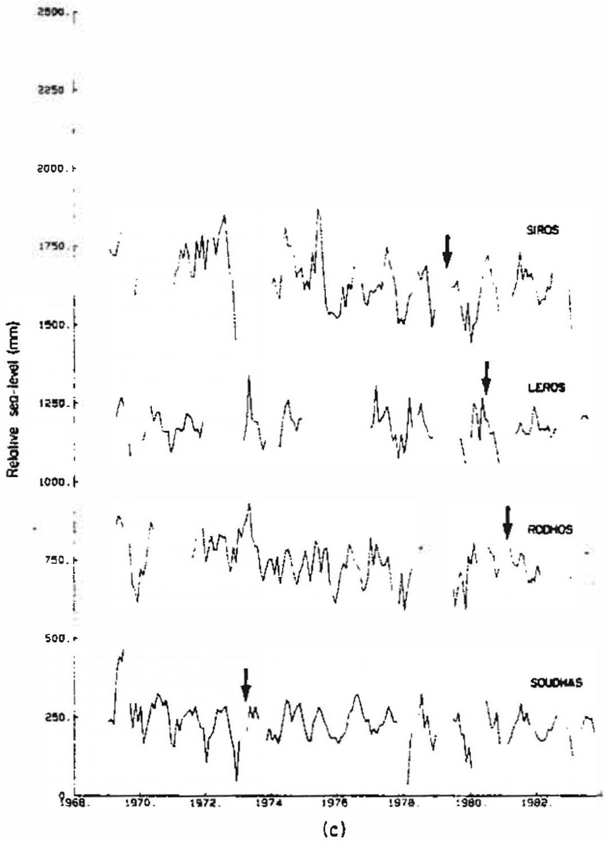

Fig. 2. (continued).

which would enable sea levels at one site to be related to those at other sites. Most measurements were obtained from gauges recording hourly heights and employing stilling wells, although for the majority of stations the stilling well technique has only been in operation since the mid-1970's when it replaced tide pole measurements. The arrows shown with the time series of Fig. 2 indicate when the changes took place; in each case there appears to have been no systemmatic shift in sea level due to the changeover.

The analyses described below make use of the entire 1969-1983 data set as obtained from the PSMSL with two exceptions:

(1) Data from Kavalla (northern Aegean) were not used, reducing the number of stations to fifteen. The sea level record at Kavalla is considerably more variable than those of the other stations and exhibits little coherence with neighbouring station records.

(2) Data from Levkas for 1979–1980, which appear anomalous and which may be associated with the tide pole to stilling well conversion, were not used in the analysis.

All the time series contain many short gaps, the record from Katakolon being the most complete

TABLE 1

Number of monthly mean values of sea level available from each station for the period 1969–1983; number of complete years of data (Jan–Dec) during 1969–1983; amplitude (mm) and peak month (from the beginning of the year) of the observed annual and semi-annual cycles of sea level; rates of change of sea level (in mm/yr) relative to that at Katakolon *

Station	No. of monthly means	No. of complete years	Annual cycle		Semi-annual cycle		Relative trend
			amp	peak	amp	peak	
Preveza	96	2	–	–	–	–	-5.6 ± 1.1
Levkas	120	6	58	11.5	9	4.5	3.4 ± 1.1
Posidhonia	133	7	17	8.3	10	0.4	-3.4 ± 1.2
Patrai	139	7	37	11.0	7	4.9	21.3 ± 1.3
Katakolon	166	8	42	10.3	13	2.1	–
Kalamai	136	4	55	10.0	11	1.1	5.7 ± 1.0
Piraievs	137	8	38	8.8	26	0.7	-0.4 ± 0.8
Khalkis north	139	6	23	10.3	19	0.3	-2.4 ± 1.3
Thessaloniki	156	10	32	7.6	11	0.0	1.0 ± 0.9
Alexandroupolis	145	3	–	–	–	–	-1.7 ± 1.1
Khios	148	5	26	10.9	19	0.2	4.2 ± 1.0
Siros	147	7	53	7.6	25	0.7	-11.2 ± 1.3
Leros	115	3	–	–	–	–	-0.9 ± 0.9
Rodhos	146	6	18	8.4	9	1.4	-5.9 ± 1.2
Soudhas	163	8	46	8.1	5	2.0	-5.5 ± 0.8

* See the text for a discussion of errors on the trends

while that from Preveza contains measurements from little more than half the total number of months. Table 1 shows the number of monthly means of sea level available from each station.

Average seasonal cycle of mean sea level

The 15-year Greek sea level data set enables an accurate assessment of the average seasonal cycle of mean sea level in Ionian and Aegean waters. These estimates can be used as a comparison to oceanographic computations of the seasonal variations in water density and meteorological forcing (Pattullo et al., 1955: Woodworth. 1984). In addition, the average seasonal cycle can in principle be employed, along with tidal and barometric terms, as a small correction factor to estimates of current sea levels, relative to historical sea levels, obtained during short archaeological and geological field surveys (Flemming and Webb. 1986).

The seasonal cycle of mean sea level in Greece has a peak-to-peak swing of the order of a decimetre with a maximum in late summer (approximately August) in the Aegean or Crete, and a maximum in the latter months of the year along the Ionian coast. Figure 3 shows the seasonal cycle for the seven stations with the largest number of complete years of data (i.e. Jan-Dec).

Each observed seasonal cycle can be described as the sum of an annual cycle, a semi-annual cycle and higher harmonics. Table 1 lists the parameters describing the annual and semi-annual cycles for those stations containing at least 4 complete years of data. The four stations on the Ionian coast (Levkas, Patrai, Katakolon and Kalamai, see Fig. 1) all show large annual amplitudes with a peak in early December for the two northernmost and early November for the two southernmost. However, their semi-annual cycles can be seen to be very different with all amplitudes around a decimetre but with a peak in May (and November) for Levkas and Patrai in the north, March for Katakolon and February for Kalamai. The observed phases of the northern stations are confirmed by inspection of neighbouring Adriatic data (Woodworth, 1984). At Split in Yugoslavia the annual cycle was found from two separate data sets to have an amplitude of approximately 50 mm

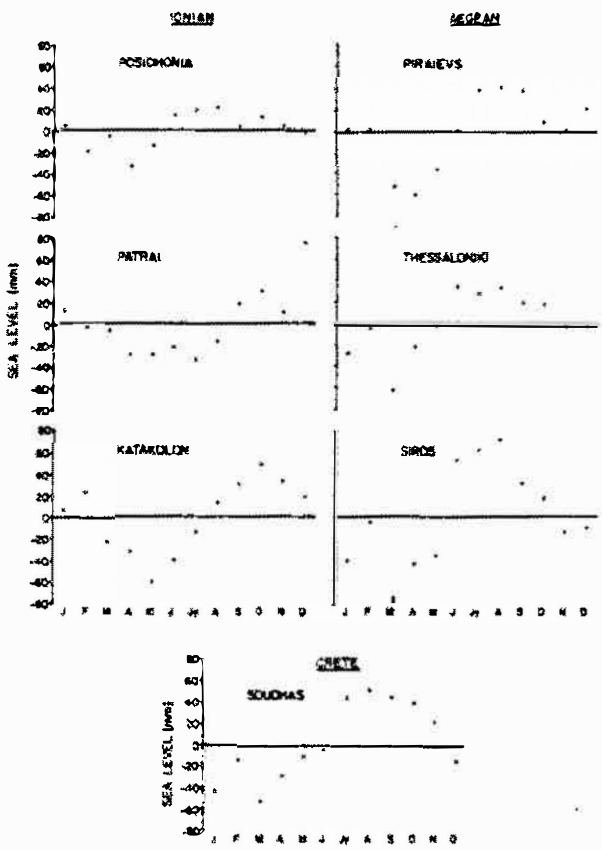

Fig. 3. Average seasonal cycle of mean sea level at the seven stations with the largest number of complete years of data.

peaking in mid-December and a semi-annual cycle of approximately 25 mm amplitude peaking at the start of June. There is, therefore, a clear phase progression of the seasonal cycle from north to south along the Adriatic–Ionian coast as one goes from a typical eastern Adriatic cycle (annual peak in December, semi-annual peak in June) to a typical Aegean–Mediterranean cycle (annual peak in late summer, semi-annual peak around January)

In the Aegean, the annual cycle is observed to mostly peak in August or September, although Khalkis North and Khios in mid-Aegean show evidence for an annual peak in November. Meanwhile, the semi-annual cycle can be seen to be more comparable in amplitude to the annual cycle than is the case for the Ionian stations, and to peak very early in the year. Woodworth (1984) also includes neighbouring data from Izmir, Turkey which show similarly an annual cycle of 36 mm amplitude peaking in late August and a semi-annual cycle of 21 mm amplitude peaking in

January. Interestingly, Posidhonia, in the Gulf of Corinth on the Ionian side of Greece, has a seasonal cycle more typical of Aegean than Ionian stations.

We make no attempt here to explain the distribution of the seasonal cycle of mean sea level in terms of meteorological and oceanographic forcings, but merely present the observations as a demonstration of the quality of the data, as a potential source of correction factors to other studies of Greek sea levels, and as an important contributor to the variability in the sea level time series which has to be parameterised in the trend calculations described below.

Interannual variability of Greek Sea levels (1969–1983)

Figure 4 shows the time series of montly mean values of sea level from the longest record, Katakolon. A strong seasonal cycle in the record can be clearly seen, as discussed above, together with a small average trend (2.1 ± 2.1 mm/yr calculated from "quasi-annual" means, see below). In addition, occasional peaks and dips, untypical of the average seasonal cycle, appear in the Katakolon and most of the other time series. Some of these anomalies are confined to individual records. However, the majority are seen throughout the region. For example, the peak observed in the December 1981 mean value can be seen in the records for most northern Mediterranean stations east of Almeria, Spain (Rickards, 1985). Figure 4 shows Katakolon sea levels to be generally lower in the mid-1970's than at the beginning or end of the record.

The coherent fraction of Greek sea level interannual variability has been studied by means of a principal components analysis (PCA) of detrended "quasi-annual" mean sea level values for the five stations (Katakolon, Thessaloniki, Alexandroupolis, Khios and Siros) which have the largest number of acceptable quasi-annual means and which provide a representative distribution of sea level measurements across the region.

The quasi-annual means were calculated in the following way, in order to make maximum use of time series with many small gaps. At each station the average seasonal cycle was computed using complete years of data only, as described in the previous section. Monthly anomalies were thereby defined as the observed monthly mean minus the value for that month from the average seasonal cycle. In turn, quasi-annual anomalies were computed as the average of the monthly anomalies for those years which contained at least 6 monthly mean values. The PCA employed detrended quasi-annual mean values in order to isolate the coherent interannual (i.e. timescales of years to decades) fluctuations in sea level rather than the low-frequency changes primarily associated in this region with land movements. Note, however, that the detrending will omit from the analysis any

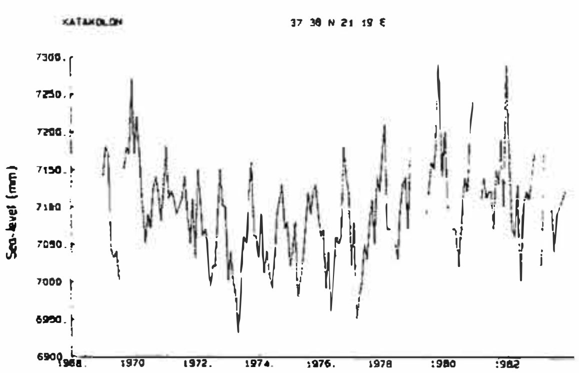

Fig. 4. Time series of montly mean values of sea level at Katakolon.

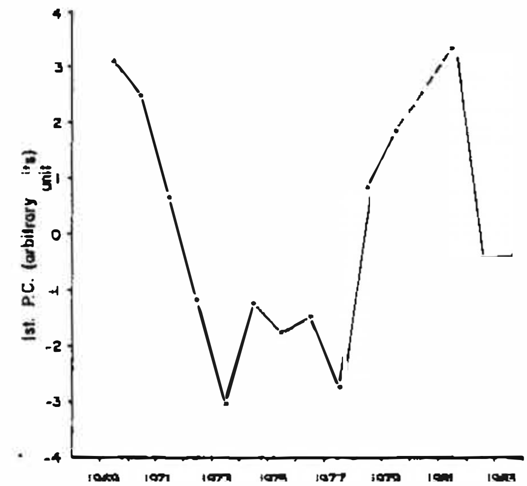

Fig. 5. Time series of the 1st. principal component of "quasi-annual" mean values of sea level at five tide gauge stations (arbitrary units). There are no data for 1980.

'eustatic', or real low-frequency, changes in the regional sea level.

Figure 5 shows the 1st. principal component of a PCA of the quasi-annual means for the five stations using a PCA technique similar to that of Barnett (1983) which employs the correlation rather than the coherence matrix. The five time series in fact show a large degree of coherence and 87% of the total variance is describable by the 1st. principal component. A general drop in Greek sea levels is observed in Fig. 5 during the mid-1970's, as can also be seen from Fig. 4, and as has been commented on previously by Maroukian et al. (1986). Again, no attempt has been made in this analysis to model these fluctuations in terms of meteorological or oceanographic forcings. Rather, the results of this section are presented as a demonstration of the coherence of the sea level data set in this part of the frequency spectrum.

Secular trends in relative sea levels

We now turn to a discussion of the secular trends (i.e. low-frequency variations which can be approximated by a linear trend) in relative sea levels between stations as observed in the tide gauge data. These trends are believed to be dominated by vertical land movements as any slow "eustatic" sea level change would be expected to be considerably smaller than the land movements and to be coherent over a region the size of the northeast Mediterranean. The resolution of the ambiguity of eustatic changes and absolute vertical land movements, and the decoupling of ocean and land changes in the tide gauge records, has to await the deployment of advanced geodetic methods for determining land movements at each tide gauge site (IAPSO, 1985). In the present analysis, the use of relative sea levels avoids the necessity for considering the magnitude of any eustatic change.

Figure 2 shows the monthly values of sea level at each tide gauge measured with respect to those at Katakolon. For each time series a relative sea level trend has been computed by making a least squares fit to the monthly values of sea-level-difference in terms of the linear trend together with an annual and semi-annual cycle to describe the seasonal-cycle-difference. The trend values so

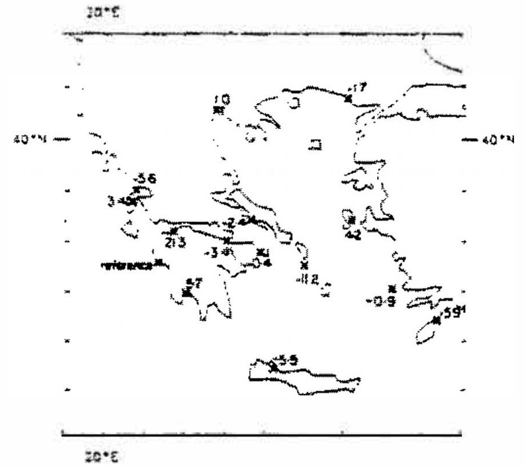

Fig. 6. Geographical distribution of observed sea level changes relative to that at Katakolon.

calculated are shown in Fig. 6 and Table 1. No meteorological or oceanographic corrections have been applied to these results; secular trends in air pressure and spatial air pressure gradient around Greece during 1969–1983 were found to be consistent with zero (using a data set of northern hemisphere air pressures supplied by the U.K. Meteorological Office).

It is useful to employ monthly rather than annual means in the determination of the relative trends in order to maximise the amount of information from records which contain many short gaps. However, this can result in the under-estimation of the standard errors on the trends, compared to the standard errors obtained using annual mean values, if the residuals from the linear trend are not normally-distributed; the worst case would be a factor $\sqrt{12}$ under-estimation of the standard error on the computed trend. This under-estimation has been investigated in the present case by also computing trends from quasi-annual means of sea-level-difference (see the previous section for the definition of "quasi-annual"). In general, the standard errors on the trend from quasi-annual means are less than a factor 1.5 larger than those from monthly means, with the exceptions of Levkas, Posidhonia, Kalamai and Soudhas which are approximately twice as large, and Khalkis North which is approximately 2.5 times as large. One concludes, therefore, that the standard errors on the trends shown in Table 1 are reasonably well estimated, except for the exceptions named above whose errors should conservatively be increased by approximately a factor of 2.

If there were no gaps in the records, then the replacement of Katakolon by a new reference station would leave the overall pattern of relative sea level changes shown in Fig. 6 unchanged. Conversely, the replacement of Katakolon by one of the stations with many gaps might alter the pattern to some extent as a different data-selection is implied in the sea-level-difference calculation. The stability of the pattern of relative sea level changes shown in Fig. 6 has been investigated by replacing Katakolon by the three next-longest records (Soudhas, Thessaloniki and Khios) which have gaps in different parts of their time series. The overall pattern was found to be the same to within ± 1.5 mm/yr which constitutes a systemmatic error estimate which should be considered in addition to the statistical standard errors on the trends of Table 1, if the overall pattern of Fig. 6 is to be compared to evidence of land movements from different data sets. An alternative approach to the employment of reference stations would be the use of a PCA which attempts to handle gaps in the data (e.g. that of Aubrey and Emery, 1986), although in the present case as the records are on average almost 80% complete virtually the same pattern would be obtained.

Relative vertical land movements over different timescales

The analysis of the tide gauge data has shown that there is a residual relative vertical change between land sites at each location which can be approximated as a linear trend over the decade or more of recording. Since the direction and magnitude of this trend varies from site to site, there is necessarily a component due to local earth movements, of whatever cause.

There is no evidence for vertical displacement of any of the tide gauges due to short term earthquake events during the period of observation, even though several large seismic events did occur in Greece (Drakopoulos and Ekonomides, 1972; McKenzie, 1978; Dewey and Sengör, 1979; Mercier et al., 1979; Vita-Finzi and King, 1985). The evidence in this respect is inconclusive, since major seismic events may have occurred far from the tide-gauges, or at times such that they coincided with data gaps in the recording. We have not made a complete check to establish this possibility. Whatever the explanation, there are no sudden jumps in the records which might correlate with almost instantaneous earth movements.

Vertical earth movements in the Mediterranean have been studied by several researchers over periods from a few hundred to several million years. We shall concentrate only on those works which seek directly to quantify the magnitude and rate of vertical movements. On a time scale of 10^2–10^4 yrs, these studies include the works of Schmiedt (1972); Kraft et al. (1975); Pirazzoli (1976); Flemming (1978) and Paskoff and Sanlaville (1983). On a time scale of 10^4–10^{5-6} yrs, the tectonics of the Aegean have been studied by Angelier (1976); Le Pichon and Angelier (1981); Peters (1985); Vita-Finzi and King (1985) and others. On a timescale of 10^6–10^7 yrs, we shall refer to data from Le Pichon and Angelier (1981).

Earth movements tend to be episodic and irregular. Thus a location may be stable or aseismic for hundreds of years between sudden movements (Ambraseys, 1971) or a point may move slowly and aseismically in one direction between sudden short movements in the opposite sense (Scholz, 1972). It is presumably possible for seismic events to result in movements in the opposite sense on successive occasions at the same location, although examples of this have not been documented in the present study. In consequence, it is not necessary that the relative vertical movement at one site observed over a short period should be similar in either magnitude or direction to the observed magnitude and direction measured over a similar short period at a different date, or over a longer period. In this context a decade is a short period.

Given the probability of long periods of quiescence and possible reversals of direction, the cumulative averaged rate of vertical movement at any one point will generally be less than the rate measured over a short period. If the secular trends of the relative tide gauge data can be integrated as reliable indicators of earth movements, it is important to see whether the observed short term trend correlates with the longer term trends from other data types, and in what way. Poor correlation, or total lack of correlation, would indicate that data gathered over one decade are very poor indicators of the long term trend.

Decade to millenium timescales

The data obtained from the tide gauges are shown in Table 1. Flemming and Webb (1986) correlated archaeological and historical data from over 300 sites on the Mediterranean coast, and computed local and regional earth movements. These calculations showed that there was variability of rates of earth movement on a lateral scale of 10–20 km, especially in the Aegean area. If data are to be compared from different sources, data sites must therefore be closer than this. As a result, only eight stations are found with sufficiently close spacing, and these are listed in Table 2, together with the data from the tide gauges.

Sea level studies conventionally report a rise of sea level as positive data, whilst geological and archaeological studies report a rise in the land as positive data. In terms of relative change at the shoreline, these events are physically opposite. Table 2 shows the data from each source in terms of its own convention. The data sets show no obvious correspondence. The tide gauge data are presented relative to the annual sea level at Katakolon as zero; the geological data are presented relative to mean sea level in the mid-1970s–1980s, with an error of ±20–30 cm. If Katakolon itself is not tectonically stable, there is no reason to suppose that the figures would correspond, since their zero is different. For example, if Katakolon is actually rising rapidly in relation to present sea level, another site might be rising slowly relative to mean sea level, but subsiding relative to Katakolon.

There is no absolute method for determining the rate of vertical movement of any of the tide gauges relative to the centre of the earth, in the

TABLE 2

Comparison of tide gauge and archaeological data *

Station	Relative trend (a)	Adjusted trend, X (b)	Nearest archaeological site	Earth movement, Y (c)	Ratio X/Y (d)
Preveza	−5.6	−2.1	-		
Levkas	3.4	6.9	-		
Posidhonia	−3.4	0.1	Lechaeum	−0.35	0.28
Patrai	21.3	24.8	-		
Kalamai	5.7	9.2	Akovitika	−0.71	13.1
Piraievs	−0.4	3.1	Phaleron	−0.5	6.2
Khalkis north	−2.4	1.1	Anthédon	−0.13	8.46
Thessaloniki	1.0	4.5	-		
Alexandroupolis	−1.7	1.8	-		
Khios	4.2	7.7	Cesme	−2.0	3.85
Siros	−11.2	−7.7	-		
Leros	−0.9	2.4	-		
Rodhos	−5.9	−2.4	Rhodos	0.35	6.86
Soudhas	−5.5	−2.0	Marathi	0.68	2.94
Katakolon	0	3.5	Katakolon–Pheia	−0.5	7.0

* Notes: (a) displacement in mm/yr is shown as positive for rising sea level, negative for falling sea level, relative to the tide gauge at Katakolon, as shown in Table 1; (b) the baseline for the tide gauge data has been altered so as to maximise the correlation with the archaeological data. Empirically, this requires assuming that Katakolon is submerging at 3.5 mm/yr; (c) uplift of land is shown as positive, submergence of land negative, in m/ka; (d) the sign conventions for the tide gauge data and the archaeological data have been made consistent in calculating the ratio, so that a positive ratio indicates the same direction of movement of the land as derived from both sources.

absence of suitable geodetic methods. The strategy, therefore, is to add or subtract an arbitrary rate of movement to the tide gauge data, uniformly at all sites, so as to produce a revised data set in which all data points have at least the same sign as the geological data.

Table 2 shows the adjusted data set, with the tide gauge data adjusted by 3.5 mm/yr. This figure is reasonable on general grounds, being small compared to the average rates of movement for several of the sites with tide gauge data, and consistent with the absolute relative sea level trend for Katakolon of 2.1 ± 2.1 mm/yr for 1969–1983 reported above. Geologically, the west coast of the Peloponnesos is warped steeply down to seawards, with uplift inland, and stability of the Katakolon tide gauge would depend critically as to whether it were landward or seaward of the hinge line (Flemming, 1972 (p. 193); Le Pichon and Angelier, 1981). Hall (1969) shows that the ancient site of Pheia immediately adjacent to Katakolon is submerged, and Flemming (1973, p. 22) estimates this submergence at 1.0 ± 0.5 m over 2000 yrs. Thus there is corroborative evidence that Katakolon is submerging on the longer timescale.

The data from Table 2 are plotted in Fig. 7. This shows an approximately linear correlation between the rate of secular trend determined by the tide gauges, and that determined on archaeological evidence. A least squares linear approximation indicates that the rate of movement over a decade timescale is six times the rate of movement over the millenium timescale (with a correlation coefficient of 0.82). This is inherently reasonable, but, for reasons already given, is partly chance. One or two sites might have been moving in opposite senses over the two time periods, and, given the small number of data points, this would have undermined the correlation.

Millenium to million year timescales

The goodness of fit at the millenium scale suggests that the technique might be extended to a greater part of the temporal spectrum of vertical earth movements. The number of well-controlled data sets available is limited, but there are just enough data from the central-Aegean area to make the attempt feasible (Fig. 8).

Further data on altitudes of fossil beaches and

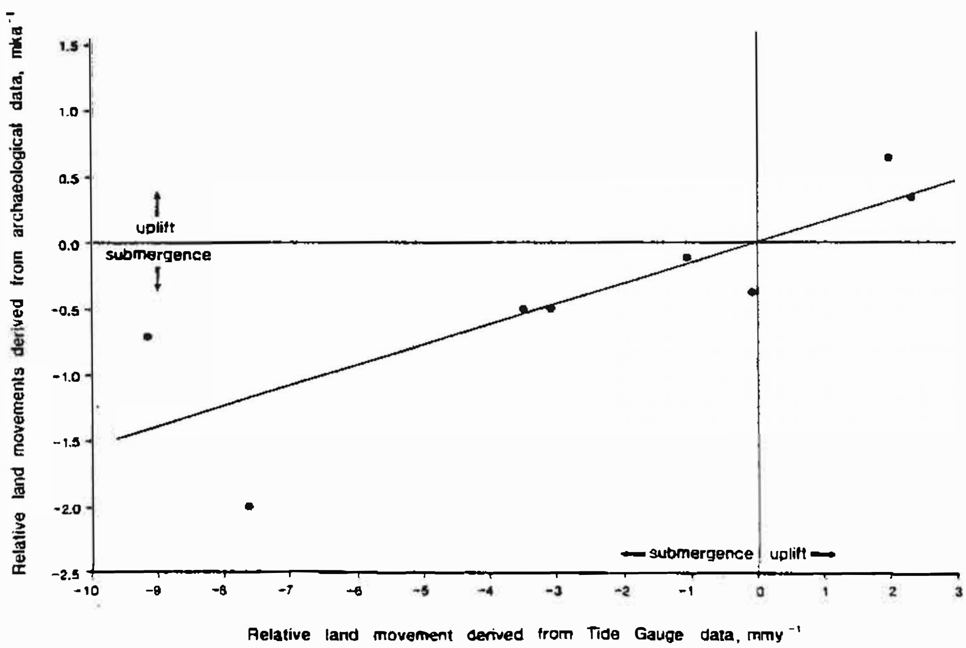

Fig. 7. Comparison of relative vertical land movements derived from tide gauge data over timescales of order 10^1 yrs and those from archaeological sources over timescales of order 10^3 yrs. Tide gauge data are presented as mm/year and archaeological data as m/ka to emphasise the averaging periods but the units are, of course, identical.

TABLE 3

Site numbers, names and displacement data for uplift/submergence comparison over different timescales *

No.	Age (yrs)	Rate (mm yr^{-1})	Originator	Nearest location
1	10	−0.1	PLW	Posidhonia
2	10	−9.2	PLW	Kalamai
3	10	−3.1	PLW	Piraievs
4	10	−1.1	PLW	Khalkis
5	10	−7.7	PLW	Khios
6	10	2.4	PLW	Rhodos
7	10	2.0	PLW	Soudhas
8	10	7.7	PLW	Siros
9	10	−2.4	PLW	Leros
10	10	−3.5	PLW	Katakolon
11	2000	−0.35	NCF	Lechaeum
12	2800	−0.7	NCF	Akovitika 2
13	5000	−2.2	NCF	Akovitika 1
14	4000	−0.5	NCF	Phalerura
15	1.5K	−0.13	NCF	Anthedon
16	100	−2.0	NCF	Cesme
17	5K	0.35	NCF	Rhodos
18	2.2K	0.68	NCF	Marathi
19	2K	−0.5	NCF	Katakolon
20	33K	0.68	C.V-F	Corinth area
21	32K	0.63	C.V-F	Corinth area
22	32K	0.24	C.V-F	Corinth area
23	6.9K	0.24	C.V-F	Corinth area
24	32K	0.73	C.V-F	Corinth area
25	36K	0.20	C.V-F	Corinth area
26	38K	0.31	C.V-F	Corinth area
27	36K	0.01	C.V-F	Corinth area
28	36K	0.68	C.V-F	Corinth area
29	32K	0.79	C.V-F	Corinth area
30	31K	0.84	C.V-F	Corinth area
31	31K	0.32	C.V-F	Posidonhia
32	31K	2.93	C.V-F	Corinth area
33	32K	2.83	C.V-F	Corinth area
34	35K	2.01	C.V-F	Corinth area
35	0.1–0.2M	0.019	X.LeP	Katakolon
36	0.1–0.2M	−0.007	X.LeP	(Patrai) (Far)
37	0.1–0.2M	0.010	X.LeP	Posidonhia
38	0.1–0.2M	−0.006	X.LeP	Kalamai
39	0.1–0.2M	0.012	X.LeP	Rhodos
40	0.1–0.2M	0.019	X.LeP	Soudhas
41	0.1–0.2M	−0.005	X.LeP	(Siros) (Far)
42	0.1–0.2M	0.01	X.LeP	(Leros) (Far)
43	12–13M	0.022	X.LeP	Patrai
44	12–13M	0.026	X.LeP	Rhodos
45	12–13M	−0.021	X.LeP	(Leros) (Far)
46	12–13M	0.032	X.LeP	Soudhas
47	12–13M	−0.020	X.LeP	Kios

* All rates of displacement are shown as land uplift positive: PLW = data from tide gauges, this paper; NCF = data from Flemming and Webb (1986); C.V-F = data from Vita-Finzi and King (1985); X.LeP = data from Le Pichon and Angelier (1981). The locations shown with brackets (far) indicate that the data are not geographically very close to the named sites.

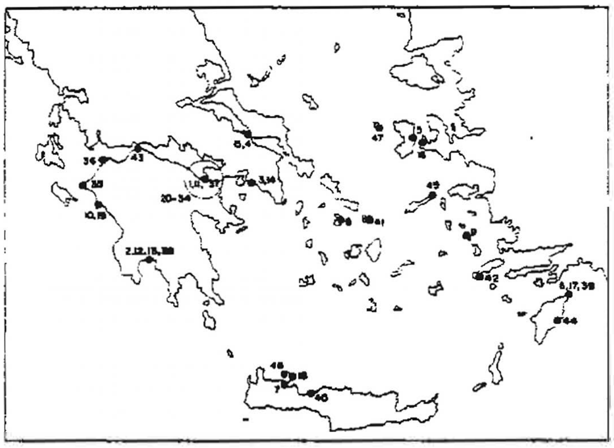

Fig. 8. Map of the South Aegean area showing the location of data points listed in Table 3.

shorelines, and vertical rates of movement, were obtained from Le Pichon and Angelier (1981), Vita-Finzi and King (1985) and Flemming and Webb (1986). In each case data points were selected, so far as possible, close to the original tide gauge locations of Fig. 1. Table 3 details the site locations and the rates of vertical land movements derived from the various data sources of Fig. 8. (No arbitrary overall rates of movement have been applied to the different data sets other than the adjustment to the tide gauge data described in the previous section.)

On the assumption that the rates of vertical movement averaged over longer periods would progressively decrease, the data were plotted on

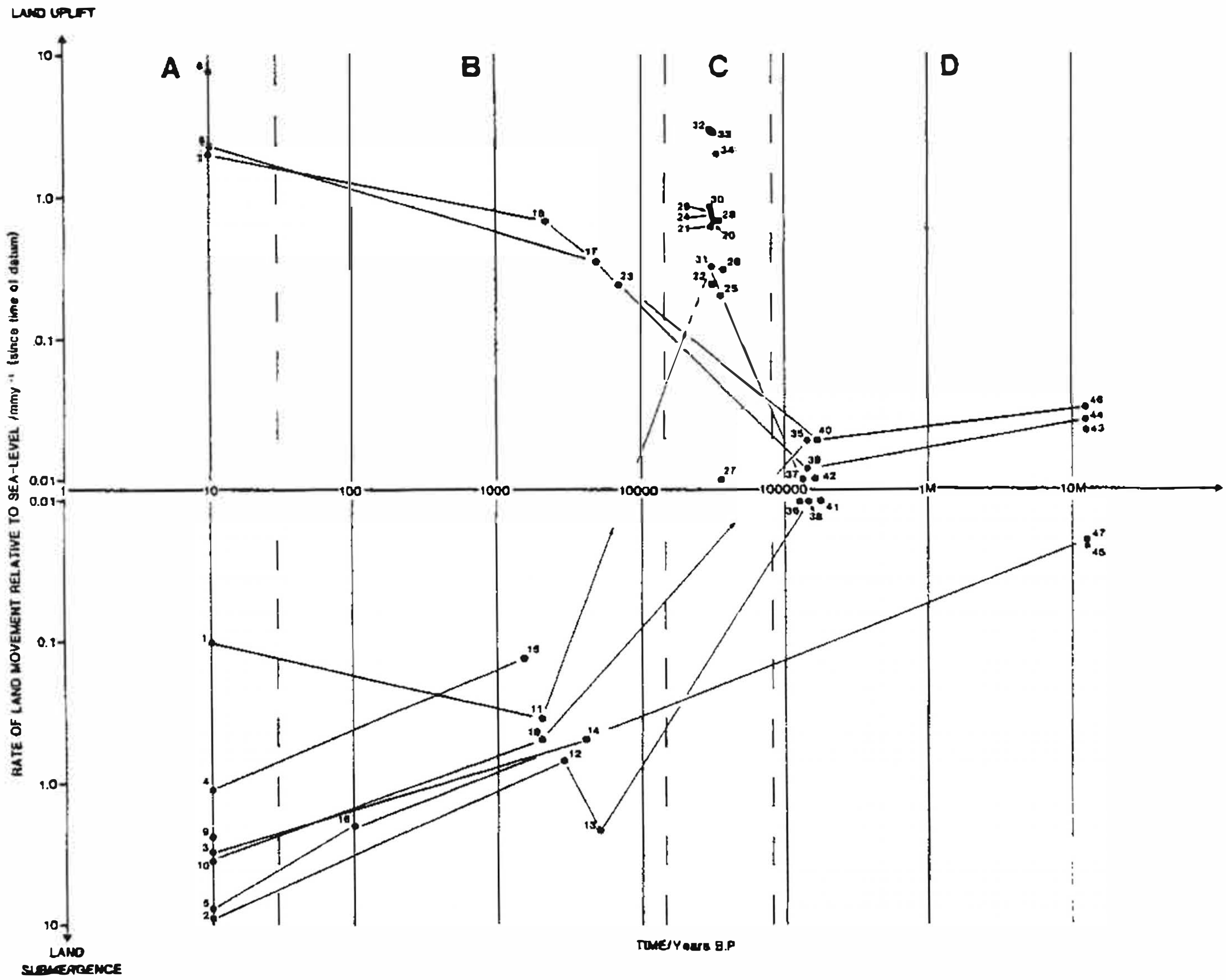

Fig. 9. Data indicating vertical displacement of coastal land plotted from different sources: *A*—tide gauge data from Greece, this paper; *B*—archaeological data from Flemming and Webb (1986); *C*—^{14}C beach data from Vita-Finzi and King (1985); *D*—Quaternary terrace data from Le Pichon and Angelier (1981). Numbers refer to sites shown in Fig. 8 and Table 3. The sloping lines join observations which describe the same site, or closely adjacent sites, over different time periods. Note the log-log scales.

log-log axes, as shown in Fig. 9. Adjacent data sources are shown connected by "site-time lines". With the older data, derived from published sources, it is difficult to be sure that horizontal proximity is really being maintained from period to period. Data used by one author, and used to create a regional average, may originate from a structural block only a few kilometres away from data used by another author, and moving at a different rate, or in the opposite sense. Notwithstanding this source of possible error, the trends shown in Fig. 9 are consistent. The fine lines track identical, or closely similar points, from period to period. Several factors stand out. The rate-period diagram is almost identical for uplift and subsidence, in that the upper and lower segments of the diagram are mirror images of each other. Sites which are uplifting on one timescale are generally uplifting on all timescales. Similarly for subsidence. There are certain sites which appear to change sign. These include 1–11–31–37 around Posidhonia (Corinth isthmus) with Katakolon (10–19–35) changing sign between 2×10^3 and 2×10^5 years ago.

Relatively few site-time lines cross over. That is to say, a fast site tends to remain fast; and a slow one tends to remain slow. The principal anomaly is 1–11–31–37 again.

The relationship between period over which displacement is averaged and the resulting average rate of vertical displacement can be given approximately as follows. Let Z be the displacement in metres for an archaeological or geological site over time T, where T is measured in thousands of years. Then the rate of displacement on this time scale is $R = Z/T$. Let $R0$ be the rate of displacement over a short time of the order of a decade, $T0$. Then descriptively:

$$\log(R) - \log(R0) = k(\log(T0) - \log(T))$$

or $(R/R0) = (T0/T)^k$.

From Fig. 9, k can be seen to be of the order of 0.4, indicating that the rate of vertical earth movement measured over a period of time decreases approximately as $(1/T)^{0.4}$, where T is the measurement averaging period.

Figure 9 shows a reasonably consistent correlation, with the exception of some of the data derived from Vita-Finzi and King (1985). These data-points are all of closely similar age, but show very different rates of movement within horizontal distances of a few kilometres to a few tens of kilometres. The purpose of the study by Vita-Finzi and King (ibid) was to study the processes of tilting on listric faults, and the mechanisms of multiple normal faults and graben-like features in the neighbourhood of the Gulf of Corinth and the Bay of Salamis. The lower rates produced by that study are consistent with the trends shown in Fig. 9, but the higher rates appear as anomalous. The shores of the Gulf of Corinth may, however, be an area where very rapid processes of vertical movement are indeed taking place. The rate of submergence of Patrai measured as 24.8 mm/yr from the tide gauge appears at first sight to be extraordinarily high. However, there are good reasons for accepting this value as correct. The log-log scale of Fig. 9 is such that the value would plot only slightly below the data points already shown. That is, the inclusion of Patrai would not singificantly alter the scatter of data already accepted. Secondly, the high rate of submergence of Patrai can logically be correlated with the high rates of uplift found by Vita-Finzi and King (1985) in the same region of the Gulf of Corinth. It is indeed a very unstable area.

Conclusions

The recording of sea levels at sixteen tide gauge stations in Greece by the Hellenic Navy over the period 1969–1983 has allowed the computation of the average seasonal cycle of mean sea level throughout the region. These results can be subsequently employed in oceanographic comparisons of seasonal variations in water density and meteorological forcing in the area, and as correction factors to archaeological and geological field survey data. The interannual variability of Greek sea levels in this fifteen year period has been found to have been composed of a general drop of levels during the mid-1970's, and spatially coherent peaks and dips in the records. A principal components analysis has shown that 87% of the total variance of interannual variability in the sea levels of the area can be described by the 1st. principal component (i.e. is coherent).

Calculations of the secular trends in sea levels at each tide gauge station, measured relative to sea levels at a reference station such as Katakolon, have provided a good description of the large geographical variability in vertical land movements in progress during the period 1969–1983. These in turn have been compared to measurements obtained from previously published datasets of vertical land movements averaged over timescales from 10^3 to 10^7 yrs. The four major conclusions from this comparison have been found to be:

(1) Although there are many reasons for suspecting that observations of secular trends of vertical earth movements over short periods of the order of a decade may not correlate with longer periods of observation, the tide gauge data in the present study do show a good correlation for most sites in terms of direction of movement.

(2) With relatively few exceptions, sites which are uplifting relatively quickly averaged over one timescale, are observed to rise relatively quickly at all timescales from 10^1 to 10^7 yrs. The same is true of subsidence.

(3) There seems to be an area of exceptionally high rates of uplift and subsidence on the flanks of the Gulf of Corinth at timescales of both 10^1 and 10^5 yrs.

(4) The rate of vertical movement in the Aegean and southern Greece usually preserves the same sign for a given point over timescales 10^1 to 10^7 yrs but reduces by a factor of $(1/T)^{0.4}$, where T is the period over which the observed net movement is averaged.

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1	Belo	1	2.00	0.00
3	Carteia	1	2.00	0.00
13	Hemeroskopeion	1	2.50	0.00
17	Tarraco	1	2.00	0.00
21	Emporiae	1	2.00	1.00
25	Leuxos	1	7.00	-10.00
26	Narbo	1	2.00	0.00
27	Agathe	1	2.60	0.00
29	Artemis	1	2.50	-1.00
30	Arelate	1	2.00	-1.00
31	Fossae Marinae	1	1.80	-4.00
32	Massilia	1	1.80	-0.40
37	Olbia	1	2.40	0.00
38	Forum Iulii	1	2.00	0.00
39	Insula Lero	1	2.00	-0.50
40	Antipolis	1	2.00	0.00
43	Albintimilium	1	2.00	0.00
49	Luna	1	2.10	-1.00
51	Populonia	1	2.00	-2.00
55	Cosa	1	2.20	-1.00
60	Alsium	1	2.00	0.00
62	Antium	1	1.90	-0.50
64	Astura	1	2.00	-0.60
65	Circeii	1	2.00	-1.00
66	Tarracina	1	1.80	0.00
68	Formiae	1	2.00	-0.50
71	Misenum	1	2.00	-3.20
72	Baiae	1	2.00	-5.50
72	Baiae	2	1.30	4.00
73	Puteoli	1	2.00	-4.00
73	Puteoli	2	1.30	5.80
74	Nesis	1	2.00	-4.00
75	Pausilypon	2	1.30	4.80
75	Pausilypon	1	2.00	-4.00
77	Herculaneum	1	2.00	-2.00
80	Surrentum	1	2.00	-2.00
84	Velea	1	2.50	0.00
93	Zankle	1	0.30	-0.50
96	Megara Hyblaea	1	2.30	-1.70
97	Thapsos	1	3.40	-0.90
98	Siracusa	1	2.50	0.00
104	Selinunte	1	2.50	0.00
105	Mazara	1	2.00	0.00
106	Lilybaeum	1	2.30	0.00
107	Motya	1	2.50	0.00
115	Leptis Magna	1	2.00	0.00
117	Sabrata	1	2.40	0.00
121	Thaenae	1	2.00	0.00
124	Alipota (Africa)	1	2.60	0.00
125	Thapsus	1	2.00	0.00
126	Leptis Minor	1	2.00	0.00
127	Ruspina	1	2.00	-0.30
128	Hadrumentum	1	2.00	0.00
129	Heraklea	1	2.00	-0.20
136	Carthago	1	2.30	-1.00
136	Carthago	2	2.00	-1.50
136	Carthago	3	1.30	-0.15
137	Utica	1	2.50	1.00
148	Rasguniae	1	2.00	-1.00
150	Tipasa	1	2.00	-0.50
151	Caesarea	1	2.00	-1.00
160	Nora	1	2.40	-4.50
164	Neapolis	1	2.00	-1.00
168	Turris Libisonis	1	2.00	-1.00
174	Rosh Hanniqra	3	1.50	-0.50
175	Achzib	2	3.50	0.00
175	Achzib	4	2.00	0.00
176	Achzib, Islands	1	2.70	-0.40
176	Ros.Han'qra Isle	1	2.50	-0.30
179	Shavei Zion (N)	1	2.00	0.00
180	Shavei Zion (S)	1	2.00	0.00
181	Yassif River	1	2.00	0.00
182	Acco	2	2.70	-0.50
182	Acco	6	0.80	-0.50
188	Tell Abu Hawam	1	3.30	0.00
190	Bat Galim	1	2.00	-0.40
191	Tell Shikmona	2	2.00	0.00
193	Atlit	1	10.00	-10.00
193	Atlit	2	6.00	-2.50
193	Atlit	3	3.80	0.00
193	Atlit	4	3.40	0.00
193	Atlit	5	2.70	0.00
193	Atlit	7	1.90	0.00
193	Atlit	8	0.80	0.00
194	Newe Yam	1	6.00	-2.00
195	Tell Nami	1	3.80	-0.50
195	Tell Nami	2	3.40	-0.50
197	Tell Nami (S)	1	0.80	-0.50
198	Dor (N)	1	2.00	0.50
199	Dor (Tantura)	1	3.20	-0.80
199	Dor	2	2.80	-0.90
199	Dor	3	2.60	-0.50
199	Dor	4	2.50	-0.40
199	Dor	5	2.40	-0.30
199	Dor	6	2.20	-0.10
199	Dor	7	1.90	0.20
199	Dor	8	1.50	0.80
199	Dor	9	1.30	0.50
199	Dor	0	0.80	-1.00
199	Dor	1	0.60	-1.00
199	Dor	2	0.20	-0.20
199	Dor	3	0.10	-0.10
200	Nahal Dalia	1	6.00	-4.00
201	Magan Mikhael	1	1.90	0.00
202	Crocodilopolis	1	2.20	-0.30
203	Caesarea	2	2.00	-5.00
203	Caesarea	3	0.80	-1.00
205	Mikhmoret	1	3.30	0.00
207	Apollonia	1	1.90	0.00
207	Apollonia	2	0.80	0.00
215	Palmachim	1	3.40	0.00
215	Palmachim	2	2.70	0.00
215	Palmachim	3	1.90	0.00
215	Palmachim	4	1.50	0.00
218	Tel Mor (Ashdod)	1	3.80	0.00
218	Tel Mor (Ashdod)	2	3.40	0.00
220	Ashdod-Yam	1	1.40	0.00
221	Ashkelon	1	3.80	0.00
221	Ashkelon	2	0.80	0.00
223	Gaza Maiumas	1	1.50	0.00

224	Tell el Ajjul	1	3.80	0.00
225	Tell el Qatifa	2	2.80	-0.30
225	Tell el Qatifa	1	7.00	-1.00
226	Tell el Ridan	1	3.50	-0.50
229	Gytheum	1	1.50	-2.50
230	Trinasus	1	1.00	-1.00
231	Asopus	1	3.0●	-3.00
231	Asopus	2	1.50	-2.00
232	Arkangelos	1	2.00	-0.20
233	Onugnathus	1	3.50	-4.00
234	Kythera	1	4.00	0.00
235	Antikythera	1	5.00	3.00
236	Boeae	1	1.50	-0.30
237	Minna	1	2.00	-1.00
238	Zarax	1	2.50	-3.00
239	Asine	1	3.00	-2.00
240	Halieis	1	2.40	-5.00
241	Lorenzon	1	1.00	-2.00
242	Epidaurus	1	2.00	-2.70
243	Cenchreae	1	2.50	-2.00
244	Lechaeum	1	2.00	-0.70
245	Phea	1	2.00	-1.00
246	Pylus Coryphasi.	1	2.00	-1.00
247	Methone	1	1.00	-1.50
248	Asine	1	0.60	-1.20
250	Cardamyle	1	1.00	-1.00
251	Leutra	1	2.00	-2.50
252	Pephnus	1	1.00	-1.00
253	Tigani	1	2.00	-0.50
254	Teuthrone	1	1.00	-1.00
255	Skoutari	1	1.50	-3.50
256	Acriae	1	3.00	-2.00
256	Elaea	1	2.30	0.00
258	Cyme	1	2.40	-1.00
259	Smyrna	1	4.00	-3.00
259	Smyrna	2	2.50	-1.00
260	Clazomenae	1	2.30	-1.00
261	Urla Beach	1	0.30	-0.50
262	Erithrae	1	2.40	-1.40
262	Erithrae	2	0.20	-0.50
262	Erithrae	3	0.10	-0.30
263	Yali	1	1.00	-0.50
264	Ilica	1	2.40	-0.50
265	Cesme	1	0.10	-0.20
266	Ciftlik	1	0.10	-0.10
267	Teos	1	2.30	-0.80
267	Teos	2	2.30	-0.80
267	Teos	3	0.10	-0.10
269	Notium (Claros)	1	2.60	-1.00
271	Miletus	1	3.20	-1.50
271	Miletus	2	2.00	-1.50
272	Heraclea Latmus	1	2.50	-1.50
273	Ghioucker I.	1	1.20	-1.50
274	Panormus	1	2.60	0.00
275	Iasus	1	2.00	-0.50
275	Iasus	2	1.00	0.00
276	Bargylia	1	2.00	-0.50
277	Caryanda	2	0.30	0.00
277	Caryanda	1	1.50	-0.30
279	Myndus	1	2.00	-1.20
280	Karatoprak	1	1.00	-0.50
281	Halicarnassus	1	2.40	-1.00
282	Cedreae	1	1.50	-0.30
283	Cnidus	1	2.30	0.00
284	(Old Cnidus)	1	2.50	0.00
285	Orhaniye	1	1.00	0.00
286	Bozburun	1	1.00	-1.00
287	Loryma	1	1.50	-1.00
288	Saranda	1	1.00	-0.50
289	Telmessus	1	1.50	-1.20
291	Antiphellus	1	2.20	-2.20
291	Antiphellus	2	1.00	-1.00
292	Myra	1	1.00	-1.00
293	Chersonissos	1	1.90	-1.00
294	Malia	1	3.60	-1.00
295	Spinalonga	1	2.00	-1.00
296	Fort Kolokithia	1	1.00	-1.00
297	Olous	1	2.00	-1.90
298	Minoa	1	2.20	-1.50
300	Psira	1	1.90	-0.75
301	Gemili	1	1.40	-2.00
302	Simena	1	2.50	-2.20
302	Simena	2	1.50	-1.20
303	Phaselis	1	2.50	-0.20
304	Lara	1	1.70	0.00
305	Side	1	2.20	0.00
306	Kara Burun	1	2.00	0.00
308	Coracesium	1	0.70	0.00
310	Syedra	1	1.50	0.00
311	Sellinus	1	1.80	0.00
312	Hamaxia	1	1.50	0.00
315	Anemuriam	1	1.50	0.00
316	Mamuriye	1	0.60	0.00
317	Arsinoe	1	1.50	0.00
319	Mellaxia	1	2.00	0.00
320	Celendris	1	0.50	0.00
321	Holmus	1	0.60	0.00
322	Agalimani	1	0.60	0.00
323	Agalimeni Fort	1	0.60	0.00
325	Persente	1	1.50	0.00
326	Corycus	1	1.50	0.00
328	Soli	1	2.00	0.00
329	Megarus	1	2.00	0.00
330	Aegeae	1	2.00	0.00
331	Baiae	1	0.50	0.00
332	Fort Bonnel	1	2.00	0.00
333	Seleucia Pieria	1	1.80	0.00
334	Amnisos	1	3.60	-1.50
335	Nirou Khani	1	3.60	-1.75
337	Mokhlos	1	3.60	-1.75
337	Mokhlos	2	1.90	-0.25
338	Eteia	1	1.80	-0.80
339	Itanos	1	2.00	-2.20
340	Capa Plaka	1	1.00	-0.20
341	Zakros	3	1.50	0.00
341	Zakros	2	2.00	-0.50
341	Zakros	1	3.00	-1.00
343	Akri Goudara	1	5.00	3.50
344	Hierpatra	1	1.80	-0.50
346	Mon Arvi	1	0.50	-0.25

347 Metallon	1	1.90	0.00
347 Metallon	2	1.10	-2.00
350 Plakios	1	1.90	2.00
351 Leuce	1	1.90	2.20
352 Lasea	1	1.80	0.00
353 Agia Marina	1	1.90	2.00
355 Sphakia	1	1.90	3.50
356 Phoenice	1	1.90	3.50
357 Kalamydes	1	1.90	7.50
360 Plakaki Krio	1	2.20	8.00
362 Musagores	1	2.20	8.50
363 Khrysoskalitissa	1	2.20	7.50
364 Sphinarion	1	2.20	7.00
365 Phalasarna	1	2.20	6.60
367 Agneion	1	2.20	6.00
368 Kisamos	1	2.20	5.20
369 Napia	1	2.20	5.00
370 Dhiktinaia	1	2.20	3.00
371 Burdroae	1	2.20	3.00
372 Chor Fakia	1	2.20	1.10
373 Marathi	1	2.20	1.50
375 Amphimalla	1	2.20	1.50
376 -	1	2.20	1.00
377 -	1	2.20	0.80
378 Rethymne	1	2.20	-0.20
379 Panormus	1	0.50	-0.50
380 Varignano	1	2.00	-0.50
382 Lapethus	1	2.00	0.00
384 Cerynia	1	2.30	0.00
385 Vrisi	1	3.00	0.00
386 Platymeis	1	2.00	0.00
388 Agios Thyrsos	1	2.00	-0.25
389 Carpasia	1	2.00	0.00
392 Salamis	1	1.70	-2.00
392 Salamis	2	1.00	-0.30
393 Ammochostos	1	2.00	-0.50
395 Dades	1	2.00	-0.20
396 Kitium	1	5.00	-7.00
396 Kitium	2	2.00	-0.50
399 Amathos	1	1.50	-0.75
399 Amathos	2	0.50	-0.20
400 Curias	1	0.50	-0.10
401 Dreamer's Bay	1	1.80	-2.00
404 Paphos	1	2.00	-0.30
405 Drepanum	1	2.00	-0.30
409 Agios Nikolos	1	2.00	-0.75
410 Marium Polis	1	2.00	-0.75
413 Bema	1	2.00	0.00
414 Camiras	1	1.00	0.00
415 Rhodus	1	5.00	1.75
416 Zimbule	1	0.70	-0.25
417 Calithea	1	5.00	3.70
417 Calithea	2	2.40	2.70
417 Calithea	3	0.70	-0.25
418 Aphandos	1	5.00	5.24
419 C.Teodoco	1	5.00	3.40
420 Tsambika	1	5.00	3.25
421 Lindus	1	5.00	2.00
422 Merminga	1	5.00	1.00
423 C.Istros	1	5.00	0.33
425 Lephkos	1	2.00	-1.00
426 Vurgunda	1	2.00	-0.75
427 Tristoma	1	0.80	-0.25
428 Palatea	1	1.00	0.00
430 Vathi Potamus	1	2.00	-1.10
431 Makriyalo	1	2.00	-0.90
431 Makriyalo	2	1.00	0.00
433 St. Rocchino	1	2.60	-1.80
433 St. Rocchino	2	2.50	-1.40
438 St.Liberata	1	1.90	-0.60
439 Orbetello	1	2.30	-1.00
440 Giglio I.	1	1.90	-0.60
441 Pianossa I.	1	2.00	-0.90
444 Martanum 1	1	2.00	-0.50
447 Torre Valdaliga	1	2.00	-0.60
448 Mattonara	1	2.00	-0.60
449 Punta St.Paolo	1	2.00	-0.50
450 Punta de Vipera	1	2.00	-0.60
451 Fosso Guardiole	1	2.00	-0.70
453 Grottacce	1	1.90	-0.60
457 Porto di Claudio	1	1.90	-0.50
458 Il Palazzo	1	2.00	-0.50
459 Casarina	1	2.00	-0.50
460 Lago di Paolo	1	1.90	-0.50
461 Pisc. di Lucullo	1	1.90	-0.40
462 nr. Sperlonga	1	2.00	-0.50
464 Nave	1	2.00	-0.50
466 Scauri	1	2.00	-0.40
467 Ponza (Pontia)	1	2.00	-1.00
468 Ventotene	1	2.00	-0.90
471 C. Ognina	1	3.40	-1.00
519 Aquilaea	1	1.80	-1.50
519 Aquilaea	2	0.70	-4.00
567 Phalerura	1	4.00	-2.00
604 Troy	1	7.00	-2.00
604 Troy	2	4.50	2.00
604 Troy	3	3.30	0.00
604 Troy	4	2.00	0.00
638 Mytilene	1	2.20	-0.50
646 Phylakopi	1	3.20	0.00
710 Ravenna	1	2.50	-3.00
710 Ravenna	2	2.00	-2.00
710 Ravenna	3	1.50	-1.00
743 Naupactus	1	2.40	0.00
798 Anthedon	1	1.50	-0.20
899 Paros	1	7.00	-5.00
899 Paros	2	2.40	-3.00
923 Ras et Tarf	1	2.00	-0.30
931 Aradus	1	3.00	-1.00
931 Aradus	2	2.80	1.00
939 Sidon	1	2.80	-1.00
939 Sidon	2	2.00	1.00
940 Sarepta	1	1.70	0.00
941 Tyre	1	2.40	0.00
949 Apollonia	1	2.40	-2.10
949 Apollonia	2	2.00	-2.70
950 Ptolemais	1	2.00	-1.50
952 Euhesperides	1	2.00	0.00
956 Phycus	1	1.50	-1.50
957 Cercina	1	2.20	-0.50

958	Gov'nor BE, Gib.	1	12.00	-10.00
963	Saliagos	1	7.00	-4.50
964	Agios Petros	1	7.00	-10.00
965	Franchthi	1	6.50	-10.00
966	Hof Dado	1	6.00	-1.20
967	Kefar Samir	1	5.70	-5.40
969	Lagoon of Thau	2	5.20	-1.00
980	Vieille-Couronne	1	2.20	-0.50
981	Meryem	1	2.70	0.60
982	La Gaillarde	1	2.00	-0.40
985	Bouar	1	2.00	0.80
986	Machroud	1	3.00	-1.00
987	Akovitika	1	5.00	-11.00
987	Akovitika	2	2.80	-2.00
988	St.Cecile	1	2.50	-1.00
990	Son Real	1	4.00	0.00
990	Son Real	2	0.50	0.00
994	Port de Carro	1	2.20	-0.50
995	Anse de Verdon	1	2.20	-0.50
996	Beaumaderie	1	2.20	-0.50
997	St. Croix	1	2.20	-0.50
998	Lixus	1	2.00	0.00
999	Cotta	1	1.80	0.00
1000	Asilah	1	0.60	0.00
1001	Sidi Kacem	1	4.00	0.00
1002	Cave of Hercules	1	10.00	-10.00
1004	Malabata	1	0.60	0.00
1005	Ksar es Seghir	1	0.60	0.00
1006	Lattes	1	5.00	-3.00
1027	Sullectum	1	2.00	-1.00
1028	Bizerta	1	2.00	-0.50
1030	Koutsoundri	1	2.00	-0.20
1031	Tell Harez	1	6.00	-2.60
1039	Oikonomos I.	1	5.00	-3.00
1040	Aperlae	1	2.40	-2.50
1040	Aperlae	2	1.30	-2.50
1042	Naousa Bay	1	2.50	-3.00
1043	Venice	1	2.00	-0.90
1044	Tabbat el Hamman	1	2.90	0.00
1045	Phoukeri	1	1.60	-2.00
1048	Minturnae	1	2.20	0.00
1049	Can Picafort	1	2.00	0.00
1049	Can Picafort	2	0.50	0.00
1051	Caesarea B	1	2.20	0.00
1051	Caesarea B	2	2.00	0.00
1051	Caesarea B	3	0.80	0.00