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COASTAL NEO-TECTONICS OF THE MEDITERRANEAN FROM TIDE-GAUGE RECORDS

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Abstract

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Records from tide gauges in Israel and Egypt supplement the many geological and archeological investigations that have contributed information about relative sea-level changes in the Mediterranean region. Seven such records reveal changes during the past few decades that accord with prior inferences about land movements in this region (emergence along the coast of Israel and at Alexandria and subsidence at the Nile Delta and the head of the Gulf of Suez). Twenty-four other tide-gauge records for the rest of the Mediterranean region indicate more uniformity (submergence of land or rise of sea level) in the west, but with greater movements of the land attributed to probable plate underthrusting in Turkey and Greece, to volcanism near Mount Etna, to deltaic compaction at Izmir, and to deltaic compaction coupled with water pumping at the Po Delta.

Introduction

The coasts of the Mediterranean Sea, just as others of the World's oceans, exhibit evidence of relative vertical movement during the Holocene. Evidence for submergence is derived from physiography (eroded seacliffs and submerged beaches, river valleys, deltas, reefs, and wave-cut benches and terraces), from sediments (submerged forests, marshes, beach and dune sands, and mudflats), and from history and archeology (submerged cities, coastal roads, harbors, and other structures). During the same time span other areas were uplifted, as shown by raised terraces, uplifted Holocene marine sediments, and man-made structures such as the Temple of Serapis at Pozzuoli, Italy that was built on-shore, became submerged and drilled by boring marine mollusks, and then was uplifted partly again (see illustration by Lyell, 1850, frontispiece drawn in 1836 and pp.489–498). Geological evidence from Crete and Rhodes (Pirazzoli et al., 1982a, b) confirms the tendency for successive submergence and emergence over short intervals of time (10^2–10^3 yrs).

During Pleistocene glacial epochs the ice masses on land stored enough water that sea level was lowered an estimated 130 m below the present. Beginning 18,000 to 15,000 yrs ago ice melt rapidly returned the water so that sea level rose to a few meters below the present about 5000 yrs ago, followed by a more gradual subsequent return. The rapid return of water during late Pleistocene and early Holocene obscured concurrent movements of land level, but the return during late Holocene appears to have been slow enough that both rises and lowerings of land level are more apparent in the geological and archeological records. In

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fact, the rise of land around the Baltic Sea was noted long before the existence of glaciers and their weighting effect were realized, giving rise to controversy about whether or not the ocean level was falling everywhere (Lyell, 1850, pp.498–511). Clearly, the two distinct processes of returning meltwater and ocean warming that cause an eustatic rise of sea level and simultaneous rise and fall of coasts (only locally associated with ice unloading or eustatic water loading of adjacent shelf areas) do occur. For many scientific, socioeconomic, and political reasons we should try to evaluate the relative roles of the two processes.

The geology of the Mediterranean Sea region indicates prevalent land movements. Most of its length is occupied by a major belt of Alpine (Late Cenozoic to present) folding that locally is interrupted by deltas in which compaction of thick sediments is likely. Abundant earthquakes in the region are recorded in ancient literature (Poirier and Taber, 1980), especially in Israel, as compiled by Ben-Menahem (1979); some of them initiated tsunamis, perhaps via landslides (Shalem, 1956; Ambraseys, 1962; Striem and Miloh, 1975). Specifically, 34 (or 29%) of the 119 well-known large earthquakes that occurred in Greece and the surrounding region during the period 479 BC–1799 AD were followed by seismic sea waves. Subsequent seismic data are more complete. Taking the entire period (479 BC–1981 AD), 17 (or 7%) of the 249 known large earthquakes were followed by "damaging or disastrous" tsunamis (Papadopoulos and Chalkis, 1984). An example of a modern tsunami recorded at the Yafo tide gauge on 9 July, 1956 is presented by Goldsmith and Gilboa (1985). This recorded tsunami ($T = 12–15$ min, $H = 28$ cm) was caused by an undersea earthquake having a magnitude of 7.5 that occurred the same day in the Greek Archipelago (Papadopoulos and Chalkis, 1984). Thus seismic activity continues, as mapped for the period 1900–1965 by Ambraseys (1971) and for 1960–1980 by Espinosa et al. (1981).

Archeology is a useful tool for determining direction and rate of relative change of sea (land) level especially in the Mediterranean Sea, whose coasts have been the sites of human habitation and construction for thousands of years. Leaders in this archeological work have been N.C. Flemming and his associates, and in Israel, Flemming et al. (1978), Raban (1983), Adler (1985), and Nir and Eldar (1987). The results of several investigations (dives beginning in 1958) at 1053 sites that date as far back as 10,000 years and extend along all coasts of the Mediterranean Sea were summarized by Flemming and Webb (1986). Relative sea (land) level changes were derived from 335 sites having 406 dated materials or sequences, of which 156 show land uplifted (to +8.5 m), 204 are stable, and 46 denote submergence (to −11 m). Displacements vary with location and with age since date of construction. The variation with location was attributed to tectonism caused by probable underthrusting of the African plate beneath the Aegean plate along the Hellenic Arc, to volcanism (as at Pozzuoli), and to compaction of deltaic sediments. Spatial variations due to most of these tectonic causes were considered constant through time, and the remaining variations with age were attributed to eustatism — return of meltwater to the ocean. In this way, Flemming and Webb (1986) derived a eustatic rise of sea level from -1.1 ± 0.5 m 5000 yrs ago, to about 0.0 ± 0.3 m 2000 yrs ago, to 0 m at present.

Use of archeological sites alone is somewhat equivalent to inferring a person's career solely from birth and death certificates. Physiographic or sedimentary evidence before or between archeological data may provide equivalents of graduation, employment, and marriage notices, although Flemming and his associates (Flemming et al., 1978; Flemming and Webb, 1986) considered the geological evidence less accurate and the inferences probably uncertain. Nevertheless, they can be a useful supplement, as illustrated by radiocarbon-dated raised shorelines and shore sediments in the eastern Mediterranean Sea described by Pirazzoli et al. (1982a, b). An approach that combines archeological data and physiography, sediments, and geophysics was followed by Neev et al. (1987) in a study of coastal movements along Israel and Sinai, a region chosen because of the abundance of archeological sites and the intensity of geological studies. The results extended considerably Flemming and Webb's (1986) observation of more than a single direction of relative change of relative sea level at many sites. All 30 geological and archeological coastal sites of Israel and Sinai that were examined were found to exhibit repeated opposite directions of movement at different times. For example, structures had been built on dry land that not long before had been a swamp; later the structures were buried under beach sand containing naturally deposited shells and pebbles; and still later the structures became uplifted and exhumed. Moreover, uplifts and submergences of the land were far from being simultaneous along the coast and even more commonly were out of phase at sites along and across the coast owing to repeated activity of coastal faults.

Analysis of tide gauge records has supplementary value. A study made by Emery (1980) showed that of 247 accepted world tide-gauge stations, 73 exhibited relative land rise of 0 to more than 12 mm yr^{-1} whereas 174 exhibited relative land submergence (or rise of sea level) of 0 to more than 12 mm yr^{-1}. This spread was strongly suggestive of dominance by tectonic movement during the past several decades to a century rather than by simple eustatic rise of sea level. Subsequent work by others (Gornitz et al., 1982; Barnett, 1984) attempted to identify and eliminate known regions of tectonic uplift and to subdivide and statistically weight the world ocean area according to the uneven distribution of acceptable tide-gauge records. Nevertheless, detailed analysis of records in regions of closely-spaced stations showed that relative movements formed patterns to be expected of tectonism caused by plate movements. An example is the relative sinking of the southwest coast of Japan averaging 20 mm yr^{-1} and relative emergence of the northwest coast averaging 5 mm yr^{-1} (Aubrey and Emery, 1986a). The general conclusion of dominance of tectonism over eustatism was suppported by another analysis of world tide-gauge records by Pirazzoli (1986).

After the study of coastal tectonism in Israel and Sinai (Neev et al., 1987) and of tide-gauge records in Japan (Aubrey and Emery, 1986a) and other coastal regions of the world, we decided to investigate hitherto unpublished tide-gauge records from Israel and to compare them with acceptable records from Egypt and from the rest of the Mediterranean Sea. The first to report on sea-level changes along the coast of Israel were Uziel (1968) and Striem and Rosenan (1972) and for Alexandria, Sharaf El Din and Moursy (1977). Goldsmith and Gilboa (1985) tabulated, checked, and reported all the data from the four Israeli tide gauges, and extended the Israeli data by comparing them with six other contemporaneous Mediterranean gauges (Goldsmith and Gilboa, 1987). This study indicated variations in sea-level changes suggestive of tectonism, and led to the more intensive present study. The Israeli and Egyptian records are short ones, but their study appears to be worthwhile in view of the many other supporting investigations of archeology, geology, and geophysics in these countries.

Tide-gauge records

Tide-gauge data were obtained from the Permanent Service for Mean Sea Level (PSMSL) at Bidston, England. Two data sets were provided on magnetic tape: RLR and Metric. RLR (revised local reference) data are those that have been researched extensively and the history of tide-gauge shifts and datum changes recorded and corrected. The remaining data are classified as Metric, where shifts in datum and possible changes in location are not corrected because complete history is lacking. Where possible, RLR data were relied upon, but gaps were filled using Metric data (Table 1). Of the 36 series selected for analysis, 21 are from the RLR data set.

Although these data are extensive, other data exist for the Mediterranean Sea that have

TABLE 1

Tide-gauge station data for the Mediterranean region

Country	Station	Lat.	Long.	Start and end year	Slope (mm yr^{-1})	t-confidence	Number of years of record
Spanish north Africa	Ceuta	35°54.00′N	05°19.00′W	1944–1964	−0.4	0.90	21
Egypt	Alexandria[1]	30°51.00′N	29°53.00′E	1958–1976	+0.7	0.96	19
Egypt	Port Said[1]	31°15.00′N	32°18.00′E	1923–1946	−4.8	0.98	24
Egypt	Kabret[1]	30°16.00′N	32°30.00′E	1923–1941	−0.6	0.98	15
Egypt	Thewfik[1]	29°57.00′N	32°34.00′E	1923–1946	−0.7	0.98	23
Israel	Ashdod[1]	31°28.48′N	34°22.48′E	1958–1983	+0.5	0.98	26
Israel	Jaffa[1]	32°03.00′N	34°27.36′E	1955–1981	+0.5	0.997	27
Israel	Haifa[1]	32°30.00′N	34°35.24′E	1957–1975	+2.8	0.87	19
Turkey	Antalya[1]	36°53.00′N	30°42.00′E	1936–1972	+3.8	0.95	36
Turkey	Izmir[1]	38°24.00′N	27°10.00′E	1937–1971	−4.6	0.96	35
Greece	Thessaloniki[1]	45°37.00′N	23°02.00′E	1933–1982	−4.0	0.9997	22
Yugoslavia	Dubrovnik	42°40.00′N	18°04.00′E	1956–1974	−0.8	0.91	18
Yugoslavia	Split Harbour	43°30.00′N	16°23.00′E	1954–1974	−1.3	0.95	20
Yugoslavia	Bakar	45°18.00′N	14°32.00′E	1930–1974	−1.1	0.9995	33
Yugoslavia	Rovinj	45°05.00′N	13°38.00′E	1955–1974	−0.9	0.93	19
Italy (Adriatic)	Trieste	45°39.00′N	13°45.00′E	1905–1982	−1.4	1.00	72
Italy (Adriatic)	Venezia (Arsenale)	45°24.00′N	12°21.00′E	1889–1913	−2.6	0.98	25
Italy (Adriatic)	Venezia (San Stefano)	45°25.00′N	12°20.00′E	1896–1920	−3.7	0.96	25
Italy (Adriatic)	Venezia (Punta Della Salute)	45°26.00′N	12°20.00′E	1953–1966	−7.3	0.82	15
Italy (Adriatic)	Venezia (Diga Su)[1]	45°21.00′N	12°23.00′E	1917–1934	−2.6	0.87	18
Italy (Adriatic)	Porto Corsini[1]	44°30.00′N	12°17.00′E	1896–1922	−1.6	0.94	27
Italy (Adriatic)	Porto Corsini[1]	44°30.00′N	12°17.00′E	1937–1972	−8.2	0.96	32
Sicily	Catania	37°30.00′N	15°08.00′E	1896–1920	−0.6	0.997	25
Sicily	Palermo	38°08.00′N	13°20.00′E	1896–1922	−0.6	1.00	27
Sicily	Messina[1]	38°12.00′N	15°34.00′E	1909–1923	−19.4	0.79	15
Sardinia	Cagliari	39°12.00′N	09°10.00′E	1896–1933	−1.8	1.00	38
Sardinia	La Maddalena	41°14.00′N	09°22.00′E	1896–1913	−0.9	0.98	17
Italy (Mediterr. Sea)	Napoli (Arsenale)	40°52.00′N	14°16.00′E	1899–1922	−2.6	0.994	24
Italy (Mediterr. Sea)	Napoli (Mandracc)	40°52.00′N	14°16.00′E	1896–1922	−2.4	0.999	27
Italy (Mediterr. Sea)	Civitavecchia	42°03.00′N	11°49.00′E	1896–1922	−0.6	0.999	27
Italy (Mediterr. Sea)	Genova	44°24.00′N	08°54.00′E	1884–1982	−1.3	1.00	79
Italy (Mediterr. Sea)	Porto Maurizio	43°52.00′N	08°01.00′E	1896–1922	−1.2	0.999	27
Monaco	Monaco[1]	43°44.00′N	07°25.00′E	1902–1921	−1.6	0.96	20
France (Mediterr. Sea)	Marseille	43°18.00′N	05°21.00′E	1885–1978	−1.4	1.00	86
Spain (Mediterr. Sea)	Alicante I	38°20.00′N	00°29.00′W	1916–1969	−0.8	1.00	41
Gibraltar	Gibraltar	36°07.00′N	05°21.00′W	1961–1982	−1.1	0.97	22

[1]Indicates non-RLR data were used.

been reported on previously. In particular, stations from north Africa (Algeria and Tunisia) have been reported by Pirazzoli (1986) but were not available for this study; these data are referred to for interpretation based on prior analysis but were not included in our analysis. Some data for the Israel coastline were updated by Goldsmith and Gilboa (1985) by perusing the original tide-gauge records. This update provided a few additional data points for analysis.

All data were screened prior to use. Each tide-gauge series had to exceed 15 years to be admitted. Particularly for Metric data, all series were examined visually to eliminate any stations having sudden large deviations or other characteristics indicating datum shifts. Finally, all data were subjected to linear regression analysis. The slopes of the regression lines were analyzed using a *t*-test, where the level of probability was determined that the slope obtained by regression was within $+1$ mm yr^{-1} of the true slope (actually a null-hypothesis test). The results of this *t*-test were used for further screening. Most (32 of 36 series) of the accepted *t*-confidence levels exceeded 90%. Of the remainder, two exceeded 85% while two were slightly below 85%. At Venezia, one station had a slope of -7.3 mm yr^{-1}, so the 82% *t*-confidence was considered a reliable indicator that the actual slope was far below 0 mm yr^{-1}. At Messina, Italy, the slope was -19.4 mm yr^{-1}, so the 79% *t*-confidence indicates that the actual slope was far below 0 mm yr^{-1}.

The screening procedure left 36 series (out of the original 90 gauges) for analysis, representing 31 different geographic locations (Table 1; Figs.1–5). Of this total, 7 stations were selected in the Israel/Egypt region (Fig.1). Although data were available for Elat at the head of the Gulf of Elat, this station record (1965–1970, 1975–1983) was too short for inclusion in the analysis. The remaining 30 records are distributed throughout the Mediterranean Sea and its internal marginal seas (Fig.2). Multiple records at certain stations (Venezia, Porto Corsini, and Napoli) were retained to examine temporal trends in tide-gauge results.

A simple linear regression model was chosen to represent relative sea (land) levels for the Mediterranean Sea. Although much of our previous work (e.g., Aubrey and Emery, 1983, 1986a, b) incorporated eigenanalysis methods for interpretation, such analysis applied to the Mediterranean region does not clarify any of the spatial trends; hence it is not reported here. The simple linear model is different from that of Pirazzoli (1986) and is preferred because it is more easily testable. Although the data length that we admit in our records is less than the 50 years admitted by Pirazzoli (1986), we recognize the limitations imposed by such short record lengths and accordingly limit our interpretations, particularly in this known area of highly variable submergence and emergence rates.

Changes in rates of relative sea-level changes

Three sites have more than one tide-gauge station in their immediate vicinity: Venezia, Porto Corsini, and Napoli (Table 1). These stations are of interest, because they reveal temporal patterns that are suggestive of recent changes in rates of relative sea-level change. Venezia, for example, has four stations, three of which reported during the early twentieth century, whereas the fourth station reported later in the century. The three early tide-gauge records indicate a relative drop in land level of from 2.6 to 3.7 mm yr^{-1}, suggestive of some undefined eustatic change in sea level or local deltaic subsidence. The later record, though only 15 years long, indicates a much accelerated sinking of 7.3 mm yr^{-1}, consistent with the analysis of Venezia (Pirazzoli, 1982). This acceleration also is consistent with known sinking of land due to human activities, notably groundwater withdrawal (Dolan and Goodell, 1986). A single continuous record presumably would reveal more clearly this gradual increase in rate of submergence.

Porto Corsini shows results similar to Venezia. Both are situated on the Po River delta, although on different branches. The early

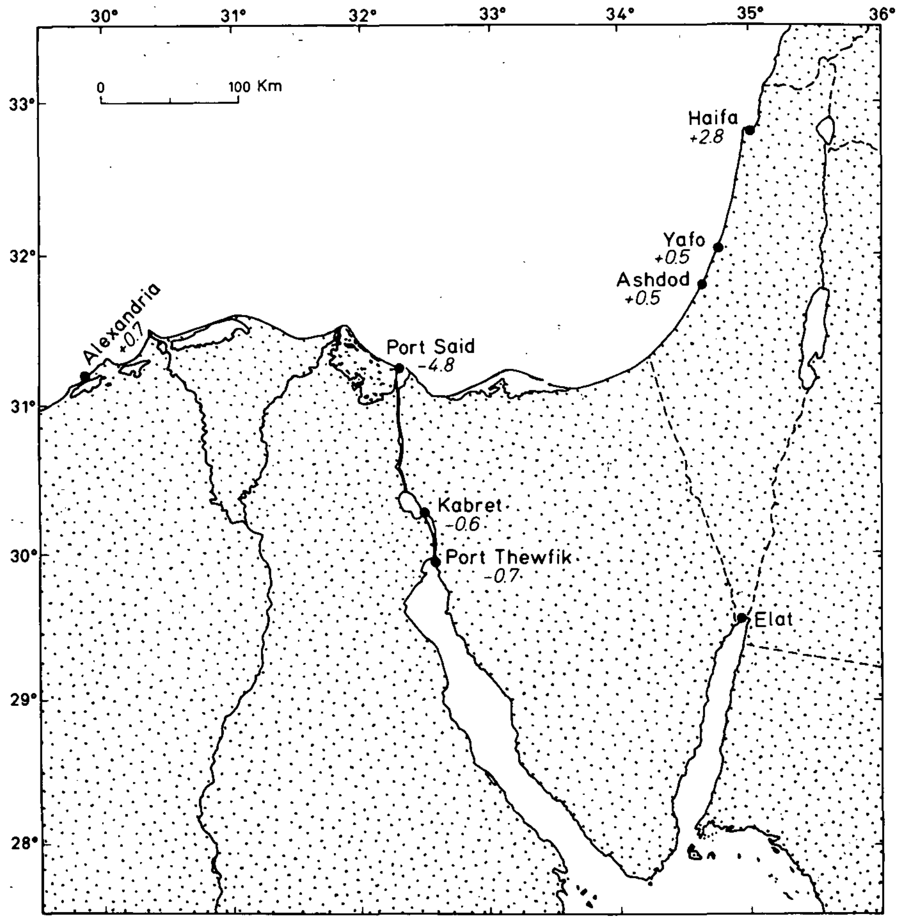

Fig.1. Tide-gauge stations of Israel and Egypt that have acceptable records. The one at Elat is not acceptable because the time span is too short (1965–1970, 1975–1983).

record at Porto Corsini reveals a relative rate of submergence of 1.6 mm yr^{-1}. The later 32-year record, however, indicates a rapid increase in rate of submergence to 8.2 mm yr^{-1}. This rapid increase may reflect a higher groundwater withdrawal, as at Venezia.

The two final stations are at Napoli, recording contemporaneously during the early twentieth century. These stations, at nearly but not identical locations, indicate rates of submergence that are nearly identical (2.6 mm yr^{-1} versus 2.4 mm yr^{-1}). The proximity of these estimates suggests that some confidence can be given to their interpretation. Such proximate locations do not always result in nearly equal estimates, as shown in previous studies in other regions (for instance, stations at Newcastle, Australia; Aubrey and Emery, 1986b), perhaps reflecting local effects such as groundwater withdrawal or pier subsidence.

Geological relationships

Mean annual changes of land level derived from regression analyses (Fig.2) show close correspondence with the geology. The three acceptable tide-gauge records of Israel denote uplift, with greatest changes (+2.8 mm yr^{-1}) for Haifa on the northern slope of Mount Carmel, a known uplifted block (Ben-Avraham and Hall, 1977). This tectonic uplift, over a geological time scale, is consistent with geo-

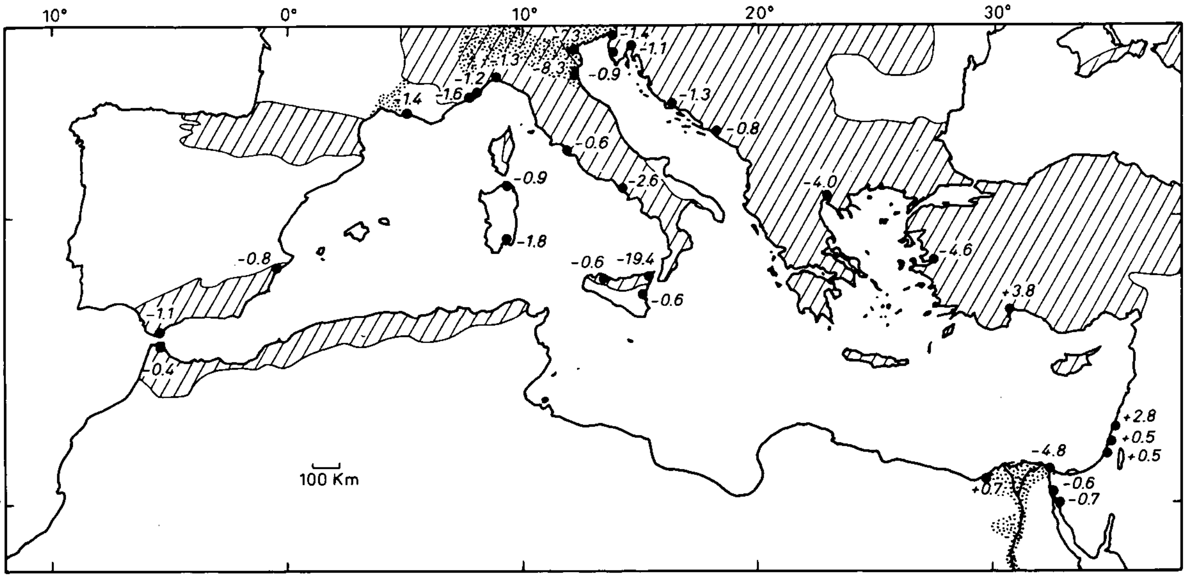

Fig.2. Acceptable tide-gauge stations of the Mediterranean Sea with slope of regression line for each station expressed as relative movement of land level per year. Diagonal shading — areas of Alpine folding; blank areas of Europe — areas of Hercynian folding and later sediments; blank areas of Africa and Asia Minor — areas of Paleozoic to Neogene platform sediments (from Yanshin, 1966); stippling — areas of deltas (from UNESCO and Bundesanstalt für Bodenforschung, 1962–1980).

detic releveling measurements of Kafri (1969), also suggesting a contemporary uplift in the Haifa area, and of the same scale indicated by the tide gauges (Fig.3). Even the lesser uplifts at Yafo and Ashdod ($+0.5$ mm yr^{-1}) are supported by comparison of two sets of precise leveling measurements made 9 years apart. They also reveal an uplift in the order of millimeters per year of the coasts with respect to the inland area that includes the Judean Mountains (Kafri and Karcz, 1975). These releveling measurements show variations through time in rates of vertical movements. However, releveling technology and experience now have advanced, and measurements in progress in these same areas will enhance these earlier releveling results.

Had the tide-gauge stations been more numerous and closely spaced along the Israeli coast, they likely would have revealed differential vertical movements associated with a series of faults oriented approximately perpendicular to the shore, which appear to be active presently (Neev and Ben-Avraham, 1977; Mart, 1982, 1984; Garfunkel and Almagor, 1985). The most notable example of this activity is the Carmel block (Ben-Avraham and Hall, 1977) near Haifa, with the fault still obviously active today (an earthquake, $M = 5.1$, occurred in August 1984 with its epicenter on the north face about 50 km southeast of Haifa). The Gulf of Elat–Dead Sea Rift, along the eastern border of Israel (Fig.1), also indicates tectonic activity in this region (Girdler, 1958; Quennell, 1958; Freund et al., 1970; Neev, 1977; Bartov et al., 1980; Ben Menachem, 1981; Garfunkel, 1981; Cochran, 1983; Mart, 1987).

The Israeli data are consistent with the record at Alexandria, which shows land uplift of $+0.7$ mm yr^{-1} (Fig.1). Alexandria is at the western margin of the Nile Delta and is underlain by pre-delta Miocene bedrock (Said, 1962, pp.201–209). Ben-Menahem (1979) discussed several major earthquakes in the region of Alexandria during historic times, indicating active tectonism. One (320 AD) caused great damage and casualties in Alexandria; a second (796 AD) toppled the Pharos lighthouse; a

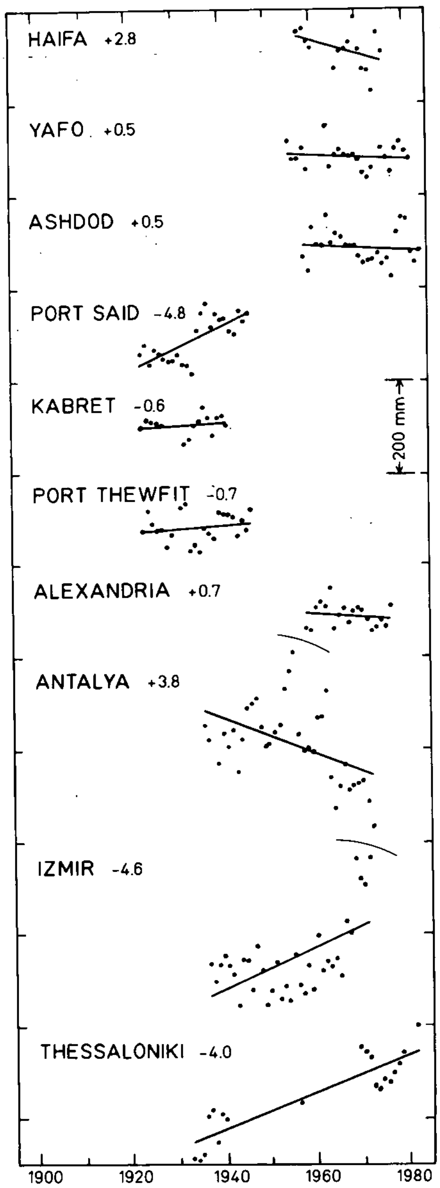

Fig.3. Mean annual sea levels at stations in Israel, Egypt, Turkey and Greece. The numbers indicate slope (mm yr^{-1}) of a linear regression line through data points for mean annual relative sea levels (expressed as movement of land level). See Table 1 and Fig.2 for positions. Thin curved line segments separate data points for adjacent stations where otherwise they could be confused.

third (1303 AD) damaged city ramparts and battlements and destroyed the remnants of the Pharos lighthouse; while a fourth (1870) caused damage and generated a tsunami. The latter three earthquakes exceeded 7.2 in magnitude (Ben-Menahem, 1979).

The other tide gauges of Egypt reveal subsidence of the land along the eastern side of the Nile Delta, with much faster subsidence (-4.8 mm yr^{-1}) at Port Said near the front of the delta. This subsidence of -4.8 mm yr^{-1} is supported by borehole sediment studies (Stanley, in press) that reveal sinking of an adjacent lagoon floor at a rate between -4.5 and -5.0 mm yr^{-1}. Lesser subsidence of -0.6 and -0.7 mm yr^{-1} occurs at Kabret and Port Thewfik farther inland, at Bitter Lake and the head of the Gulf of Suez, respectively (Fig.3). Seismic reflection profiles offshore, supplemented by seismic and well data on-shore (Ross and Uchupi, 1977; Rizzini et al., 1978; Ryan, 1978; Coutellier and Stanley, 1987) indicate that post-Miocene sediment has a thickness of 2.5 s (about 2.5 km) at Port Said and a lesser thickness of 0.0–0.5 s (0 to ~0.5 km) at Kabret and Port Thewfik, where there are outcrops of Miocene strata (Said, 1962, p.218). Sediment at the latter stations appears to be a post-Miocene but pre-delta filling of an ill-defined trough (Brown, 1980), whose origin is due to plate extension accompanied by uplift along the flanks due to lithospheric heating, according to Steckler (1985).

For comparison are 24 other stations along the Mediterranean coast (Fig.2). Most are located on the Alpine fold belt or related belts. Rapid submergence and emergence (from $+3.8$ mm yr^{-1} at Antalya to -4.6 mm yr^{-1} at Izmir) occur in Greece and Turkey, in areas most likely to be affected by underthrusting along the Hellenic Arc, as shown by seismicity and seismic reflection profiles (Mascle et al., 1986). Tide-gauge data do not match exactly with the archeological observations of Flemming and Webb (1986) in southern Turkey. Antalya is near the border between Flemming's regions 14 and 17. He interprets region 17 to be a quiet (aseismic) zone with little movement, but it borders the area of rapid land motion revealed by tide-gauge records. Ben-Menahem (1979) listed ten earthquakes exceeding $M=6.7$ within eastern Turkey between

1840 and 1976 also at odds with Flemming et al.'s (1986) classification. However, the Izmir gauge, with its relatively large downward movement (land relative to sea level), is within Flemming's region 14, which also had a relatively large recent downward displacement based on archeological considerations (Flemming and Webb, 1986, fig.10). The continental shelf of outer Izmir and Candarli bays is underlain by thick superimposed deltaic sequences formed during the Late Quaternary and earlier, and which manifest themselves as widespread normal block faulting. The Izmir coastal subsidence, estimated to be 1 m/1000 yrs over geological time (Aksu et al., 1987), is consistent with the tide-gauge and archeological evidence. Both Izmir and Port Said deltaic areas are subsiding at the same rate. Naples, also with a slightly larger submergence rate (2.6 mm yr^{-1}), appears to be at the boundary of two plates. An exceptional subsidence of -19.4 mm yr^{-1} is recorded at Messina, but this city is on the flank of Mount Etna in northeastern Sicily and the movement probably is associated with volcanic activity.

Several other stations are on deltas other than that of the River Nile. These are Venezia and Porto Corsini (Fig.4; both of which are affected by pumping of water from the Po Delta), and perhaps Marseilles (Fig.5) on the Rhône Delta. The 20 stations on the Alpine belt not extremely affected by volcanism or deltaic subsidence exhibit similar rates of subsidence with a mean of -1.2 mm yr^{-1}. The Spanish and French stations are not at present active plate boundaries (Flemming and Webb, 1986); their subsidence might be attributed to cooling of ancient rifted crust (Pitman, 1978), or to subsidence of a coastal upwarp associated with weighting and sinking of the Mediterranean basin by 1.6 km of evaporites and by the return of sea water after the Messinian desiccation 5.5 m.y. ago (Norman and Chase, 1986).

Although the region has 31 tide-gauge records acceptable to our analysis; an usually large concentration for the World's oceans, their time spans are too short, all do not overlap, and they are too far apart to provide

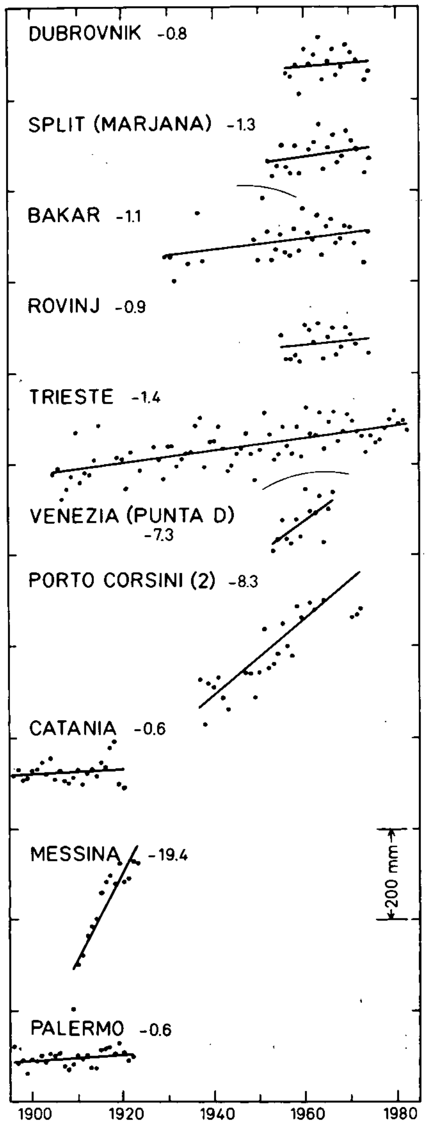

Fig.4. Mean annual sea levels at stations in Yugoslavia and Italy. See Fig.3 for explanation.

more than general geological information. The area is one of complex tectonism with closely-spaced discontinuities of geological structure. The reason for poor records is that the Mediterranean Sea is so nearly tideless that knowledge of the tide provided little aid to ship navigation in days of sailing ships, and the broader use of tide measurements for finding changes of mean annual sea level is only a recent development. Nevertheless, such

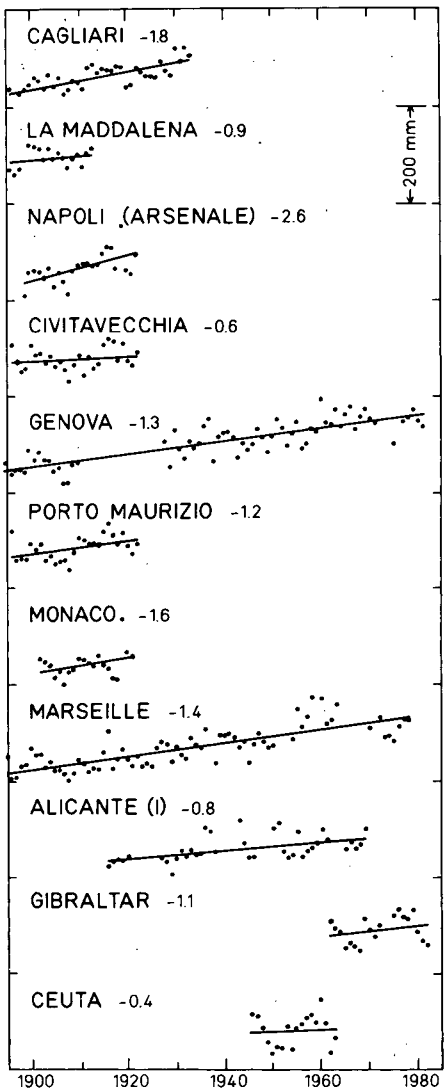

Fig.5. Mean annual sea levels at stations in Italy, Monaco, France, Spain and Gibraltar. See Fig.3 for explanation.

changes are so important in coastal habitation by man and for understanding rates of geological processes that increased establishment of tide-gauge stations is strongly recommended especially in the tectonically active Mediterranean coastal regions.

Conclusions

Analysis of tide-gauge records in the Mediterranean shows the records to be dominated by tectonism, although the sparse coverage compared with the small sizes of crustal blocks having tectonic homogeneity preclude precise definition of neo-tectonic provinces. The data show Israel to be emergent along with Alexandria, Egypt, whereas the Nile Delta and Gulf of Suez Rift in Egypt are submergent. Such a pattern attests to strong tectonic dominance in the region. The rest of the Mediterranean except southern Turkey is submergent. Much of the submergence is at a low rate (near -1.2 mm yr^{-1}), although local rates exceed this in regions of tectonism (Messina) and deltas (Venezia, Porto Corsini, and Izmir). The extensive studies of Flemming and Webb (1986) and Pirazzoli et al. (1982a,b) must be relied on to examine longer time scales of change over smaller coastal reaches, because the tide-gauge data are sparse both spatially and temporally. Apparent stability of the northwestern Mediterranean as indicated by tide-gauges (1.2 mm yr^{-1} submergence) appears to be due to positions of gauges in areas distant from presently active plate boundaries. However, this stability may be misleading, as the region has undergone periodic cycles of emergence and submergence and is seismically active. Considerable consistency is shown between recent land emergence and submergence delineated by these tide-gauge records with geological relationships (such as probable underthrusting of the Hellenic Arc), with archeological data (Izmir), and with geodetic releveling (Israel). However, inferences about modern trends of sea-level change derived from tide-gauge data limited to durations of a half-century or less, and having influences from both the ocean and land, may be quite tenuous in some places.

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