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Sedimentation rates in the Sea of Marmara: a comparison of results based on organic carbon—primary productivity and ^{210}Pb dating

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Abstract—A large number of surficial sediment samples (75 grab samples, one boomerang core, four box cores) as well as primary productivity measurements have been used to estimate the rates of sediment accumulation in the Sea of Marmara; using an empirical expression for the relationship between surface productivity and organic carbon content of the sediment (MÜLLER-SUESS formula). It was found that calculated low sedimentation rates occurred on the inner southern Marmara shelf (ave. 8 cm 1000 y^{-1}) where the primary production was relatively high (ave. 161 gC m^{-2} y^{-1}); and vice versa, high sedimentation rates were calculated for the southwestern shelf (123 cm 1000 y^{-1}), an area with very low primary productivity (64 gC m^{-2} y^{-1}). This discrepancy among the values, is probably due to the combined effects of the distinctive and peculiar oceanography of the Sea of Marmara (well stratified flow, strong horizontal transport, and varying conditions for mineralization of organic matter etc.).

Utilizing the ^{210}Pb method, sediment accumulation rates have been determined of approximately 190 cm 1000 y^{-1} on the northeastern shelf, 120 cm 1000 y^{-1} in the eastern depression, 260 cm 1000 y^{-1} in the central depression, 100 cm 1000 y^{-1} in the western depression and 280 cm 1000 y^{-1} on the southwestern shelf of this sea. These generally high rates of sedimentation using this method further support the conclusion that the amount of primary produced organic carbon preserved in the recent bottom deposits of the Sea of Marmara seems not to be universally related to the rate of sedimentation.

INTRODUCTION

IT has been shown by numerous studies that the concentration of organic carbon in marine deposits is mainly controlled by the interplay between the processes of supply and preservation of the various components, in any given region (e.g. ROMANKEVICH, 1968; IBACH, 1982; ARTHUR *et al.*, 1984; CALVERT, 1987). In general, the high organic carbon contents in the sediments are universally related to the high sedimentation rates and/or high primary production rates (e.g. STEVENSON and CHENG, 1972; HARTMAN *et al.*, 1976; NAIDAU, 1990). This relation between sedimentary organic carbon content and phytoplankton productivity (MÜLLER and SUESS, 1979), if verified by comparison with independent dating techniques, such as ^{210}Pb geochronology (e.g. KOIDE *et al.*, 1973; NITTROUER *et*

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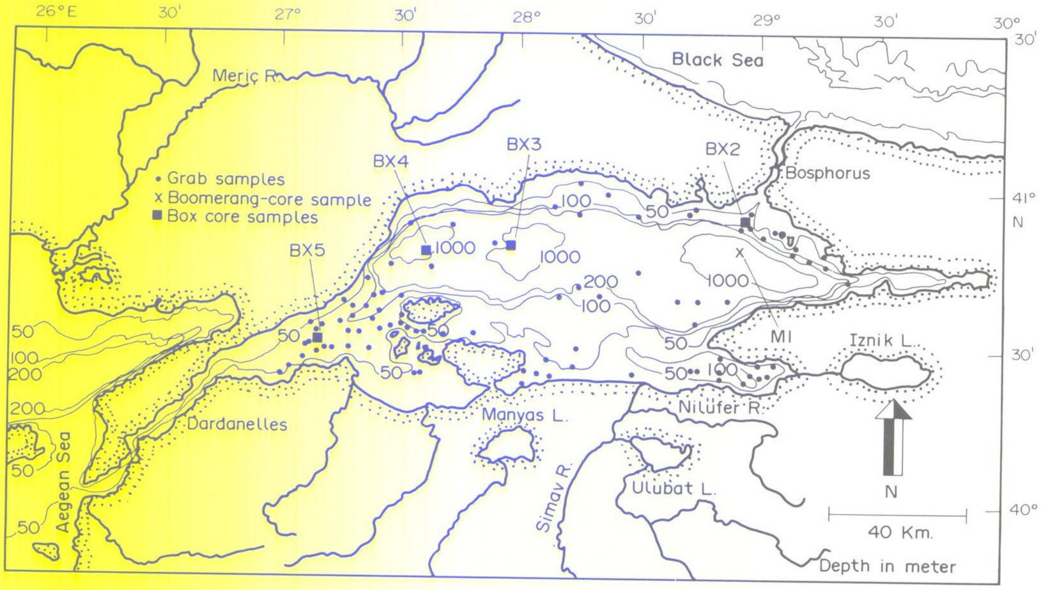

Fig. 1. Location of the study area (Sea of Marmara) showing the sampling stations for surface sediments. BX2, BX3, BX4 and BX5 are sites of box core sediment sampling stations and M1 is site of boomerang-gravity coring.

al., 1979; TANAKA *et al.*, 1991), can be successfully used to investigate sedimentation rates in a wide range of marine environments.

Studies on sediment accumulation rates with emphasis on organic carbon contents in the sediment and primary productivity in the overlying surface waters, at large-scale, are very poorly known from the Sea of Marmara and the only available data comes from the easternmost part of this sea, the İzmit Bay (ERGIN and YÖRÜK, 1990). Radioactive dating techniques have been used to investigate the geochronology of surficial sediments in the Eastern Marmara Basin by using the ^{14}C (STANLEY and BLANPIED, 1980) and ^{210}Pb (EVANS *et al.*, 1989; ERTEN, 1991) methods.

In this present work, an attempt has been made to determine the sediment accumulation rates using the relationships between organic carbon contents in sediments and primary productivity rates in surface waters and this has been compared to the independent determinations of the rates of sedimentation derived from radioactive dating. It is demonstrated that both organic carbon-primary production-related and radioactive-dating sedimentation rates appear to be in fairly good agreement in the deep waters of the Central Marmara Basin; and this is in contrast to the relatively shallower waters, where a discrepancy exists among the values obtained from the above two different methods, probably due to increased influences from adjacent water and land masses and to prevailing particular hydrodynamic conditions in this sea.

ENVIRONMENTAL SETTING

The Sea of Marmara, with a surface area of approximately 11500 km^2 and a total volume of 3380 km^3, forms a transitional link between the Black Sea and Aegean Sea, Eastern Mediterranean (Fig. 1) whereby the two narrow straits of Çanakkale ("Dardanelles") and

İstanbul ("Bosphorus") provide connections between these two adjacent seas. The most prominent morphological feature of the Sea of Marmara is an east–west trending trough (Fig. 1) which separates the relatively narrower northern shelf (2–13 km in width) from the much broader southern shelf (about 30 km wide) (CARTER *et al.*, 1972). The Marmara Trough, which is a continuation of the North Anatolian Fault, is divided into three small depressions (basins) that have maximum depths from west to east of 1097, 1389 and 1238 m (CARTER *et al.*, 1972).

The hydrographic characteristics of the Sea of Marmara and its straits have been discussed in detail by ARTÜZ and BAYKUT (1986), MILLER (1983), and ÜNLÜATA *et al.* (1990) and many references cited thereof. In general, the less saline waters (22–24 ppt) of Black sea origin enter this sea from the north-northeast at the surface, whereas the high-saline (38.5 ppt) waters of Eastern Mediterranean enter from the southwest, as a subsurface flow. As a result of the stratified two-layer flow in the Sea of Marmara, a permanent halocline occurs usually between 20 and 30 m.

MATERIAL AND METHODS

Seventy-five surface (top 4–6 cm of the sea floor) sediment samples have been used for this study (Fig. 1; Table 1), collected during the 1988–1990 cruises of R.V. *Bilim* in the Sea of Marmara using a grab sampler in water depths ranging from 10 to 855 m (Table 1). A boomerang core (approx. 1 m in length) taken from the Eastern Marmara Basin (approx. 1200 m water depth) onboard the R.V. *Bilim* in 1984 was also available (kindly provided by G. Evans, Imperial College, London) for this work (Fig. 1; Table 1). In addition, four of six box cores (50 × 50 × 60 cm) were collected during the 1988 cruise of R.V. *Knorr* in the Sea of Marmara at depths from 54 to 1226 m (Fig. 1; Table 1) were used for this study. From each of the cores or subcores, several samples were taken at 2–3 cm intervals. In this study, fine-grained surface sediment samples with mud fraction greater than 90% were chosen to normalize organic carbon data and thus to reduce the diluting effect of grain size (caused by siliciclastic sand and gravel, and benthic debris). Both surface and core sediment samples were analyzed for grain size, organic carbon, carbonate, porosity and density.

The grain-size was determined using standard procedures for the mud (<0.063 mm), sand (0.063–2.0 mm), and gravel (>2.0 mm) fractions as outlined by FOLK (1974). Total organic carbon was determined by oxidation via sulphochromic acid and back titration of the excess, following the procedures described by GAUDETTE *et al.* (1974). The standard deviation was from 5 to 8% for an organic carbon content of 0.86–1.21%. Calcium carbonate of the evolved CO_2 was determined using a modified volumetric method of SCHEIBLER (MÜLLER, 1967), with a standard deviation of less than 2%. The determination of water content in the sediment was performed by weight loss after oven drying at 90–100°C, in order to calculate sediment porosities (ϕ) according to BERNER (1971):

$$\phi = \frac{W \times ds}{(W \times ds) + (1 - W)dw}.$$

Here W is the weight percent of water (wet weight)/100, ds is the average density of sediment particles, and dw is the density of pore water (1.025). Dry bulk density of the sediment ($P\sigma$) was calculated simply from the relationships between the weights (g) and volumes (cm^{-3}) of dry sediment samples and density of the water (LEWIS, 1984).

*Table 1. Summary of data for the studied surficial sediments from the Sea of Marmara. Sediment accumulation rates are calculated using the empirical expression for the relationship between surface productivity and organic carbon content of sediment (Müller–Suess formula). *Box core stations; +boomerang-gravity core station*

Station	Water depth (m)	Latitude N	Longitude E	Mud (%)	Organic C (%)	$CaCO_3$ (%)	Porosity ϕ	Dry sediment density (g cm^{-3})	Sediment accumulation rate (cm 1000 y^{-1})
Northeastern Marmara Shelf									
KO4	75	40 56 18	28 43 08	96	1.16	15	0.67	2.57	78
M13C1	79	40 56 18	28 43 12	96	1.06	15	0.70	2.71	51
M13C2	67	40 57 00	28 44 30	95	1.16	17	0.71	2.60	56
M16′	72	40 54 00	28 55 36	91	1.18	12	0.71	2.60	52
M19	94	40 49 06	29 08 30	93	1.17	15	0.67	2.61	84
M20	85	40 48 00	29 12 30	97	1.14	14	0.64	2.57	94
M21	85	40 46 48	29 16 30	98	1.14	12	0.68	2.82	80
N7	60	40 56 24	28 58 06	90	1.31	11	0.67	2.88	148
N11	219	40 43 48	29 21 40	96	1.00	9	0.70	2.92	41
V2	65	40 54 48	28 56 00	91	0.76	15	0.72	2.80	15
V5	70	40 52 00	29 01 06	94	1.07	13	0.72	2.43	27
V6	80	40 49 54	29 08 54	95	1.15	14	0.65	2.51	83
BX-2*	64	40 54 48	28 56 03	87	1.10	12			
Mean	85			94	1.08	14	0.68	2.67	67
Northern Marmara Shelf									
N24	180	40 51 18	27 28 30	96	0.81	9	0.65	2.62	52
N3	77	40 57 36	28 08 48	91	1.14	16	0.75	2.70	75
L02K15	56	41 02 00	28 15 00	98	1.37	13	0.74	2.83	166
N18	61	41 00 00	28 22 00	100	1.22	13	0.73	2.64	102
K59K30	53	40 59 00	28 30 00	100	0.85	15	0.72	2.60	36
Mean	131			97	1.10	13	0.71	2.68	86
Central Marmara Deep Basins									
M1+	1200	40 49 15	28 56 00	99	1.10	10	0.68	2.63+	218
BX-3*	1226	40 49 48	27 57 35	99	0.97	10	0.74	2.63	80
BX-4*	1106	40 48 26	27 36 35	99	1.16	8	0.80	2.63	48
K46J28	760	40 46 00	27 28 00	99	1.20	9	0.37	2.63+	n.d.
K46J37	700	40 46 00	27 37 00	100	1.16	9	0.75	2.63+	109
K50J53	855	40 50 00	27 53 00	99	1.04	10	0.76	2.63+	68
Mean	975			99	1.10	9	0.75	2.63+	104
Southern Marmara Outer Shelf									
K40K10	100	40 40 00	28 10 00	94	1.11	14	0.73	2.55+	30
K40K20	130	40 40 00	28 20 00	98	1.11	14	0.74	2.79	35
N17	72	40 34 00	28 35 00	93	0.95	18	0.71	2.66	31
K40K40	370	40 40 00	28 40 00	99	1.28	10	0.74	2.43	30
K40K45	320	40 40 00	28 45 00	99	1.01	12	0.71	2.54	25
K40K52	200	40 40 00	28 52 00	98	1.90	13	0.65	2.45	355
Mean	198			97	1.22	14	0.71	2.57	30
Southern Marmara Inner Shelf									
V15	50	40 26 00	28 02 10	95	0.85	7	0.62	2.43	6
V14	50	40 23 12	28 02 06	95	0.95	6	0.71	2.37	3
N21	46	40 25 30	28 05 00	97	1.00	7	0.68	2.71	9
K25K08	53	40 25 00	28 08 00	91	1.14	9	0.71	2.67	10
K28K08	50	40 28 00	28 08 00	95	1.09	8	0.65	2.69	16
V13	50	40 26 48	28 14 06	99	0.90	9	0.74	2.66	3
V9	10	40 25 00	28 29 01	98	1.10	6	0.71	2.45	6

Continued

Table 1. *Continued*

Station	Water depth (m)	Latitude N	Longitude E	Mud (%)	Organic C (%)	$CaCO_3$ (%)	Porosity ϕ	Dry sediment density (g cm^{-3})	Sediment accumulation rate (cm 1000 y^{-1})
K26K45	64	40 26 00	28 45 00	99	1.27	8	0.73	2.59	10
N13	64	40 28 30	28 51 30	99	1.07	8	0.72	2.67	7
N15	74	40 26 00	28 51 00	99	1.26	7	0.68	2.24	10
K25K50	65	40 25 00	28 50 48	99	1.17	8	0.68	2.23	8
K27K54	100	40 27 06	28 54 36	99	1.46	6	0.78	2.57	7
N14	104	40 25 00	28 58 00	100	1.22	7	0.77	2.74	6
K24K57	107	40 24 00	28 57 00	99	1.31	7	0.76	2.50	6
K27L00	81	40 27 00	29 00 00	99	1.11	7	0.63	2.43	14
K27L04	70	40 27 00	29 04 00	99	1.14	7	0.75	2.56	5
K25L02	69	40 25 00	29 02 30	99	1.12	7	0.74	2.40	6
V8	80	40 24 48	29 01 10	99	1.29	7	0.72	2.39	9
Mean	66			98	1.15	7	0.71	2.51	8
Southwestern Marmara Shelf									
BX-5*	65	40 32 02	27 09 37	99	0.85	11			
V45	66	40 26 24	27 02 48	98	0.95	10	0.65	2.26	132
C2S	68	40 28 06	27 05 24	95	1.06	11	0.65	2.39	248
N27	68	40 31 00	27 07 00	90	1.00	10	0.70	2.47	127
C2Y	67	40 31 30	27 08 18	99	1.04	10	0.69	2.35	135
C2Z	67	40 29 48	27 09 00	99	1.06	10	0.70	2.55	169
K30J11	68	40 30 18	27 11 18	99	1.11	10	0.68	2.49	229
K33J10	71	40 33 00	27 10 00	99	1.06	10	0.71	2.51	143
V47	66	40 34 24	27 15 00	99	0.78	10	0.66	2.30	65
K35J09	70	40 35 00	27 09 00	90	0.99	10	0.68	2.25	112
V46	66	40 30 00	27 13 12	99	0.95	10	0.71	2.61	114
K30J17	66	40 30 00	27 17 00	99	0.99	9	0.73	2.56	92
K33J17	74	40 33 00	27 17 00	99	0.99	10	0.72	2.49	101
K35J15	84	40 35 00	27 15 00	99	0.94	10	0.71	2.59	107
K39J16	55	40 39 00	27 16 00	99	0.80	11	0.61	2.35	124
K33J20	69	40 33 00	27 20 00	99	1.01	8	0.64	2.20	136
K30J22	59	40 30 00	27 22 00	99	1.14	6	0.74	2.86	172
K38J22	122	40 38 00	27 22 00	99	0.87	9	0.75	2.39	37
V53	88	40 35 54	27 23 12	99	0.90	9	0.70	2.62	106
K34J25	70	40 34 00	27 25 00	97	1.09	7	0.75	2.47	83
V20	46	40 25 14	27 33 18	97	0.93	6	0.72	2.87	114
V49	43	40 25 12	27 35 00	93	1.07	6	0.71	2.50	129
V19	68	40 33 00	27 40 00	93	0.80	9	0.71	2.50	55
K33J34	64	40 33 00	27 34 00	93	0.80	10	0.74	2.58	42
N26	70	40 33 30	27 31 00	97	1.00	9	0.70	2.50	125
V52	70	40 34 12	27 30 36	97	1.05	9	0.73	2.56	114
N25	65	40 36 00	27 30 00	98	1.02	7	0.72	2.61	114
V21	86	40 39 48	27 31 00	97	0.85	9	0.73	2.53	54
K43J22	70	40 43 00	27 22 00	99	0.99	11	0.67	2.65	221
K40J24	150	40 40 00	27 24 00	94	0.82	13	0.68	2.61	109
K37J25	100	40 37 00	27 25 00	100	1.11	8	0.69	2.61	222
K33J48	70	40 33 00	27 48 00	98	1.09	9	0.75	2.61	105
Mean	70			98	0.98	9	0.70	2.51	123

Table 2. Distribution of annual primary production rates in the Sea of Marmara based on monthly or seasonal measurements in 1986. *Calculations are made using an average assimilation number of* 3.7 mg chl mgC h^{-1} *given by* Ryther *and* Yentsch (1957)

Region	Rates of annual primary production (gC m^{-2} y^{-1})
Northeastern Sea of Marmara	56–163 (ave. 104; 4.71–13.59 monthly)
Northern Sea of Marmara	6–41 (ave. 83; 0.51–34.26 monthly)
Central Sea of Marmara	25–185 (ave. 68; 2.09–15.42 monthly)
Southern Sea of Marmara	134 (ave.)
Outer Shelf	33–351 (ave. 107; 2.79–29.28 monthly)
Inner Shelf	27–558 (ave. 161; 2.58–46.50 monthly)
Southwestern Sea of Marmara	22–151 (ave. 64; 1.86–12.59 monthly)

Primary productivity rates were obtained by converting the chlorophyll-*a* measurements to gross primary productivity values using the method of Ryther and Yentsch (1957). Chlorophyll-*a* was determined after membrane filtration by the fluorimetric and photometric method of Yentsch and Mentzel (1963): no correction was made for phaeophytin-*a*. Chlorophyll-*a* surveys were conducted in the Sea of Marmara, from 1986 to 1990, on monthly or seasonal basis depending on many circumstances (rough sea conditions, availability of ship time etc.). To estimate bulk sedimentation rate, the empirical expression of Müller and Suess (1979) has been used, such that:

$$\%\ Org.\ C = \frac{0.003 \times R \times S}{Ps \times (1 - \phi)}.$$

Here *Org.C* is the percentage of total organic carbon in the sediment, *R* is the rate of annual primary production, *S* is the bulk sedimentation rate, *Ps* is dry density of sediment, and ϕ is the porosity.

The sediment accumulations rates were also determined from the activity of ^{210}Pb over its granddaughter ^{210}Po. For this purpose, subcores were taken from each box core of Stas BX-2, BX-3, BX-4, BX-5 and cut at 2–3 cm intervals and the samples were sent to Chemical Department of Middle East Technical University in Ankara. The alpha activity of ^{210}Po was counted with a silicon surface barrier detector (ORTEC BA-018-300-100). Accumulation rates were calculated from profiles of excess ^{210}Pb activity and the excess ^{210}Pb activity was determined by subtracting supported ^{210}Pb activity from the total measured ^{210}Pb activity. Details on the analytical procedures and further results of ^{210}Pb dating of the sediments discussed here are given elsewhere (Yildiz, 1992).

RESULTS AND DISCUSSION

Primary production rates in the Sea of Marmara

Significant variations occur in the regional distribution of average annual primary production rates in the Marmara waters (Table 2 and Fig. 2), mainly due to differences in the environmental setting and hydrography (Ergin *et al.*, 1992). For example, high values

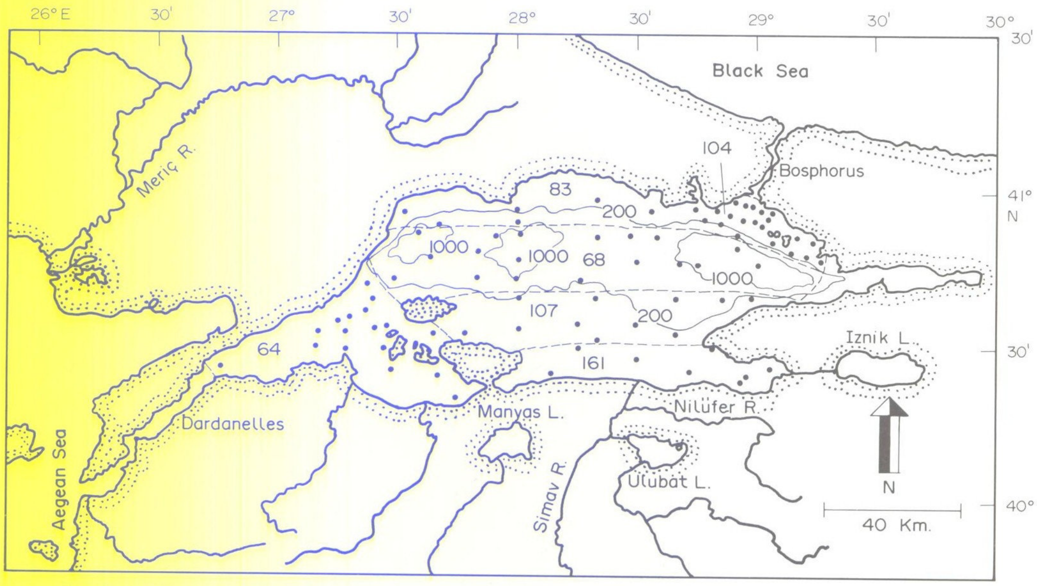

Fig. 2. Distribution of average annual primary production rates in the Sea of Marmara based on monthly or seasonally measurements in 1986. Calculations are made using an average assimilation number of 3.7 mg chl mgC h^{-1} given by RYTHER and YENTSCH (1957). Dots indicate locations of stations for chlorophyll-*a* measurements. For details see text.

were found in the southern and northeastern shelf areas of the Sea of Marmara (104–161 gC m^{-2} y^{-1}) while other regions show much lower levels (64–83 gC m^{-2} y^{-1}) (Fig. 2).

The highest rates found on the southern shelf may result from: conditions leading to supply of external nutrients by rivers; nearshore upwelling of nutrient-rich waters along the continental shelf/slope; regenerated–new production; and maybe to a lesser extent, from the anthropogenic influences (i.e. southerly located fertilizer industries) or some combination above. Occurrences of very high plankton density in shallower waters (<45 m depth) along the southern coasts (CEBECI and TARKAN, 1990) also confirms the high organic production in this region.

In general, increasing primary production is the dominant trend in nearshore/deltaic environments reflecting the important effect of river-derived nutrients as shown in many shelf regions of the world (e.g. SCHEMAINDA *et al.*, 1975; ROMANKEVICH, 1984). For example, in the eastern Arabian Sea, the maximum primary production was found in areas around the mouth of the Indus River (NAIDU, 1990). It is more likely that the influence of river discharge is of great importance along the southern Marmara coasts where there is large siliciclastic input (ERGIN *et al.*, 1991) and thus, it is reasonable to expect that higher proportion of terrestrial organic matter/nutrients would be introduced onto the southern Marmara shelf (ERGIN *et al.*, 1992). Here, the primary productivity rates gradually decrease offshore (Fig. 2): for example, the values vary from 161 on the southern inner shelf to 107 on the southern outer shelf and further to 68 gC m^{-2} y^{-1} in the deeper waters. On the other hand, the lower primary productivity rates (83 gC m^{-2} y^{-1}; Fig. 2) calculated for the northern Marmara shelf were about what would be expected from the absence of major rivers in the north, in contrast to the southern shelf with significant riverine inputs.

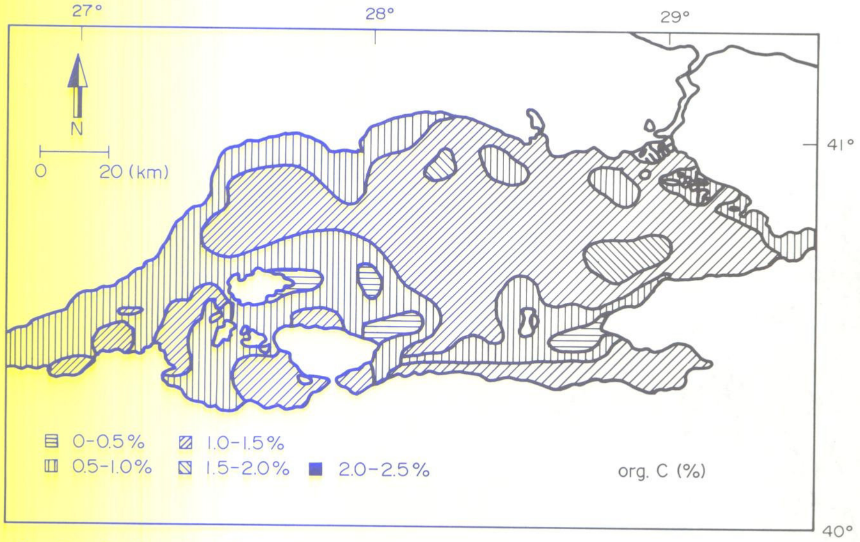

Fig. 3. Distribution of total organic carbon contents in surface sediments (0–6 cm) from the Sea of Marmara (after ERGİN *et al.*, 1992).

Although shelf regions can be sites of relatively high primary production due to coastal upwelling, as found off Benguela (CALVERT and PRICE, 1983), Peru–Chile (REIMERS, 1981) and in the Arabian Sea (NAIDAU, 1990), no good evidence is yet available to support this hypothesis in the southern Sea of Marmara but it remains a possibility (ERGİN *et al.*, 1992).

The differences in the primary productivity rates of between the northeastern (104 gC $m^{-2} y^{-1}$) and southwestern (64 gC $m^{-2} y^{-1}$) parts of the Sea of Marmara (Fig. 2) have been interpreted (ERGİN *et al.*, 1992) as results of the interactions between the organic-rich surface inflow from the Black Sea (52–250 gC $m^{-2} y^{-1}$: SOROKIN, 1983; GÖÇMEN, 1988) and organic-poor subsurface-inflow from the Aegean (36 gC $m^{-2} y^{-1}$: YILMAZ, 1986) or Eastern Mediterranean (16–25 gC $m^{-2} y^{-1}$: MURDOCH and ONUF, 1974; YILMAZ, 1986; GÖÇMEN, 1988). The resultant transport of organic matter from the Black Sea towards the Aegean Sea have already been recognized by ÜNLÜATA and ÖZSOY (1986), GÖÇMEN (1988), POLAT (1989) and ERGİN *et al.* (1991).

Sedimentary parameters

Total organic carbon contents of the sediments ranged from 0.76 to 1.90% by weight (Table 1); the lowest organic carbon values are generally confined to the Dardanelles approach of the Sea of Marmara (ave. 0.98%; Fig. 3) where organic- and nutrient-poor subsurface inflow from the Aegean or Mediterranean is prominent. The sediments from other parts of the Sea of Marmara showed slightly higher Corg contents (mainly between 1.08 and 1.22%, Fig. 3, Table 1) but do not seem to agree with the distribution of primary productivity rates in this sea (Figs 2 and 4). For example, a 2.5-fold increase in the primary productivity (from 64 to 161 gC $m^{-2} y^{-1}$) is accompanied by only a small increase of sedimentary organic carbon content (from 0.98% to 1.22%) by a factor of 1.2 in bottom sediments. Although, generally high accumulations of organic matter are known to occur

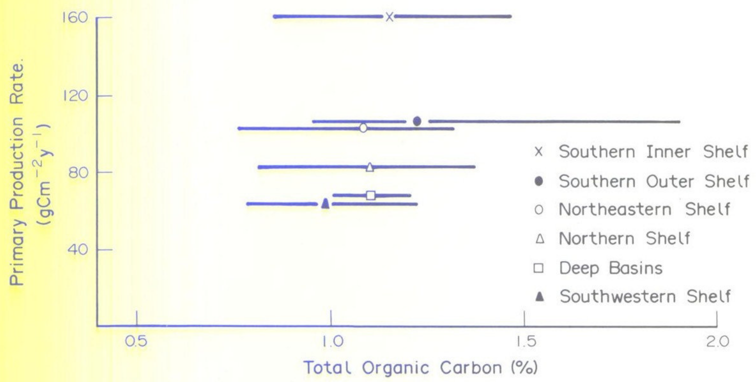

Fig. 4. Total organic carbon versus primary production rates (after ERGIN *et al.*, 1992). For details see text.

on the sea floor beneath the highly productive surface waters (e.g. NAIDAU, 1990), the results presented here indicate that the amount of organic material settling from the euphotic zone and reaching the sea floor show little relationship to production. This imbalance between primary production and sedimentary organic carbon in the Sea of Marmara seems likely to be because of the lateral transport of organic matter through the surface-outflow in view of particular oceanography of this sea (ERGIN *et al.*, 1991, 1992).

The sediment porosities were between 0.61 and 0.80 (Table 1), being generally low in the northeast (ave. 0.68) and high in the central deep basins (0.75). Otherwise, sediments showed porosities about 0.70–0.71 (Table 1). In general, the variations in the porosities of sediments are believed to represent slight variations in the lithology and texture (perhaps clay content).

The bulk solid densities of the sediments ranged between 2.20 and 2.92 g cm^{-3} (Table 1); they were generally high in the north (ave. 2.68 g cm^{-3}) and northeast (ave. 2.67 g cm^{-3}) and low in the remaining regions (ave. 2.51–2.57 g cm^{-3}). Since no data is available from central Marmara basins, an average value of 2.63 g cm^{-3} was taken which represents the southern and northern Marmara sediments (Table 1). Overall, the differences in the sediment densities in the study area are related to the variations in lithology, and maybe to some limited extent, to the type and degree of decomposition of organic matter prevailing in the sediment samples.

Sediment accumulation rates

Using the sedimentary parameters given in Table 1 and the Müller–Suess formula, based on sedimentary organic carbon and primary productivity data, the sediment accumulation rates have been calculated for the Sea of Marmara (Table 1; Fig. 5). Surprisingly, however, it has been found that sedimentation rates on the southern Marmara shelf seem unrealistically low (3–35 cm 1000 y^{-1}, except at Sta. K40K52 with 355 cm 1000 y^{-1}, Table 1) in view of river input and highest primary productivities (Fig. 2; Table 2) in this region. In particular, the inner shelf with relatively higher primary productivity rates (ave. 161 gC m^{-2} y^{-1}) showed the lowest sedimentation rates (ave. 8 cm 1000 y^{-1}) in contrast to the outer shelf where lower productivity values (107 gC m^{-2} y^{-1})

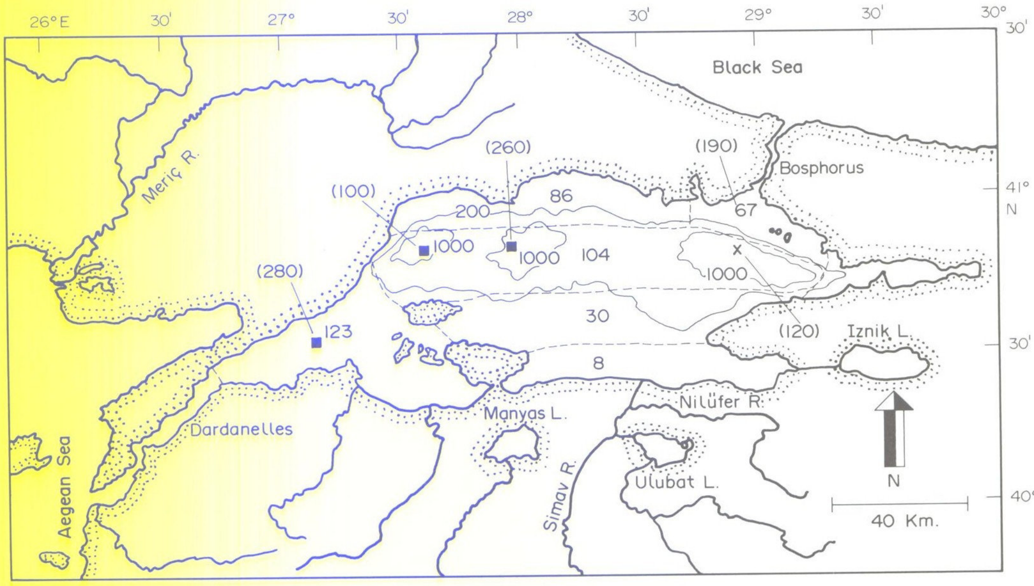

Fig. 5. Distribution of sediment accumulation rates (cm 1000 y^{-1}) in the sea of Marmara based on calculations using an empirical expression for the relationship between surface productivity and organic carbon content of sediment [MÜLLER–SUESS (1979) formula]. Sedimentation rates were also estimated using the ^{210}Pb method in core sediments and the resulting values are given in parenthesis. For sediment sampling stations see Fig. 1.

are accompanied by higher sedimentation rates (ave. 30 cm 1000 y^{-1}; Fig. 6). Unfortunately no sediment coring was done on the southern Marmara shelf to obtain any independent sediment accumulation rate data and to test this. Interestingly, the southern outer shelf (ave. 107 gC m^{-2} y^{-1}) and northeastern shelf (ave. 104 gC m^{-2} y^{-1}) regions

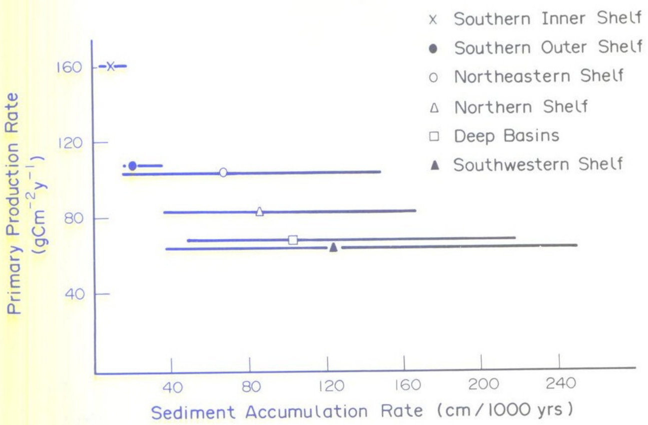

Fig. 6. Sediment accumulation rates (organic carbon-based) vs primary production rates. For details see text.

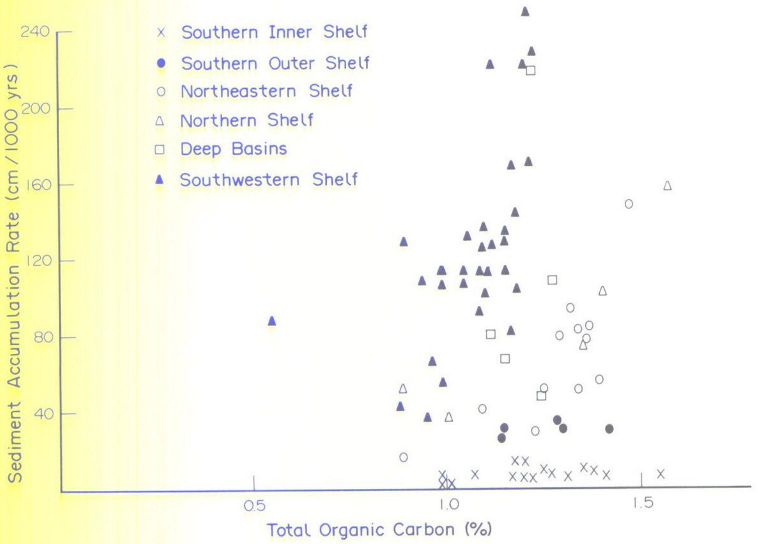

Fig. 7. Total organic carbon content in sediments vs sediment accumulation rates. For details see text.

of the Sea of Marmara were—with respect to primary production rates—at nearly the same levels, although the latter seems to be the site of much higher sedimentation rates (ave. 67 cm 1000 y^{-1}) when compared to the former, southern outer shelf (ave. 30 cm 1000 y^{-1}; Fig. 6). This means that perhaps considerable amounts of the primarily-produced organic matter must have been removed from the water column before reaching the bottom due to the prevailing surface outflow (i.e. through aggregation, flocculation, coaggulation etc.; McCave, 1975, 1984; Eisma and Kalf, 1979; Honjo and Roman, 1979), rapid microbial degradation (Tissot and Welte, 1978; Coleman *et al.*, 1979) or to the increase in grazing activities (Silver and Gowing, 1990) in this region. Also, organisms sinking and then adjusting their buoyancy can migrate upward and may cause loss in the particulate carbon fluxes (Angel, 1984; Harding *et al.*, 1987).

Therefore, it seems to be difficult to establish a trend between the organic carbon contents and sedimentation rates. In particular, such a trend is poorly defined on the southwestern shelf and in other regions that there is no significant relationship between the sedimentation rates and organic carbon contents (Fig. 7). All this suggests that the Müller-Suess formula is not suitable for application on these shelves of the Sea of Marmara is not suitable and hence it produces an answer which seems senseless.

The ^{210}Pb measurements in surficial sediments of a box core (BX-2) taken on the north-eastern shelf of the Sea of Marmara have revealed sediment accumulation rates of 190 ± 50 cm 1000 y^{-1} (Table 3) which are significantly higher than those calculated using organic carbon and primary productivity date (ave. 104 cm 1000 y^{-1}; Fig. 5). This clearly indicates that there exists no direct relationship between surface productivity, accumulation and burial of organic matter in these parts of the Sea of Marmara. The sedimentation rates from the northern shelf (ave. 86 cm 1000 y^{-1})—based on organic carbon and primary productivity data—were relatively higher than those from the southern shelf (ave. 8–30 cm 1000 y^{-1}), although the latter is known as sites of highest primary production in

Table 3. Estimated sediment accumulation rates in four box coring and one boomerang-gravity coring sites in the Sea of Marmara, based on ^{210}Pb *method. *Calculated from data in* Evans et al. (1989)

Core	Latitude N	Longitude E	Water depth (m)	Sediment accumulation rate (cm 1000 y^{-1})
BX-2	40 54.48	28 56.03	64	190 ± 50
BX-3	40 49.48	27 57.35	1226	260 ± 60
BX-4	40 48.26	27 36.35	1106	100 ± 10
BX-5	40 32.02	27 09.37	65	280 ± 60
M1*	40 48 15	28 51 30	1200	120 ± 20

this sea (Fig. 2). It was not possible to test these rates with independent radiometric data because no core sediment sample was available from this part of the sea for this purpose.

Using organic carbon and primary productivity data, somewhat high sedimentation rates have been calculated for the deep basins of the Sea of Marmara (68–109 cm 1000 y^{-1}, ave. 104 cm 1000 y^{-1}; Fig. 5), although these deep waters—together with the southwestern shelf (64 gC m^{-2} y^{-1})—are known to be sites of low primary production (68 gC m^{-2} y^{-1}; Fig. 2). To test this, sedimentation rates were determined from the ^{210} Pb method. In the deep waters of the Sea of Marmara, the ^{210}Pb-based sedimentation rates were, from eastern to central, and to western basins, 120 cm 1000 y^{-1} (Sta. M1; Evans *et al.*, 1989), 260 cm 1000 y^{-1} (Sta. BX-3), and 100 cm 1000 y^{-1} (Sta. BX-4), respectively (Table 3; Fig. 5). This indicates that, except for Central Marmara Basin, the calculated sedimentation rates, using both Müller–Suess formula (based on organic carbon and primary productivity data) and independent ^{210}Pb method, have revealed a fairly good agreement among the values obtained. It is not clear whether the highest ^{210}Pb based sedimentation rates from the Central Marmara Basin reflects increased sedimentation due to locally possible influences from gravity mass movements (slides, slumps, etc.), from shelf and slope down to the deep basin. There are some indications on seismic profiles obtained from the Sea of Marmara (Wong *et al.*, 1992) that due to neotectonics and associated recent gravity/turbidity, downslope sediment mass movements occur beneath the deep waters of this sea.

More surprisingly, however, is that the highest sedimentation rates (37–248 cm 1000 y^{-1}, ave. 123 cm 1000 y^{-1}), based on organic carbon and primary productivity, occur on the southwestern Marmara shelf where primary production rates are very low (ave. 64 gC m^{-2} y^{-1}; Fig. 6). The overall high sedimentation rates in this part of the Sea of Marmara have also been confirmed by the results of the ^{210}Pb method (280 ± 60 cm 1000 y^{-1}; Fig. 5), which can probably be explained by the effects of particular oceanographic processes prevailing in this part of the sea. From this it appears, that a considerable amount of particulate matter (both organics and inorganics) leaving the greater Marmara Basin via the surface- or near-surface-outflow should have been trapped and transported back to the southwestern shelf, mainly at the Strait of Dardanelles approach, by the subsurface inflow of Aegean or Eastern Mediterranean waters. This might have resulted in the increased accumulation of sedimentary materials in the northwestern Sea of Marmara, a fact which finds further support by the results of Bodur (1991) and Ergin *et al.* (1991) who emphasized the increased sedimentation by fine materials with increasing distance from

Table 4. Organic carbon- and primary production-related sediment accumulation rates in the Sea of Marmara. Possible effect of compaction on the calculation of rates during sediment sampling are also considered

	Northeastern Marmara Shelf	Northern Marmara Shelf	Central Marmara Basins	Southern Marara (Inner Shelf)	Southern Marmara (Outer Shelf)	Southwestern Marmara Shelf
Average porosity	0.68	0.71	0.75	0.71	0.71	0.70
Sediment rate	67	86	104	8	30	123
Minimum porosity	0.64	0.65	0.68	0.62	0.65	0.61
Sediment rate	97	179	218	20	98	295
Maximum porosity	0.72	0.75	0.80	0.78	0.74	0.75
Sediment rate	42	58	46	3	36	67
Corrected average porosity	0.78	0.81	0.85	0.81	0.81	0.80
Sediment rate	19	23	18	2	13	32

the Strait of Dardanelles towards the open sea, the eastern Marmara basins. Effects of porosity on the calculation of sedimentation rates.

It should be noted that recent marine sediments of mud types principally undergo compaction, hence a porosity reduction during the sample recovering, a fact which needs to be taken into account for calculation of sediment accumulation rates.

During the 1988 cruise of R.V. *Knorr* in the Sea of Marmara, it was found that the volume of the muddy surface sediments (top 5–10 cm sections of the box cores) was reduced by approximately 10–15% while inserting the PCV core tubes (12 cm in diameter for taking subcores) into the undisturbed box core, down to 5–10 cm depths below the surface. A compaction of up to 20% was observed while inserting the entire core tubes (50 cm) down to the base of the core box. No such experiments were made onboard the R.V. *Bilim* during the sampling of surface sediments (top 4–6 cm of the sea floor) by using a grab sampler but our former observations suggest that it is reasonable to assume a volume reduction of probably no more than 15%. This would require—for the calculation of sedimentation rates using the Müller–Suess formula—a correction of approximately 0.10, a value which should be added to the porosity values given in Table 1.

The resulting corrected average porosity values for each of the studied sub-regions of the Sea of Marmara are given in Table 4. It has been shown that changes in the porosity values may cause significant fluctuations in the sedimentation rates, although the inter-relations remain the same among the values. Based on the new estimates (porosity-corrected), the sediment accumulation rates in the Sea of Marmara are found to range between 2 and 32 cm 1000 y^{-1}, values considerably lower than those from uncorrected estimates (8–123 cm 1000 y^{-1}, Table 4). Thus, the importance of porosity is further emphasized. For example, a porosity range between 0.65 and 0.75 measured for the southwestern shelf sediments of the Sea of Marmara would produce a shift in the sedimentation rates from 40 to 240 cm 1000 y^{-1} (Fig. 8).

Consequently, if corrected for compaction ("porosity reduction") by about 15% for the upper 10–20 cm sections of box cores, the ^{210}Pb-based sediment accumulations rates would then be 218 cm 1000 y^{-1} for the box coring site BX-2 (northeastern shelf), 299 cm 1000 y^{-1} for the box coring site BX-3 (Central Marmara Basin), 115 cm 1000 y^{-1} for box coring site BX-4 (Western Marmara Basin), and 322 cm 1000 y^{-1} for the box coring site BX-5 (southwestern Marmara shelf). Thus, the ^{210} Pb-based sedimentation rates for the Eastern Marmara Basin (Evans *et al.*, 1989) would be about 138 cm 1000 y^{-1}, considering a porosity correction of about 15%.

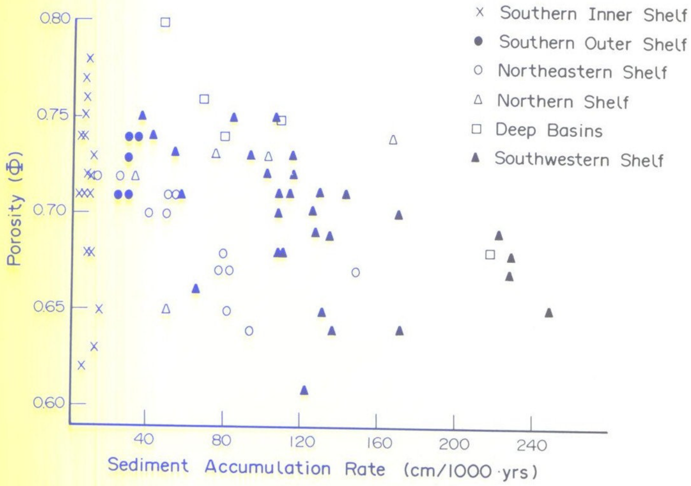

Fig. 8. Sediment accumulation rates (organic carbon-based) vs porosity. For details see text.

*Table 5. Estimated sediment accumulation rates in four gravity coring sites from the eastern Marmara basin, based on ^{14}C method. *Calculated from data in* STANLEY *and* BLANPIED (1980)

Core	Latitude N	Longitude E	Depth (m)	Depth from core top (cm)	Age (y BP)	Sediment accumulation rate (cm 1000 y^{-1})
P6507-G6*	40 40.8′	28 33.0′	384	15–25	5900	3.38
				100–110	13530	7.76
P6507-G7*	40 45.5′	28 46.5′	1193	50–60	Recent	18.30
				100–110	4970	21.00
P6507-G8*	40 44.5′	29 01.8′	1209	50–60	4755	10.51
				100–110	5470	12.00
P6507-G9*	40 44.0′	29 15.4′	795	25–37	5660	5.47
				60–70	6800	9.55

Comparisons with the ^{14}C data

Table 5 shows the calculated sediment accumulation rates based on radiocarbon (^{14}C) data obtained from gravity cores which were taken during the 1965 cruise of R.V. *Pillsbury* in the Eastern Marmara Basin (STANLEY and BLANPIED, 1980). The estimated sedimentation rates in the eastern Marmara Basin, based on ^{14}C measurements, ranged between 3 and 21 cm 1000 y^{-1}, being relatively high in deeper waters (12–21 cm 1000 y^{-1} at 1193 and 1209 m depths due to increased deposition from the gravity mass movements on shelf and upper slope) and low in shallower waters (3–9 cm 1000 y^{-1} at 384 and 795 m depths). These rates are found to be very low compared to results from ^{210}Pb dating (Sta. M1; 120 cm 1000 y^{-1}; Table 3). As expected, this suggests, that the estimates of sedimentation rates would not work on the basis of organic matter/carbon data (using both Müller–Suess formula and ^{14}C method) in the Sea of Marmara, an area with distinctive and special oceanography.

CONCLUSIONS

Sediment accumulation rates in the Sea of Marmara were calculated using the Müller–Suess formula (based on calculation from the sedimentary organic carbon and annual primary production data) and ^{210}Pb method.

From the results presented here, it is concluded that the calculated sedimentation rates—based on sedimentary organic carbon and annual primary production data—were generally low (ave. 8–123 cm 1000 y^{-1}) and do not hold for the rates of primary organic production and the content of the buried organic matter within the sediment in this sea. This is particularly true, for the calculated high sedimentation rates (ave. 123 cm 1000 y^{-1}) which were found on the southwestern shelf where the annual primary production is very low; similarly, for the low sedimentation rates (ave. 8 cm 1000 y^{-1}) which were determined for the southern inner shelf where the annual primary production (ave. 161 cm 1000 y^{-1}) is the highest in the entire area. This apparent lack of relationship between surface productivity and organic content of the sediment is most likely caused by the distinctive and peculiar oceanography of the Sea of Marmara: well stratified flow, strong lateral movements within the water column and possible variations in the conditions for mineralization of organic matter within the sediment.

Much higher sedimentations rates were obtained for the Sea of Marmara using the ^{210}Pb method (100–280 cm 1000 y^{-1}). It is also shown that the results from independent, ^{210}Pb activities are generally higher than those based upon the organic carbon-based calculations. This further confirms that a significant amount of the primarily-produced organic matter is lost in the overlying matter and/or within the sediment.

Finally, it is clear from the results of this study that the Sea of Marmara seems to be a hopeless area to attempt to apply the Müller–Suess (1979) formula and indicates that the primary production rates and sedimentary organic carbon contents should be used with great care as to calculate the rates of sediment accumulation in shelf areas especially regions with such a two-layer flow systems. Future work should therefore be directed toward obtaining more ancillary information on the particulate carbon fluxes as related to the prevailing hydrographic conditions and on the sedimentation rates using various radiometric techniques in the different parts of this sea.

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