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SEDIMENT CORE STUDIES ON THE NORTH ANATOLIAN FAULT ZONE IN THE EASTERN SEA OF MARMARA: EVIDENCE OF SEA LEVEL CHANGES AND FAULT ACTIVITY

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ABSTRACT.- Sediment cores BUC-10A and İZ-30 located on the North Anatolian Fault Zone (NAFZ), 12 km south of Büyükçekmece and İzmit Gulf in the eastern part of the Sea of Marmara, respectively, were studied to investigate tectonics and paleo-oceanographic processes, using sedimentological and geochemical methods. Total inorganic carbon (TIC as total calcium carbonate) and total organic carbon (TOC) contents in core BUC-10A range between 12.1-34.3 and 0.5-4.1 dry wt. %, respectively. The organic matter-rich sapropel unit was identified between 1.60 and 2.43 m below sea floor (bsf) in this core. The concentration ranges of the metals in core BUC-10A were: Cr: 55-96, Cu: 21-37, Ni: 63 39-74, Mn: 345-693, Pb: 19-34, Zn: 79-143 ppm and Fe: 2.30-3.15 dry wt. %. The concentration ranges of TOC, TIC, Cr, Cu, Fe, Ni, Mn, Pb and Zn in core İZ-30 were 0.40-1.70 %, 0.25-31%, 39-87 ppm, 13-32 ppm, %2.10-4.80, 18-41 ppm, 315-528 ppm, 7-21 ppm and 78-185 ppm, respectively. Chalcophile element (Fe, Mn, Cu, Pb, and Zn) concentrations in cores İZ-30 and BUC-10A give no evidence of hydrothermal activity. A debris flow characterized in core İZ-30 and dated 3276±48 a (calendar) before present (BP) was most likely triggered by tectonic activity in the İzmit Gulf. Sediments of 49.5 mbsf palaeo-shoreline dated 9364±64 a BP was also identified in the same core from the İzmit Gulf.

Key words: Sea of Marmara, Sea level change, North Anatolian Fault, hydrothermal activity, submarine mass flow.

INTRODUCTION

Sea of Marmara is connected to the Mediterranean and Black Sea via the Turkish Straits. Therefore, the Sea of Marmara has a two-layer water stratification and flow system, which separates the more saline (37.5 - 38.5 ppt) lower water layer of Mediterranean origin from the less saline upper layer of the Black Sea origin (18 - 22 ppt) (Ünlüata et al., 1990; Beşiktepe et.al., 1994). This different salinity creates a two-way system of reciprocal flow. Therefore the Sea of Marmara contains the records of climatic and tectonic changes of itself, adjacent seas and the surrounding land mass. The previous cores studies in the Sea of Marmara have indicated that the Sea of Marmara sediments deposited in the last 20 ka can be subdivided into two units according to fossil contents (Çağatay et al., 1999, 2000). The upper Unit 1 has was deposited under marine conditions after the arrival of the Mediterranean water at about 12 kyr BP, and the lower Unit-2 was deposited under lacustrine conditions (Çağatay et al., 2000, 2003; Abrajano et al., 2002; Mc Hugh et al., 2008).

Geometry, kinematics and seismic activity of the North Anatolian Fault (NAF) beneath the Sea of Marmara have been studied by many workers (Alpar 1999; Halbach et al., 2000, 2002; Gürbüz et al., 2000; McClusky et al., 2000; Okay et al., 2000; İmren et al., 2001; Gökaşan et al., 2001, 2002, 2003; Le Pichon et al., 2001, 2003; Rangin et al., 2001, 2004; Armijo et al., 2002, 2005; Alpar and Yaltırak 2002; Meade et al., 2002; Polonia et al. 2002, 2004; Yaltırak, 2002; Demirbağ et al., 2003). Although past mass flow and cold seep activities (Patzold et al., 2000; Sarı 2004; Kuşçu et al., 2005; Sarı and Çağatay 2006; Mc Hugh et al., 2006, Beck et al., 2007, Zitter et al., 2008)

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and tsunami events (Alpar et al., 2003, 2004; Hebert et al., 2005; Altınok and Alpar 2006; Tinti et al., 2006) have been reported from the Sea of Marmara, there is insufficient information on the effects of the NAF activity on the geochemistry of the Sea of Marmara sediments (Halbach et al., 2000, 2002; Armijo et al., 2005; Kuşçu et al., 2005; Zitter et al., 2008; Kuşçu et al., 2009). These geochemical studies mostly concentrated on the surface expression of cold seeps along the main Marmara fault. It would be expected that during a seismic event, the transpressional segments would release fluids, whereas the transtensional would be mainly areas recharge and deep circulation. It would also be assumed that the exiting fluids would react with the sediments causing significant changes in the composition.

In this paper sedimentological and geochemical properties of sediments related to the NAF activity and paleo-oceanographic changes, such as tectonic uplift, mass flows, hydrothermal activity, diagenetic changes and sea level changes were studied in two cores located on the northern strand of the NAF Zone (Figure 1). The cores İZ-30 and BUC-10A were recovered off the Hersek delta in the İzmit Gulf and from 12 km south of Büyükçekmece during the RV Urania cruise in 2001. The cores were studied using geochemical (TOC, TIC and heavy metals analysis) and sedimentological methods.

METHODS

Gravity cores İZ-30 and BUC-10A are 3.50 and 3.6 m long, and recovered from -46.2 and-380 m respectively. The cores were split into two halfs in laboratory and lithologically described. They were then subsampled at about 5 cm intervals, also taking into account the lithological variation. TIC, TOC and the total heavy metal content of the core samples were carried out at the Istanbul University Institute of Marine Science and Management Laboratories.

TIC content was determined using a gasometric method. This method is based on the volumetric determination of CO_2 released by acidification of the dry ground subsample with 10% HCl. The results are expressed as weight percentage of $CaCO_3$ (Loring and Rantala, 1992).

TOC analysis was performed using the Walkley - Black method, which involves the titration with ferrous aluminium sulphate of the dichromate left after a wet combustion of the sample with potassium dichromate (Gaudette et. al., 1974; Loring and Rantala, 1992).

For metal analysis, the sediment sample was treated with 10 ml HNO_3 at 120°C in an open teflon beaker for 30 min. and then heated with 5ml $HClO_4$ and 5 ml HF in closed teflon beaker for 30 min. After the formation of dense white fumes, the cover was removed to allow the $HClO_4$ to evaporate. To further digest the resistant particles, 5 ml of HF was added and the mixture allowed refluxing for a further 30 min. The remaining solution was evaporated on a hot plate at 180°C to obtain dry residues, which were redissolved in 10 ml of 1M HCl, and then diluted to 50 ml with 1M HCl and stored in a pre-cleaned plastic bottle in a deep freezer (Loring and Rantala 1992; Tessier et. al. 1979). All metals were determined by flame Atomic Absorption Spectrophotometer (AAS) after the total digestion.

Accelerated Mass Spectroscopic (AMS) ^{14}C age determination was carried out at the Woods Hole Oceanographic Institution's NOSAMS facility. Hand-picked and ultrasonicated benthic foraminifers collected from immediately below individual sediment layers were used for the analysis (Table 1). Ages were calculated as ^{14}C a BP, corrected for ^{13}C, and the error expressed as $\pm 1\sigma$. Calibrated calendar ages with a reservoir correction of 385 a (Siani et al. 2000) were calculated according to Stuiver and Braziunus (1993) reported as calendar a BP.

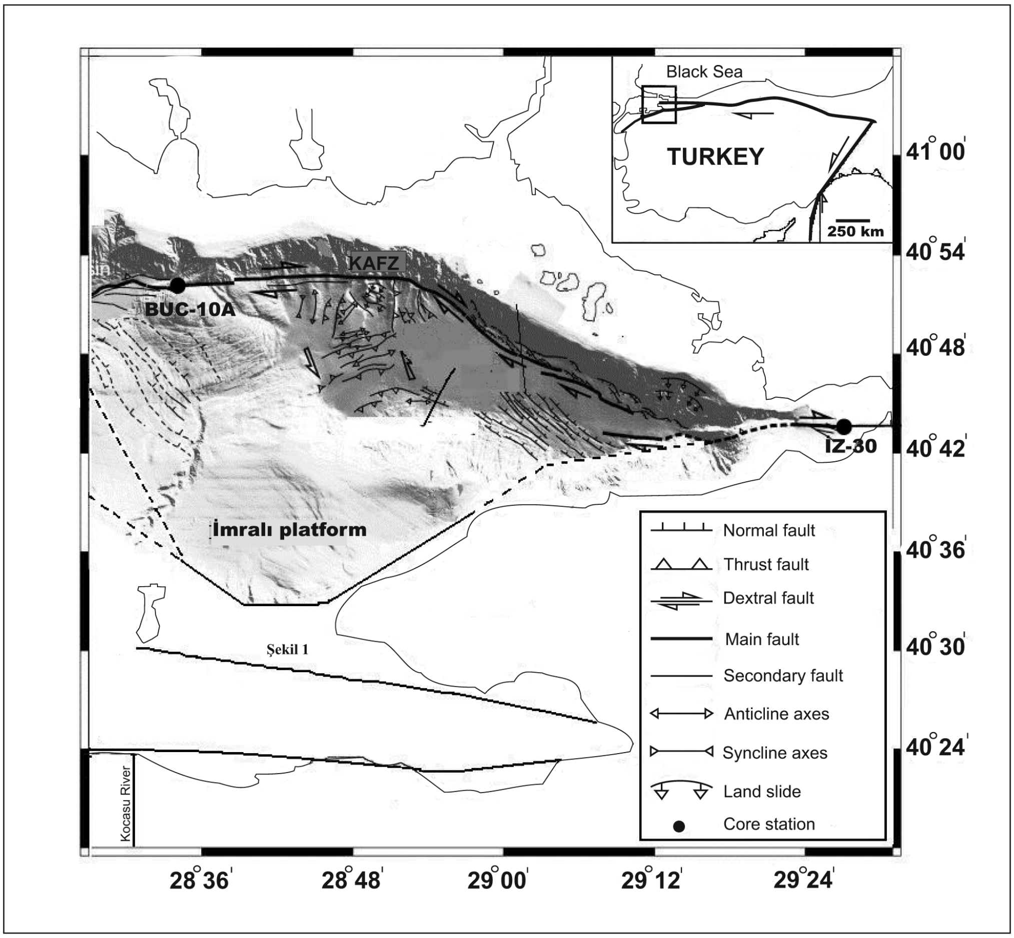

Figure 1- Bathymetric and fault map of Sea of Marmara, showing the core locations.

Table 1- Radiocarbon and calibrated ages for selected samples in the core İZ-30.

Core number	Level (cm)	Material	^{14}C date	Calibrated year (Calendar year)
İZ-30	223-224	Foraminifer	3455 ± 35	3276 ± 48
İZ-30	330	Mollusc	8740 ± 64	9364 ± 64

RESULTS

Lithological identification of cores

The sedimentary section in Core İZ-30 is composed of brown mud (0 - 0.70 mbsf), yellowish green mud (0.70-1.35 mbsf), greyish-green mud (1.35 - 1.72 mbsf) and dark grey green mud (1.72-2.09 mbsf). Bioturbation with whole and broken bivalve shell fragments are present at 0.39 - 0.47 mbsf and 1.72 - 1.90 mbsf intervals in the core (Figure 2). Alternations of dark green, fine sandy silt and mud lamina occur between 2.09 and 2.24 mbsf in core İZ-30. A poorly sorted fossil-rich sandy silt layer with sharp lower and upper contacts is present between 2.24 and 2.50 mbsf below the laminated unit. This unit presents the characteristics of mass flow. The AMS ^{14}C determination from foraminiferal tests just above its upper contact produced an age of 3276±48 a (calendar) BP. The 2.50 and 3.30 mbsf interval of Core İZ-30 consists of dark grey green mud that has a sharp lower contact with a 0.13 m thick dark green fine gravely silty sand unit. The gray gravelly sand unit contains Turritella turbana, and other marine bivalve shells and shell fragments. AMS ^{14}C age of an articulated marine bivalve at 3.30 mbsf above the sand layer gave an age of 9364±64 a (calendar) BP. The basal part of the core consists of 7 cm-thick dark green mud.

Core BUC-10A located 12 km offshore Büyükçekmece consists of two units (Figure 3). The upper Unit 1 is 2.70 m-thick and has been deposited under marine conditions. The uppermost 0.03 mbsf part of the unit consists of light brown mud, which is followed downward to 0.6 mbsf by light green homogeneous mud with gas voids. The middle part of Unit 1 between 0.60-0.72 mbsf and 2.43-2.64 mbsf in Core BUC-10A is composed of dark green homogenous mud, which contains black reduced spots and bands between 0.72 and 1.60 mbsf. The interval between 1.60-2.43 mbsf of the dark green mud is a sapropelic unit having a sharp upper and lower contact. The basal part of Unit 1 between 2.64 and 2.70 mbsf in core BUC-10A is laminated brown mud. Unit 2 constitutes the interval between 2.70 -3.60 mbsf, and was deposited under lacustrine conditions prior to 12 ka BP according to previous researchers (e.g., Çağatay et al., 2000). Unit 2 consists of greyish green mud that includes black coloured and lenticular iron monosulfide bands. No macro fossils have been found in the lacustrine unit of Core BUC-10A.

The distribution of organic carbon and total carbonate in core sediment

TOC concentration of İZ-30 varies between 0.40 and 1.70 dry wt. %. High organic carbon values (>1.0 dry wt. %) are observed at intervals; 0-0.18, 0.55-0.63, 1.35-1.43 and 1.76-2.24 mbsf. The average organic carbon value of the total 71 samples from Core İZ-30 is 1.05 dry wt.%. TIC contents vary from 0.25 to 31.10 dry wt. % (as $CaCO_3$) (Figure 4). The main part of the carbonate in the core is of biogenic origin consisting of benthic carbonate shells and shell fragments. The down core distribution pattern of total carbonate content commonly displays a narrow range (0.25 -14.20 %) in core İZ-30 with the exception of intervals 2.36-2.37 (22.90%) and 3.30-3.33 mbsf (31.10%) (Figure 4).

The concentration of TOC in the Core BUC-10A ranges from 0.5 to 4.1 dry wt.% (Figure 5). The highest TOC values are found at 1.60-1.63 mbsf and 1.70-1.73 mbsf. All the TOC values in the dark green sapropelic mud between 1.60 and 2.43 mbsf is higher than 2 dry wt.%. The concentration of TIC in Core BUC-10A ranges from 12.10 to 34.30 dry wt.% as $CaCO_3$ with a downward increase from the core top to a maximum value at 2.83 mbsf (Figure 5). The TIC values decrease downward from its maximum at 2.83 mbsf and reach 19.30 dry wt. % at 3.53 m.

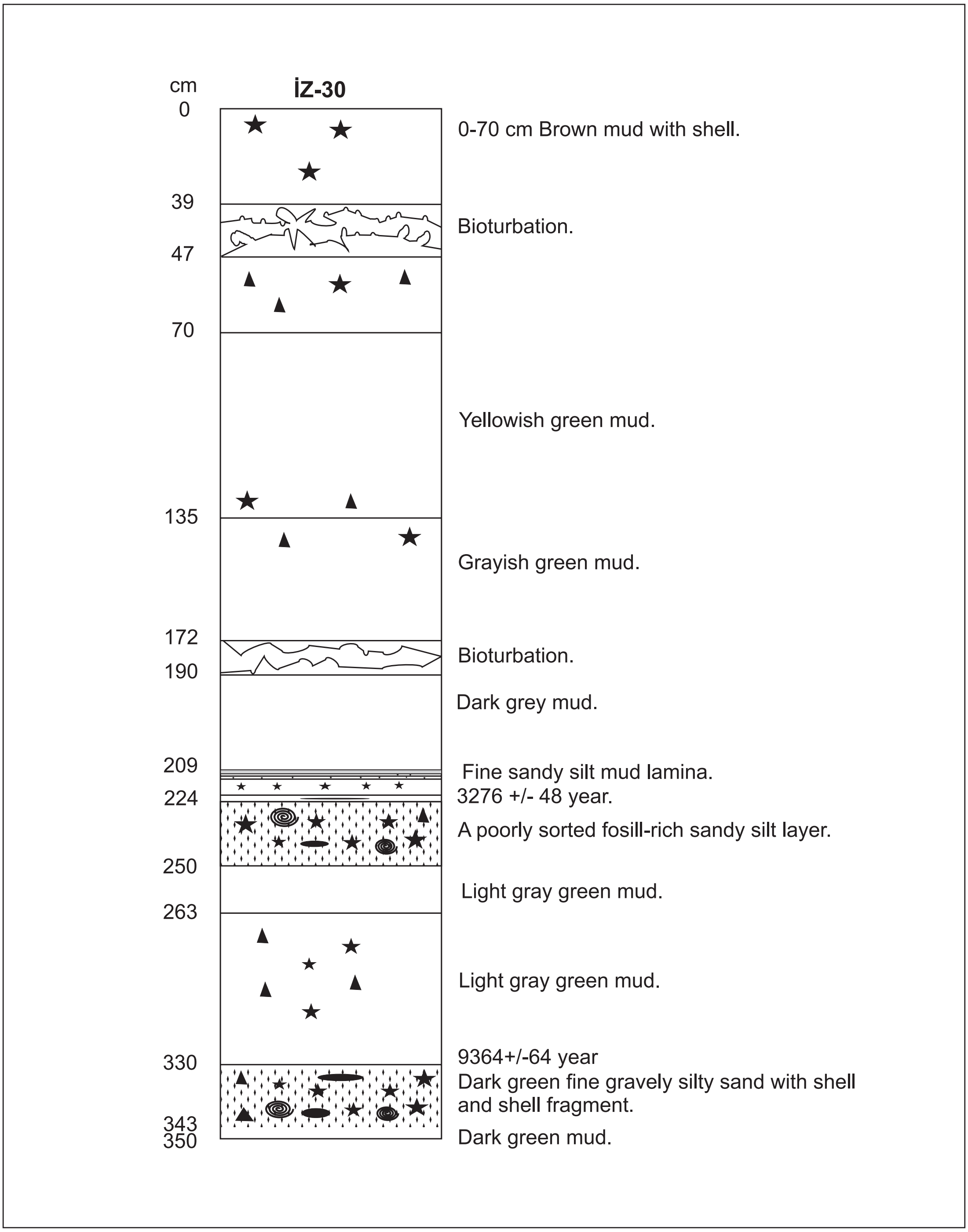

Figure 2- Lithologic log of gravity core İZ-30.

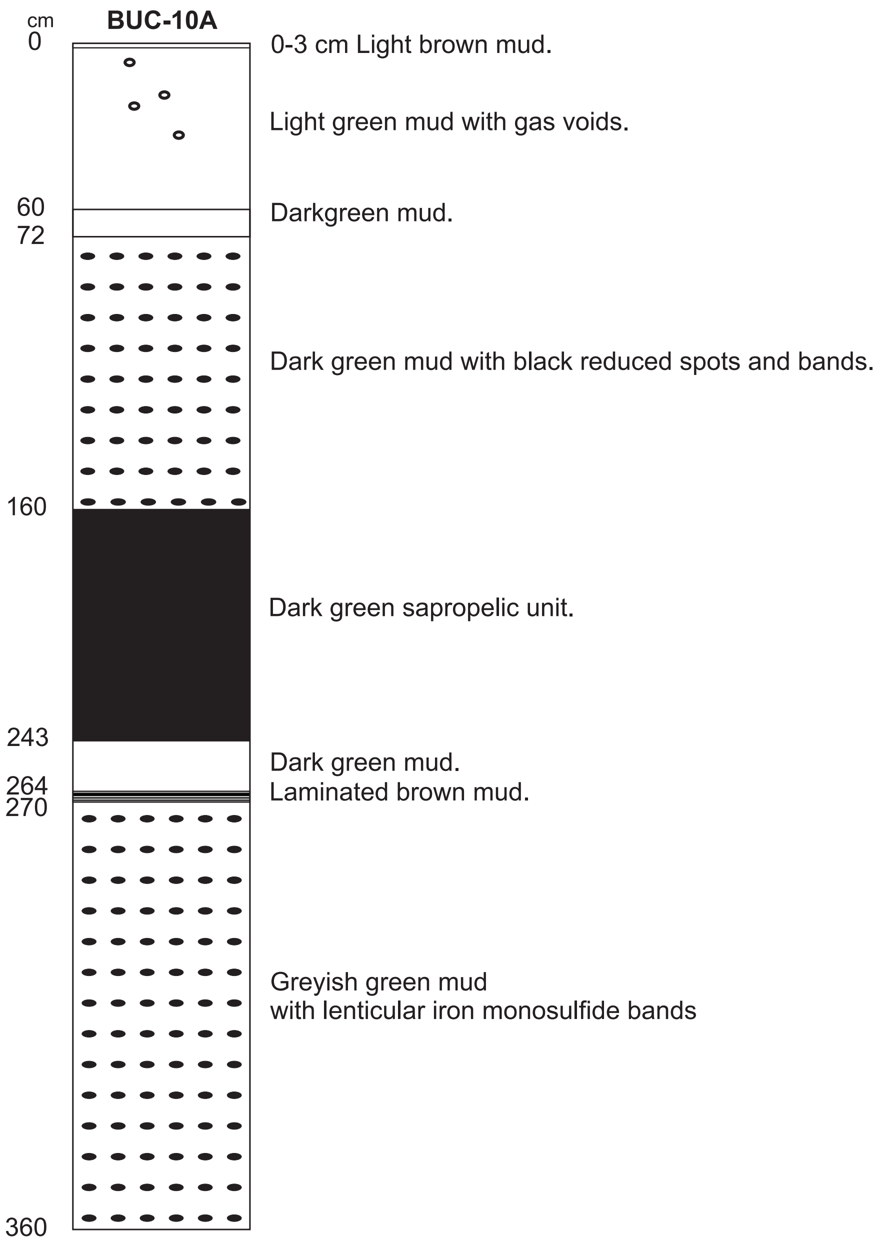

Figure 3- Lithologic log of gravity core BUC-10A.

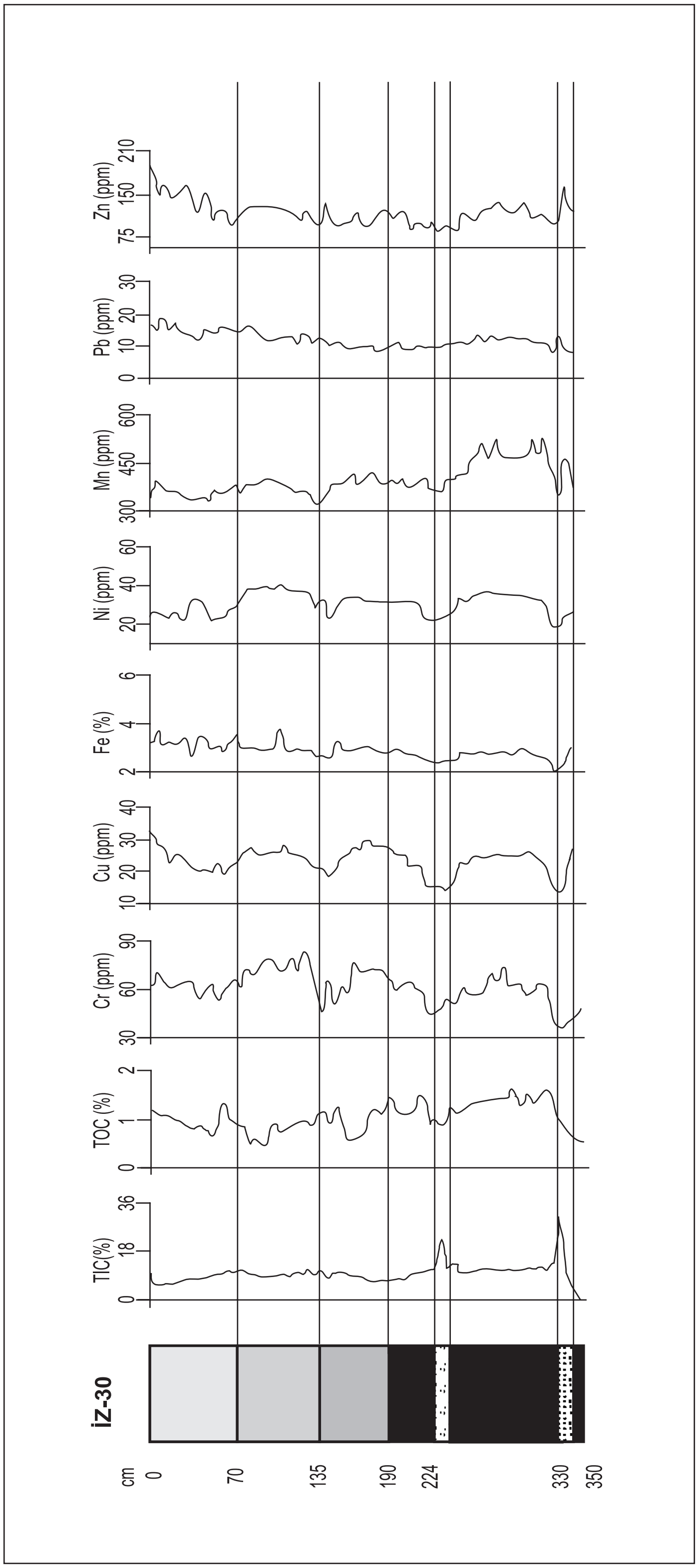

Figure 4- Distribution of TOC, TİC and metal contents in core İZ-30.

Distribution of Cr, Cu, Fe, Ni, Mn, Pb and Zn in cores

Cr, Cu, Fe, Mn, Ni, Pb and Zn contents were determined in a total of 71 sediment samples which were collected from core İZ-30. The heavy metal contents in this core range between 39-87 ppm Cr, 13-32 ppm Cu, 2.10-4.80 % Fe, 315-528 ppm Mn, 18-41 ppm Ni, 7-21 ppm Pb and 78-185 ppm Zn. The average concentration of the metals are 65 ppm for Cr, 23.50 ppm for Cu, 3% for Fe, 393 ppm for Mn, 31 ppm for Ni, 12 ppm for Pb and 112 ppm for Zn (Figure 4). The distribution of the Cr, Cu and Ni along Core İZ-30 shows similar trends (Figure 4). This similar behaviour is supported by significant positive correlation coefficients (r>0.5) between the metal values. The Fe, Mn, Pb and Zn contents display negative or weak positive correlation coefficients with TIC and TOC (Table 2). The heavy metal contents of sediments in Core İZ-30 are commonly lower than the shale averages (Krauskopf 1985), except for Zn, which is slightly higher.

Cr, Cu, Fe, Ni, Mn, Pb and Zn were determined in 37 sediment samples in Core BUC-10A (Figure 5). Mean values and variation ranges (in parentheses) of these elements are 80 ppm (55-96 ppm) Cr, 27 ppm (21-37 ppm) Cu, 2.75 % (2.30-3.15 %) Fe, 468 ppm (345-693 ppm) Mn, 63 ppm (39-74 ppm) Ni, 15 ppm (9-34 ppm) Pb and 118 ppm (79-143 ppm) Zn. All analyzed metal concentrations in core BUC-10A are lower than their worldwide shale averages (Krauskopf, 1985) except for Zn which is 1.43 times the shale average. Cu, Cr and Pb concentrations are the highest at the top 0.03 m part of the core, whereas the lowest metal values are observed at 2.80 - 3.00 mbsf interval which is characterized by the high amount (>30% $CaCO_3$) of total carbonate (Figure 5). The correlation coefficient matrix of metals, TIC and TOC were given in the table 3. Significant positive linear correlation coefficients are observed between the following pairs: Zn-Cu (r=0.74), Cr-Ni (r=0, 68), Ni-Fe (r=0.55) and Pb-Zn (r=0.52). Other elements display negative or weak positive linear correlations with each other.

DISCUSSION AND CONCLUSIONS

Possible effects of fluid activity on sediment composition along the fault

Being located on the NAF, the sediments in the cores İZ-30 and BUC-10A would be expected to have been affected by deformation and fluid activity, leaving some geochemical and sedimentological signatures. Ore group elements of Ba, Co, Cu, Ni, Pb, V and Zn are commonly enriched in hydrothermal sediments deposited close to active submarine fault zones (Hodkinson and Cronan, 1995; Gamberi et al, 1997; Kuhn et al, 2000). In the Lau Basin of the southwest Pacific, Cronan and Hodkinson (1997) have determined accumulation rates of 32.000 µg Mn cm^{-2} ka^{-1}, 52.100 µg Fe cm^{-2} ka^{-1}, 604 µg Ba cm^{-2} ka^{-1}, 234 µg V cm^{-2} ka^{-1}, 29 µg Co cm^{-2} ka^{-1}, 109 µg Ni cm^{-2} ka^{-1}, 266 µg Cu cm^{-2} ka^{-1}, 125 µg Zn cm^{-2} ka^{-1} ve 44 Pb µg cm^{-2} ka^{-1}. These studies indicate that hydrothermal sediments are highly enriched in Fe, Mn, Cu, Zn, and Pb. Such metal enrichments are not observed in sediments cores İZ-30 and BUC-10A located on the northern strand of the NAF (Figure 4, 5). Instead the metal values are represent concentration levels of semi-pelagic sediments. Zinc enrichment in the upper part of the cores (0-0.5 mbsf) is explained by anthropogenic inputs. Thus, it can be concluded that no hydrothermal fluid activity is present at the sites of cores İZ-30 and BUC-10A. Meriç and Suner (1995) and Meriç et al., (1995), based on the analysis of benthic foraminifers in the borehole samples between the Hersek Burnu and Kaba Burun promontories in the İzmit Gulf suggests some chemical changes in the tests that are possibly the result of fluid activity. This conclusion is supported by the fact that an increase in gas bubbles released into the water column was observed in the İzmit Gulf after the 1999 Kocaeli

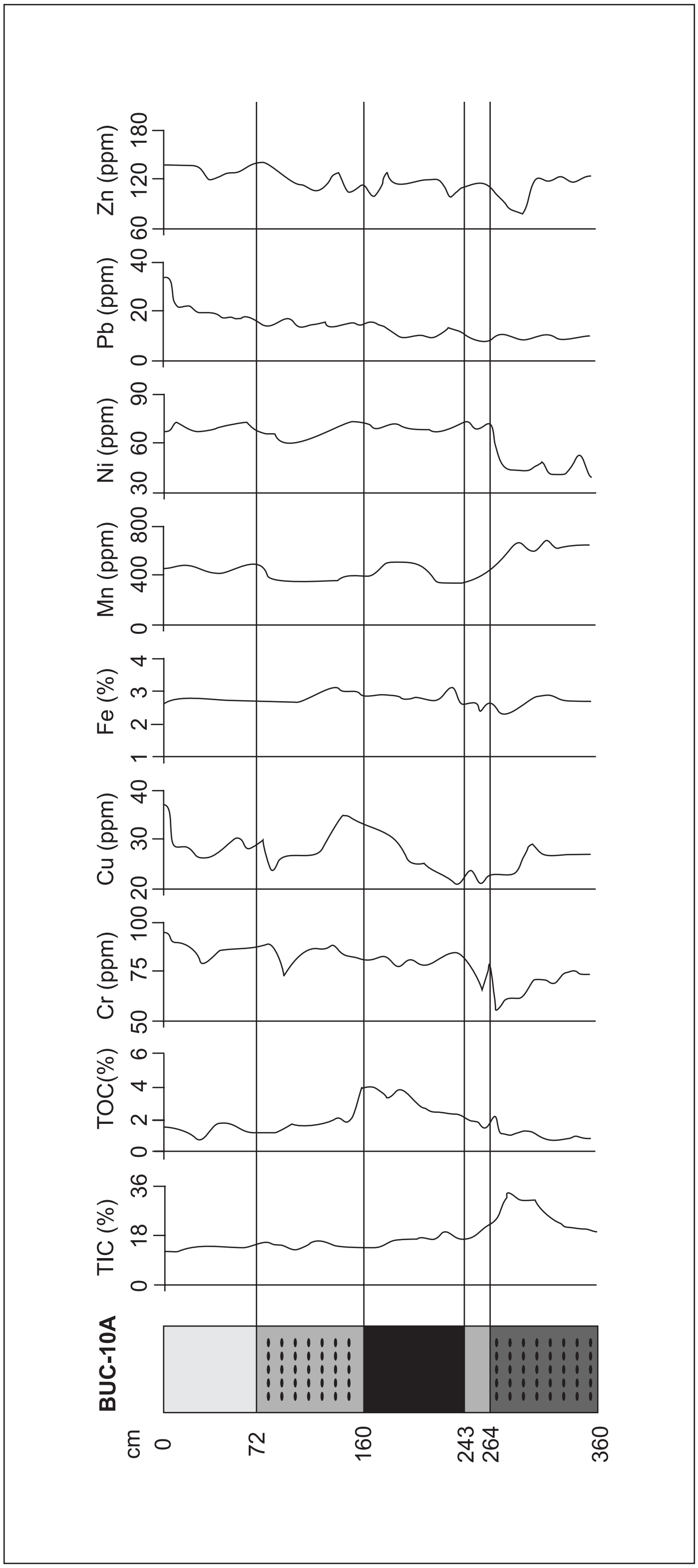

Figure 5- Distribution of TOC, TİC and metal contents in core BUC-10A.

Table 2- Correlation coefficients between parameters in sediments samples from core İZ-30.

	Mn	Fe	Cu	Ni	Pb	Cr	Zn	TOC	TIC
Mn	1								
Fe	-0.24	1							
Cu	0.16	0.51	1						
Ni	0.31	0.20	0.56	1					
Pb	-0.26	0.53	0.32	0.02	1				
Cr	-0.01	0.51	0.73	0,71	0.31	1			
Zn	0.29	0.41	0.33	-0.04	0.65	0.20	1		
TOC	0.47	-0.15	0.08	0.08	-0.11	-0,02	-0.06	1	
TIC	0.26	-0.54	-0.44	-0.14	-0.30	-0.32	-0.34	0.17	1

Table 3- Correlation coefficients between parameters in sediments samples from core BUC-10A.

	Mn	Fe	Cu	Ni	Pb	Zn	Cr	TOC	TIC
Mn	1								
Fe	-0.22	1							
Cu	-0.03	0.36	1						
Ni	-0.73	0.37	0.31	1					
Pb	-0.23	0.12	0.59	0.41	1				
Zn	-0.13	0.26	0.36	0.33	0.54	1			
Cr	-0.53	0.37	0.45	0.70	0.62	0.61	1		
TOC	-0.40	0.42	0.35	0.59	0.004	-0.18	0.16	1	
TİC	0.54	-0.49	-0.56	-0.72	-0.65	-0.60	-0.84	-0.32	1

earthquake (Alpar, 1999 and Kuşçu et al., 2002, 2005). The presence of gas voids with 0.4 mm in diameter at 0-0.40 mbsf interval in Core BUC-10A suggest gas escape at the core site. Recent surveys in the Sea of Marmara have demonstrated the widespread cold fluid activity along the NAF, indicating the tectonic control on the fluid escape (Armijo et al., 2005; Zitter et al., 2008; Geli et al., 2008 and Bourry et al., 2009). However, the surveys did not discover any hydrothermal fluid activity in the Sea of Marmara.

Evidence of tectonic activity

The mud lithology of Core İZ-30 from İzmit Gulf on the NAFZ was disrupted by coarse sediment intervals with shells and shell fragments at 2.24 - 2.50 mbsf and 3.30 - 3.43 mbsf (Figure 2). These changes are supported by total inorganic carbonate distribution curve in İZ-30 (Figure 4). Sandy silt unit between 2.24 and 2.50 mbsf is poorly sorted, contains abundant shell and shell fragments, and displays sharp upper and lower contacts. These properties are typical characteristics of mass flow deposits (Johnson, 1970; Hampton, 1972; Middleton and Hampton, 1973; Shanmugan et al., 1995). AMS ^{14}C radiocarbon dating just above the upper contact of the unit produced an age of 3276±48 a (calendar) BP for this deposit. The possible triggering mechanisms for this mass flow during the normal marine period of deposition are; volcanic eruption, (Kastens and Cita 1981; Cita and Rimoldi 1997), high tide (Bjerrum 1971; Wisenam et al., 1986), low sea level (Hampton et al., 1996; Lee et al., 1996), rapid sedimentation on shelf edge and slope, gas activity related to gas hydrate decomposition (Hampton et al. 1996; Lee et al. 1996), as well as the earthquake (seismic) activity. No volcanic activity has been observed in the Sea of Marmara during at least a couple of millenniums. Santorini is the nearest active volcanic centre, and its last eruption took place at 3 500 a B.P. (Druitt et al. 1989). This volcanic eruption occurred 200 years before the mass flow event. Therefore, the volcanic eruption cannot be a possible triggering mechanism for the mass flow in the İzmit Gulf. The study area is a small inland sea and has only low-scale tidal oscillations (between 8 and 10 cm, Damoc 1971; Alpar and Yüce 1998), hence tide can be ignored as a triggering cause of mass flows. The sea level in the Sea of Marmara started rising after the reconnection at about 12 ka BP (Aksu et al., 1999, 2002; Çağatay et al., 2000; Hiscott and Aksu 2002; Kaminski et al., 2002; Elmas et al., 2008) and stable environmental conditions reached its present shoreline in the Sea of Marmara at about 4.0 ka BP (Çağatay et al., 2000; Mc Hugh et al. 2008). With the storm wave base level at about 10-15 m the storms can not be the cause of the mass flow. The riverine input into Gulf of İzmit is via some small creeks having small drainage areas. Moreover, the location of Core İZ-30 is far away from the mouths of streams. Thus, rapid sediment loading is not possible at the core site to provide the necessary triggering for the mass flow. Water depth in the İzmit Gulf is not suitable for the gas hydrate formation that usually occurs in sediments deeper than 1000 m at temperatures of 14°C, characteristic of bottom waters in the Sea of Marmara (Kvenvolden, 1993). However, direct fluid expulsion from active faults during earthquakes (Alpar, 1999; Kuşçu et al., 2004, 2009; Geli et al., 2008; Zitter et al., 2008) could cause sediment disturbance close to the fault rupture. Such a gas escape mechanism and/or seismic shaking during earthquakes are the most likely triggering mechanism of the submarine mass flow dated 3.3 ka BP in the İzmit Gulf. Study area is tectonically very active. 20 historical and 73 instrumental earthquakes with intensity equal to or greater than 9 and 5 having occurred in the eastern Sea of Marmara over the last 2000 years (Ambraseys and Finkel 1991; Ambraseys 2002). The association of mass flows and seismic activity in the Sea of Marmara basins is supported by the occurrence of frequent sismo-turbidite units identified in cores, which can be correlated with the historical earthquake (Başaran 2002; Sarı and Çağatay 2006; Mc Hugh et al., 2006).

Evidence of sea level changes

With rising global sea level after the late glacial maximum (Fairbanks, 1989), Mediterranean waters spilled through the Dardanelles Strait into the Sea of Marmara at 12 ka B.P. (Çağatay et al. 2000, 2003; Aksu et al. 2002; Kaminski et al. 2002; Mc Hugh et al., 2008). Following this reconnection, the sea level in the Sea of Marmara has risen in tandem with global sea level. But the global transition from glacial to interglacial was interrupted by the Younger Dryas cold interstadial in the Sea of Marmara as evidenced by the presence of the -65 m paleo-shoreline and a terrace in the Sea of Marmara shelf areas (Çağatay et al., 2003; Newman 2003; Eriş et al., 2007), The coarse gravely sand unit with shell and shell fragments at 3.30-3.43 mbsf interval near the base of Core İZ-30 interrupts the homogeneous marine mud and is interpreted as the sediments of a high-energy paleo-shoreline. This paleoshoreline is dated to be about 9.4 ka BP by the AMS ^{14}C dating. This 49.5 mbsf paleo-shoreline with an age of 9.4 ka BP is in agreement with the global sea level curve (Fairbank, 1989) and the lowermost parasequences of the Kurbağalı Dere Delta package located on the eastern side of the Istanbul Strait canyon on the northern shelf of the Sea of Marmara (Gökaşan et al., 2005; Eriş et al., 2007).

Core BUC-10A located 12 km offshore Büyükçekmece consists of two units which have been deposited under marine (0-2.70 mbsf) and lacustrine (2.70-3.60 mbsf) conditions (Figure 3). The TOC profile of the core provides important chronostratigraphic and paleoceanographic information for the Sea of Marmara (Figure 3-5). In the sediment core BUC 10, a sapropelic sediment layer between 1.60-2.43 mbsf is identified. This layer was previously dated at 10.6-6.4 kyr (uncalib) BP (Çağatay et al., 1999, 2000). Foraminiferal analysis indicates that the sapropel was deposited under mainly suboxic bottom water conditions (Çağatay et al., 1999, 2000). Organic material of the sapropelic unit in the Sea of Marmara is mainly of terrestrial origin with the marine fraction becoming predominant towards the top of the unit, as global sea level rose with time and the core location became further away from the shoreline (Tolun 2002).

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