Sedimentological and Geochemical evidence for Seismoturbidite Generation in the Kumburgaz Basin, Sea of Marmara: Implications for Earthquake Recurrence along the Central High Segment of the North Anatolian Fault

Yakupoglu Nurettin ^{1,*}, Uçarkuş Gülsen ¹, Kadir Eriş K. ¹, Henry Pierre ², Namık Çağatay M. ¹

¹ Istanbul Technical University, Geological Engineering Department and EMCOL, 34469, Faculty of Mines, Ayazağa, İstanbul, Turkey

² CEREGE (UMR7330), Aix-Marseille University, CNRS-IRD, 13330, Marseille, France

* Corresponding author : Nurettin Yakupoglu, email address : yakupoglu@itu.edu.tr

Abstract :

Holocene earthquake history of the Central High Segment of the North Anatolian Fault is examined here for the first time based on analysis of seismoturbidites within a 21-m-long piston core recovered from the Kumburgaz Basin in the Sea of Marmara. The visual lithological description combined with detailed grainsize analyses indicate that the deep basin hemipelagic sediments are interrupted by 28 turbidite units during the last 6.1 cal kyrs BP. The turbidites show strong segregation and a sharp boundary between a coarse basal part and overlying homogenite as inferred from detailed sedimentological and geochemical data. Several amalgamated turbidites are recognized by repeated fining upward sequences with no intervening homogenite indicating multiple episodes of traction and deposition as a result of various slope failures and turbidity currents. Each unit was possibly triggered by the same earthquake event rupturing in the Sea of Marmara. The most common sedimentary feature is the continuous parallel lamination that was presumably introduced by long lasting water oscillations on suspended sediments due to the seiche effect. The establishment of geochemical criteria and exclusive sedimentary processes distinguish earthquake triggered turbidites (seismoturbidites) from other trigger factors. Moreover, such distinction allows us to evaluate hydrodynamic sedimentary conditions and processes in the Kumburgaz Basin. The base of most seismoturbidites are associated with a sharp increase in Mn concentration that can be explained by a diagenetic enrichment of Mn at the oxic/anoxic interface of the sediments near the seafloor prior to the deposition of the turbidite. An age-depth model of the studied core based on seven AMS ¹⁴C ages allows precise correlation between historical earthquakes and seismoturbidites in the Kumburgaz Basin. At least the latest nine of them fit well with the previously recorded major earthquake events between ca. ~500 cal yrs. BP and 2.5 cal kyrs BP.

Keywords : Earthquake geology, Seismoturbidite, Kumburgaz Basin, Sea of Marmara, North Anatolian Fault

1. Introduction

Earthquake-triggered gravity flow deposits have been used as a tool in subaqueous paleoseismology to unravel earthquake cycles adjacent to plate boundaries and regions with regular seismic activity. These deposits are studied by using various proxies in regions; the North San Andreas Fault and Cascadia subduction zone (Adams, 1990; Goldfinger et al., 2003, 2007, 2008, 2011, 2017), New Zealand (Pouderoux et al., 2012a,b; Barnes et al., 2013), the Mediterranean (Kastens and Cita, 1981; Cita et al., 1982, 1984, 1996; Kastens, 1984; Cita and Aloisi, 2000; Polonia et al., 2013a, 2017), the west coast of Iberian Peninsula (Gracia et al., 2000; Masson et al., 2011), and in Japan Sea (Nakajima and Kanai, 2000).

The term “seismoturbidite” implies triggering of the mass flow by an earthquake rather than other possible mechanisms such as; storm waves, hyperpycnal flows, gas hydrate dissociation, sediment overloading, volcanic eruptions and floods (Postma et al., 1988; Prior et al., 1989; Nemec, 1990; Mulder and Syvitski, 1995; Beck et al., 1996, 2007; Chapron et al., 1999; Cita and Aloisi, 2000; Nakajima and Kanai, 2000; Shiki et al., 2000; Arnaud et al., 2002; Goldfinger et al., 2003; Schnellmann et al., 2005; Carrillo et al., 2008). Although several criteria

based on core and seismic data have been proposed to distinguish seismoturbidites from turbidites of other origins in submarine paleoseismological studies (Nakajima and Kanai, 2000; McHugh et al., 2011; Çağatay et al., 2012; Eriş et al., 2012; Avşar et al., 2015; Goldfinger et al., 2017; Polonia et al., 2017), their origin and depositional processes are still a matter of debate.

After the devastating 1999 Izmit (Mw 7.4) and Düzce (Mw 7.2) earthquakes, submarine paleoseismological studies have become crucial to constrain the earthquake recurrence history of the North Anatolian Fault (NAF) in the Sea of Marmara (SoM) (Sarı and Çağatay, 2006, McHugh et al., 2006, Beck et al., 2007) (Fig. 1). It is well known that the Northern Branch of the North Anatolian Fault (NNAF) has generated more than 55 ($M_s > 6.8$) earthquakes in the SoM region within the last two millennia (Ambraseys and Finkel, 1991, 1995; Guidoboni et al., 1994; Ambraseys and Jackson, 2000; Ambraseys, 2002). These past earthquakes were the dominant triggering mechanism for the failure of unconsolidated sediment on the northern shelf slopes of the SoM (Sarı and Çağatay, 2006; McHugh et al., 2006; Beck et al., 2007; Çağatay et al., 2012; Eriş et al., 2012; Drab et al., 2012, 2015).

Since the deep sedimentary sub-basins in the northern SoM are aligned along the segments of the highly active dextral strike slip NNAF (Reilinger, 1997; Straub et al., 1997; McClusky et al., 2000; Flerit et al., 2003; Reilinger et al., 2006) (Fig. 1), the sedimentary sequences of the sub-basins have been interpreted to consist predominantly of turbidites of seismic origin (McHugh et al., 2006; Sarı and Çağatay, 2006; Beck et al., 2007; Çağatay et al., 2012; McHugh et al., 2014; Drab et al., 2015). These unique sedimentary units provide an important archive of long-term earthquake activity. Previous models on the distribution of palaeoevents on each individual segment suggest a non-periodic/quasiperiodic behavior for the NNAF in the SoM (Fig. 11 and Table 3 in Drab et al., 2015; Fig. 9 in McHugh et al., 2014).

Establishing a reliable paleoseismological record in the SoM will allow us to better evaluate the earthquake hazard risk for the region and İstanbul (~19 km north of the NNAF) (Fig. 1). The Central High Segment, which crosses the Kumburgaz Basin, has not had any major earthquakes at least for the last ~250 yrs (Parsons et al., 2000; Parsons, 2004; Pondard et al., 2007) (Figs. 1,2). The instrumental seismicity shows sparse activity along the segment and geodetic studies found a large uncertainty on the inter-seismic fault loading rate in this segment (Ergintav et al., 2014; Sakic et al., 2016; Klein et al., 2017). Since the earthquake recurrence intervals were not well resolved on the Central High Segment, the Kumburgaz Basin stands out as an important location to study submarine paleoseismology (Fig. 2). Most of the submarine paleoseismology studies in the sub-basins of the SoM were based on the cores collected in the Tekirdağ, Central and Çınarcık basins (McHugh et al., 2006; Sarı and Çağatay, 2006; Beck et al., 2007; Çağatay et al., 2012; McHugh et al., 2014; Drab et al., 2015). These previous studies proposed some criteria to identify seismoturbidites, which still need improvements to understand their own depositional conditions and processes.

In this study, we present detailed sedimentological and geochemical analysis of a 21-m-long giant piston core recovered from the Kumburgaz Basin. Our main objective is to establish reliable criteria for identifying seismoturbidites on the basis of multi-parameter proxies from sedimentological and geochemical analyses. We also use ^{14}C ages to constrain an age-depth model to evaluate the Late Holocene earthquake records within the piston core and relate the seismoturbidites to historical earthquakes in the catalogues (Ambraseys and Finkel, 1991, 1995; Guidoboni et al., 1994, 2005; Ambraseys, 2002; Altınok et al 2011).

2. Oceanographic and geologic setting

The SoM is located in the western part of the 1600-km long North Anatolian Fault Zone that forms a 270-km long and 80-km wide intracontinental marine basin between the Mediterranean and the Black Sea (Fig. 1). It is connected to the low-salinity Black Sea via the Bosphorus and

to the marine Aegean Sea via the Çanakkale Strait (Dardanelles). These two straits have sill depths of approximately 65 and 35 m, respectively (Ryan et al., 1997; Ryan, 2007; Gökaşan et al., 2008; Eriş et al., 2008). The shallow sill depths of the straits result in a modern two-layer flow system in the SoM with a halocline at 25 m (Ünlüata et al., 1990; Beşiktepe et al., 1994). Surface water circulation of the SoM forms an anticyclonic loop, due to the difference of water level between the Mediterranean and Black sea (Beşiktepe et al., 1994). Especially during summer to late autumn, surface water originating from the Black Sea flows through Bosphorus, impacting surface water circulation in the SoM. Incoming Mediterranean waters via the Çanakkale Strait induce bottom currents between water depths of 100 m and 500 m (Ünlüata et al., 1990). Deep waters of the Kumburgaz Basin are influenced by this salty deep water current (Beşiktepe et al., 1994). The surface and deep water masses in the SoM have the renewal time of 4-5 months and 6-7 years, respectively (Beşiktepe et al., 1994).

The NAF diverges into two main branches before entering into the SoM, a northern branch and a southern branch (Fig. 1). Based on GPS rates, the total slip rate of the NAF is 24-26 mm/yr and the most active northern branch (NNAF) accommodates 60-80% of the total plate motion (Reilinger, 1997; Straub et al., 1997; McClusky et al., 2000; Le Pichon et al., 2001, 2015; Armijo et al., 2002; Provost et al., 2003; Flerit et al., 2003; Şengör et al., 2005; Reilinger et al., 2006; Grall et al., 2013). The NNAF exhibits a segmented submarine fault zone which comprises the main İzmit, Prince's Island, Central High and Tekirdağ fault segments (Fig. 1). Four deep sedimentary basins are aligned along the submerged section of the NNAF. West to east, Tekirdağ (-1133 m), Central (-1268 m), and Çınarcık (-1276 m) basins are bounded by two major ridges which form the Western and Central highs (Fig. 1). The Kumburgaz Basin is located on the Central High with a maximum depth of 833 m (Figs. 1,2). The SoM deep basins contain up to 6 km thick sediments as observed in deep seismic profiles (e.g., Carton et al., 2003; Laigle et al., 2008), suggesting active subsidence.

3. Kumburgaz Basin: bathymetry and morphology

Kumburgaz Basin is located on the Central High and bisected by the Central High Segment of the NNAF (Figs. 1,2). The basin is elongated in the NE-SW direction and formed at a releasing bend of the NNAF (Fig. 2). Compared to deep basins of the SoM (Çınarcık, Central and Tekirdağ), the Kumburgaz Basin is shallower in depth (-833 m) and smaller in size. The eastern part of the basin is bounded by a submarine ridge, displaying 3.5-4 km offset with a right lateral motion related to the NNAF (Armijo et al., 2002) (Figs. 1,2). Kumburgaz basin is bordered by the Central Basin in the west and Çınarcık Basin in the east. The northern slope (9° - 12°) of the Kumburgaz Basin which has a ~90 m shelf break, is marked by scars of old submarine landslides and erosive features, most of which were probably enhanced by earthquake activity along the NNAF (Fig. 2) (Görür and Çağatay, 2010; Özeren et al., 2010; Çağatay et al., 2015b). The southern margin of the basin is bounded by a low-lying ridge, having a minimum depth of -380 m (Fig. 1).

Three main submarine canyons (Fig. 2) and their tributaries are presumably the main providers of turbidity currents to the Kumburgaz Basin floor. These canyons originate near the continental-shelf break and extend to the base of the continental slope. The northeastern canyon (NEC) is deflected by the NNAF and is the smallest of the three. The north western canyon (NWC) is the longest canyon showing branching towards the shelf edge and a straight course towards the base. The northern canyon (NC) and its tributaries spread with several branches along the northern slope (Fig. 2). The bathymetry and the slope gradient model expose two depocenters in the Kumburgaz Basin (Fig. 2). The eastern depocenter is larger and elongated while the western depocenter is smaller and located at the mouth of the NWC (Fig. 2). Additionally, there is a bathymetric barrier (BB) at the toe of NEC, having ca. 300 m length and 75 m height (Figs. 2,3).

4. Methods & Instruments

4.1. Core recovery and material

A giant piston core CS-01 (21 m long) was recovered from ~833 m water depth in the eastern depocenter of the Kumburgaz Basin during the “MARsite” Cruise by R/V Pourquoi pas? (Figs. 2,3). Core recovery was performed by using a Calypso piston corer. Core location was chosen by using sediment sounder (chirp) profiles (Fig. 3). The core was split into 1-meter-long sections, photographed, described and sampled at Istanbul Technical University (ITU) East Mediterranean Centre for Oceanography and Limnology (EMCOL). Core sections were split into working and archive halves. Working halves were used for lithostratigraphic studies and sampling for grain size, smear slide and radiocarbon analyses. The archive halves were used for μ -XRF (X-ray Fluorescence) and Multi Sensor Core Logger (MSCL) analyses and then placed in the core repository of ITU-EMCOL.

4.2. μ -XRF core analysis

Core CS-01 was analyzed by Itrax XRF Core Scanner (with Mo X-ray tube, at 30 kV, 50 mA; 1 mm resolution, 10 s for each measurement time) at ITU-EMCOL Core Analysis Laboratory. The relative elemental abundances of Fe, Ca, Sr, K, and Mn were recorded as counts per second (cps). Both Mn and Fe are redox sensitive elements. However, we normalized Mn and Fe elements with Ca to prevent carbonate dilution effect. Mn/Ca is mainly used for determination of migrating redox fronts due to the accumulation of gravity flow deposits (Hofmann, 1999; Çağatay et al., 2012). Fe/Ca can display both redox sensitivity (showing positive anomalies on Fe monosulfides) and detrital input. Ca and Sr are indicators of carbonate content, mainly of biogenic origin in the SoM. Abundance of K is related to detrital input, and correlate with fine silt and clay size minerals (e.g., illite, mica, feldspar).

4.3. Physical properties and grain-size analyses

The physical properties (gamma density and magnetic susceptibility) of the core were measured on the archive-half at 1 cm resolution using a Geotek MSCL at the ITU-EMCOL core analysis laboratory. Magnetic susceptibility (M.S.) analysis was performed by using a Bartington point sensor. Positive M.S. anomalies are in general related to terrigenous input. Gamma-ray density is related with density and porosity and sorting of the material. Grain-size analysis of the core was performed with 5 cm sampling interval using Malvern Mastersizer 3000 Grain-Size Analyzer without any pretreatment due to lack of macro fossil assemblages. Grain-size distribution of turbidites is determined with 0.5 cm sampling interval in order to obtain higher resolution grain-size parameters (sorting and skewness). The grain-size fractions (sand, silt and clay) for each seismoturbidite unit in the core were calculated according to the Wentworth scale (Wentworth, 1922). Mineral composition and benthic foraminifera identification in the turbidite units were made on the sieved $>63\ \mu\text{m}$ fraction at 0.5 cm sampling interval.

4.4. Radiocarbon Analysis and Age-depth model

AMS ^{14}C analyses of 7 samples were carried out at the ARTEMIS CNRS facility (Gif-sur-Yvette). Hemipelagic sediment samples from beneath the mass-flow units were wet-sieved and $>63\ \mu\text{m}$ fractions were used to hand-pick carbonate shell material under binocular microscope. Because the radiocarbon datable shell material was scarce in the samples, we also included epifaunal benthic foraminifera, echinoderm spicules and occasionally bivalve shells, in addition to the planktonic foraminifera. Care was taken to sample shells without evidence of reworking and diagenesis. All samples were washed in distilled water and dried (at 40°C) before the analysis. Results were calibrated using Calib v7.0 software with Marine13.14C calibration curve and a reservoir age correction of 390 ± 85 (Sinai et al., 2000) (Table 1). Inclusion of benthic and pelagic shells in the same sample would not affect the reservoir age because of the negligible difference (6-7 years) between the residence time of upper and lower water masses

in the SoM (Beşiktepe et al., 1994). Calibrated ages were processed with R-studio using the script “bacon.r”, based on Bayesian statistics, to obtain an age-depth model for the core’s sedimentary sequence, ignoring the mass-flow units. The script created age-depth models, calculating the 95% Gaussian confidence interval around the best model (Fig. 5).

5. Results

5.1. Lithostratigraphy and chronostratigraphy

The studied core CS-01 includes a sedimentary succession that was deposited after the latest marine connection of the SoM, sometime between 14.7-12.5 kyrs BP (Çağatay et al., 2000, 2003, 2015; Vidal et al., 2010; Eriş et al., 2011, 2012). This 21 m-long succession represents a continuous record of the last ~6.1 cal. kyrs BP (Table 1, Figs. 4, 5). and is correlated with upper part the sequence observed in 3.5 kHz seismic lines (Fig. 3).

Core CS-01 consists of continuous “background” hemipelagic/pelagic sediments that are interrupted by 28 turbidite layers identified by visual lithology and textural properties (Fig. 4). Through the core, the ‘background’ sedimentation is slightly variable in terms of siliciclastic (clay-silt) and calcareous fractions. In the first two meters, a gradual downward change in color from brownish (oxidized mud) to olive gray is observed, and thereafter the sediment color changes to gray and then dark gray between 3 m and 15 m. The rest of the core is represented by a dark greenish gray silty clay (Fig. 4). In general, the background sediments in the core display homogenous texture without distinct variations in internal sedimentary structures. The detrital carbonate grains are commonly more abundant than the biogenic components. Fe-sulfide nodules (pyrite) and patches (iron-monosulfides) are scattered throughout the core. The fine-grained ‘background’ is locally dominated by benthic foraminifera assemblages such as *ammodiscus* sp., *textularia* sp., *spiroloculina* sp., *quiqueloculina* sp., *binoculina* sp., *triloculina* sp., *dentalina* sp., *amphicoryna* sp., *lagena* sp., *bolivina* sp., *brizalina* sp., *bulimina* sp., *uvigerina* sp., *chilostomella* sp. and *ammonia* sp. However, turbidite-homogenite units are

only dominated by bivalve fragments, echinoderm spicules, *ammonia* sp., *elphidium* sp., *uvigerina* sp. and *quineloculina* sp. fossils.

5.2. Sedimentological characteristics of turbidites

A total of 28 turbidite units consisting of a basal coarse part and the overlying homogeneous mud (homogenite) were identified lithologically and labeled as ST-1 to ST-28. Their thicknesses range from 2 cm to 25 cm. The total thickness of the turbidites make up 18% of the 21 m-long sedimentary succession in the core. This ratio of turbidite to background hemipelagic sediment in the Kumburgaz Basin is low compared to the ratios (up to 75 % turbidites) in the other SoM basins (Beck et al., 2007; Çağatay et al., 2009; Eriş et al., 2012) (Fig. 1).

The lower boundary of the coarse basal part of the turbidites with the underlying hemipelagic sediments in the Kumburgaz Basin is sharp, but commonly non-erosional. Grain-size fluctuations in the coarser basal part are documented as alternations of normal and reverse grading, producing the thin parallel laminations observed in the core, radiographic images and grain-size distributions (Figs. 6,7). According to the classification of Folk (1980), basal units of the turbidites show very poorly sorted texture (ranging between 2-3) and positively skewed distribution (ranging between 0 to ~0.3) (Figs. 6,7). Smear slide microscopic observations show that most sand particles have pitted surfaces. The basal part also contains a high amount of fossils and fossil fragments of bivalves, echinoid spicules and benthic foraminifera relative to background sediments. The abrupt lithological change between the lower coarse basal parts and the upper homogeneous parts can be detected in the grain-size distribution, gamma density profiles and X-ray images (Fig. 6). Some turbidites in the core are stacked on top of each other without any interbedded homogenite part or hemipelagic sediments, showing the properties of amalgamated turbidites (Polonia et al., 2017) (Fig. 7).

Homogenite part of the turbidites represents the turbidite tail deposits and identified as homogenous mud in the visual description. This part consists of clay to fine silt fractions with a fining upward trend in grain size. Homogenite has higher gamma density values (1.59-1.62 gr/cc) than the hemipelagic sediments (1.57-1.59 gr/cc) (Fig. 6). The homogenite part is marked by poorly sorted (1.7-2) and positively skewed (0.1-0.3) sediments that are compatible with grain size fractions, since hemipelagic sediments are dominated by finer grain size fractions (lower than 8 μm) (Fig. 6). Therefore, the overlying hemipelagic layer has comparatively better sorting and uniform skewness values (Figs. 6).

5.3. Geochemistry

The μ -XRF elemental composition of turbidites in core CS-01, including Mn/Ca, Fe/Ca, K, Ca and Sr, are presented in Figs. 6,7. Elemental profiles of the turbidite units show similar distinct trends. The most remarkable feature is a sharp increase in Mn/Ca at the base of most turbidite units. The positive Mn/Ca excursion sometimes extends in the core several centimeters below the base of the turbidite layer (Fig. 6). In the case of amalgamated turbidites, a single Mn/Ca peak is generally found somewhere close to the base of turbidite stack (Fig. 7) and multiple Mn/Ca anomalies (Fig. 7) rarely occur.

The coarse basal parts of most turbidite units are associated with upward increasing μ -XRF Ca and Sr counts (Figs. 6,7). Basal parts of some turbidite units are commonly depleted in K compared to the homogenite parts and background sediments due to lower clay (illite) content and higher carbonate content (i.e., the carbonate dilution effect) (Figs. 6,7). The transition from the basal coarse part to the homogenite part of some turbidites is marked by abrupt increases in K and Fe/Ca and a sharp decrease in Ca and Sr. Since geochemical composition is mostly related to the sediment source, rather than the depositional process, the difference between homogenite and background sediments could not be determined on the basis of μ -XRF elemental changes.

6. Discussion

6.1. Triggering, deposition and sediment sources of turbidites

As it has been previously pointed out by many authors, there can be different triggering mechanisms for mass-transport deposits including turbidites. These include seismic shaking, storm waves, hyperpycnal flows, gas hydrate dissociation, sediment overloading, volcanic eruptions and floods (Postma et al., 1988; Mulder and Syvitski, 1995; Beck et al., 1996; Shiki et al., 2000; Goldfinger et al., 2003; Schnellmann et al., 2005). Hence, establishment of sedimentological and geochemical criteria for distinguishing turbidites of seismic origin from other origins has been an important objective of numerous studies.

The most plausible triggering mechanism for turbidites in the Kumburgaz Basin is seismic shaking related to the NNAF, which is known to have produced $M > 7$ earthquakes with ca. 150-250 yrs reoccurrence time (Ambraseys and Finkel, 1991, 1995; Guidoboni et al., 1994; Hubert Ferrari et al., 2000; Ambraseys, 2002). Other possible triggering mechanisms such as storm waves, sediment loading and hyperpycnal flows can be discounted for the Kumburgaz Basin for the duration of the core's record (i.e., the last 6.1 kyrs). There is no major river input on the shelf surrounding the Kumburgaz Basin, with the middle Holocene sea level stand reached already ca. 6.5 kyrs BP (Fairbanks, 1989) and the shelf edge located at ca. 100 m water depth was 7-8 km away from the coastline. Therefore, sediment loading and hyperpycnal flows are unlikely to be a causal mechanism for triggering the mass-flow events observed in this basin. With the storm wave height less than 10 m and storm base level less than 30 m in the SoM (Özhan and Abdallah, 1999), storm waves are also unlikely to be a cause of mass-wasting events on the shelf edge and slopes of the Kumburgaz Basin.

Gas hydrate dissociation as a consequence of warming during Holocene is a plausible mechanism of mass-wasting in the SoM, considering the gas hydrates discovered on the

Western High and widespread gas emissions from the active faults in the SoM (Halbach et al., 2002; Armijo et al., 2005; Géli et al., 2008; Zitter et al., 2008, 2012; Bourry et al., 2009; Ruffine et al., 2017). However, observations of gas escape and its past manifestations as carbonate crusts are scarce in the Kumburgaz Basin (Geli et al., 2008; Dupré et al., 2015; Çağatay et al., 2017), hence gas escape from sediments is a low possibility for causing turbidity currents. The two-fold division of the turbidites into a coarse basal part and a homogenite part observed in the Kumburgaz Basin is taken to be indicative of seismic triggering and associated tsunami events in the SoM and in some lakes (Beck et al., 1996, 2007; Chapron et al., 1999; Çağatay et al., 2012; McHugh et al., 2014). As a result, we consider earthquake shaking to be the most plausible mechanism to trigger turbidity currents from the shelf edge and slope to the Kumburgaz Basin. This conclusion is supported by specific sedimentary structures and depositional characteristics of the turbidites discussed below and their correlation with the historical earthquakes presented in section 6.3.

Geochemical and physical proxies of seismoturbidite units in CS-01 compare well with those in the other basins of the SoM (Sarı and Çağatay, 2006; McHugh et al., 2006, 2014; Beck et al., 2007; Çağatay et al., 2012; Eriş et al., 2012). The Mn/Ca anomalies near the base of the turbidites represent diagenetic enrichment at the oxic/anoxic interface of the sediments in a basin where the bottom waters are oxic (e.g., Çağatay et al., 2004, 2012) (Figs. 6,7). This boundary is presently located at ca. 10 cm below seafloor in the deep basins of the SoM (Çağatay et al., 2004) but was most likely shallower and closer to the sea floor during the sapropel depositional events during 12.3-5.7 and 5.4-2.7 cal. kyrs BP (Çağatay et al., 2015) in the SoM. The oxic/anoxic interface migrates continuously upward during slow deposition of "background" hemipelagic sediments but the deposition of a new turbidite unit causes the formation of a new redox front further up in the sequence while the older front will stop migrating, leaving a Mn anomaly at its final location. The elevated Ca and Sr contents in the

sandy basal part of the seismoturbidites are further enhanced in their uppermost parts (Figs. 6,7). Such enrichment is attributed to high amounts of shell material transported from the shelf and upper slope areas. The shell concentration at the top of the coarse basal part occurs because of late deposition due to the platy shape of the biogenic carbonate particles (Figs. 6,7). The presence of *ammonia* sp., *quiqueloculina* sp., *uvigerina* sp. and *elphidium* sp. in the upper part of the coarse basal layer strongly indicates infralittoral and upper circalittoral depositional settings on the shelf and upper slope areas (Van Morkhoven et al., 1986; Sarı and Çağatay, 2006). The same faunal assemblage characterizes the homogenite parts of the seismoturbidites, whereas the hemipelagic part is almost dominated by *bulimina* sp. and *bolivina* sp. This finding strongly indicates the difference in origin of sediments between the homogenite and the overlaying hemipelagic layers.

Grain-size analysis (i.e. ratio of sand, silt, clay) of the seismoturbidite units together with visual observations indicate poorer sorting values (Fig. 6) which have been proposed as the most significant feature for seismoturbidites (Shiki et al., 2000; Arnaud et al., 2002; Goldfinger et al., 2003; Schnellmann et al., 2005; Beck et al., 2007; Carrillo et al., 2008). Sorting parameter together with gamma density could explain the different depositional processes and related settings between the homogenite and hemipelagic sediments (Fig. 6). Considering the deposition of seismoturbidite as a result of earthquakes, settling of the homogenite layer must be instantaneous compared to the hemipelagic sediments, thus, the resulting grain size fractions would have formed relatively more poorly sorted sediments. This likely explains higher density values of homogenites within the turbidite sequence in the Kumburgaz Basin (Fig. 6). Moreover, the positive skewness within the same layer reveals that the homogenite is coarser than the background sediments in Kumburgaz Basin (Fig. 6).

Another important feature of seismoturbidites in confined basins is the multiple sand laminae commonly observed in the upper part of the coarse basal unit. Such a feature is the

result of long lasting water-column oscillations or “seiche” (Nakajima and Kanai, 2000; Shiki et al., 2000; Sarı and Çağatay, 2006; Beck et al., 2007; Çağatay et al. 2012; Eriş et al., 2012; Drab et al., 2012; McHugh et al., 2014; Polonia et al 2017). Polonia et al. (2017) suggests a different model for effects of water oscillations on gravity flows. They suggest that oscillations caused by earthquakes in the Ionian Sea created secondary dilute turbidity currents that deposited sediments overlaying the homogenite. Furthermore, they suggest triggering of wave-induced bottom currents that are also caused by the seiche effect. Based on the intensity of the earthquake, distance between hypocenter and basin, and size of the water mass, internal seiche can occur on the basin floor. Hence, the highly fluctuating grain size within the laminated part could be generally regarded as due to oscillatory currents following an earthquake or large landslide, although the hydrodynamic processes by which these oscillatory currents are generated may depend on the case. Similarly, the laminated texture of the seismoturbidites in the Kumburgaz Basin is most likely produced from the “to and fro” oscillating bottom currents after earthquakes (Figs. 6,7).

Such an oscillatory mechanism in the Kumburgaz Basin may also be responsible for a segregation of the bed load from the suspended load, sharpening the boundary between coarse and fine-grained layers. The overlying finer part consists of silt and silt-clay size fractions, where the transition zone is between the basal flow and the suspended cloud, was intensely affected by seiche oscillations resulted in formation of multiple laminations (Figs. 6,7). A similar depositional process was previously described by Beck et al. (2009) for Lake Annecy in France, which is a much smaller basin compared to the Kumburgaz Basin. The “homogenite” part overlying the coarse basal part in core CS-01 represents the mud deposited from the suspended load derived from the outer shelf and slope, and the basinal sediments re-suspended from the Kumburgaz Basin floor (Figs. 1, 2). The relatively uniform elemental composition as inferred from XRF analysis support this conclusion. The lack of vertical changes in texture and

chemical composition implies deep horizontal spreading, similar to any hyperpycnal depositional process in deep marine basins (Mulder et al., 1994; Mulder and Cochonat, 1996; Bouma, 2000).

Apart from the overall physical and geochemical data discussed for the seismoturbidites above, the coarse-grained lower parts, represent a coarse-tail, graded unit that is indicative of low shear stress during a period of rapid sediment fall-out as a traction carpet formed at the base of a turbulent suspension. The general normal grading texture in the seismoturbidite layer is attributed to the waning phase of the turbidite flow (Fig. 6) (Bouma, 1962; Lowe, 1979), when the energy of flow drops gradually. Whereas, grainsize grading is disturbed by fluctuations based on the grainsize parameters (Figs. 6,7). This can be explained by existence of seiche effect during or just after the earthquake, giving rise to strong segregation on suspended particles. This kind of water column oscillations might have produced poorer sorted homogenite in contrast to finer part of a classical turbidite sequence (e.g., division E; Bouma, 1962). Moreover, the only significant sedimentary structure in the basal part of the seismoturbidite is a parallel lamination that is mostly associated with a silt dominated layer. Apart from the lamination (Figs. 6,7), the lack of other internal structures defining a classical Bouma turbidite sequence (Bouma, 1962; Lowe, 1979,1982; Shanmugam, 1997) could be the most remarkable texture of seismoturbidites in the Kumburgaz Basin.

The thickness of the Kumburgaz Basin seismoturbidites range between 2 cm and 25 cm (including homogenite part) (Figs. 6,7), which are commonly thinner than those reported from the Tekirdağ, Central and Çınarcık basins (McHugh et al., 2006, 2014; Beck et al., 2007; Çağatay et al, 2012; Eriş et al., 2012; Drab et al., 2012, 2015). This difference is likely the result of several factors including the size of the basin, size of the drainage area, paleoclimate, sea level, size of slope failure and the distance between the depositional basin and epicentral area. During high-stand condition in the SoM after initial flooding of the shelves at 12.5 cal. kyrs

BP, the warm period would have decreased the stream power to generate low river sediment input on the shelves (Çağatay et al., 2009; Eriş et al., 2012). Several authors also note that mass transport processes and turbidity currents were more frequent and the turbidites were thicker during the lacustrine stage than during the marine episode (Beck et al., 2007, 2014; McHugh et al., 2008; Eriş et al., 2012). The seismoturbidites in core CS-01 were deposited during the high sea level stand. They have similar elemental profiles (e.g., K, Fe/Ca, Ca, Sr) (Figs. 6,7), suggesting a uniform source of the clastic fractions derived from a catchment area with relatively uniform lithology, mainly the Oligocene deltaic sandstones and siltstones (Görür and Okay, 1996; Okay et al., 2000; Adatepe et al., 2002).

We have identified 28 seismoturbidite units in the Kumburgaz Basin over the last 6.1 cal kyrs BP. This number is similar to that observed from the Central Basin depocenter (21 event in the last 5 cal. kyrs BP; McHugh et al., 2014), but more than those observed in the Çınarcık Basin (Beck et al., 2007; Eriş et al., 2012). Such inconsistency in the quantity of seismic events obtained from those basins is most probably due to the proximity of the basin to the earthquake epicenter (Fig. 1). Other factors include, susceptibility of the slopes to mass wasting, sediment storage on the shelf and slopes, and the presence of submarine canyon feeder system in the basin (Fig. 2).

6.2 Amalgamated Turbidites

Some seismoturbidites in the Kumburgaz Basin are stacked on top of each other and as such display the features of amalgamated turbidites (Nelson et al., 2012; Gutiérrez-Pastor et al., 2013; Polonia et al., 2017) (Fig. 7). In such amalgamated turbidites, several fining upward layers indicate multiple episodes of traction and deposition of mass-transport material originating from various slope failures and transported via different submarine channels. Some members of the amalgamated seismoturbidite sequences were likely triggered by the same earthquake event rupturing the basin. However, in other seemingly amalgamated

seismoturbidites, each coarser basal part is associated with a Mn/Ca-anomaly, indicating a time gap between the two events that allowed the development of new Mn/Ca-anomaly after the previous event (e.g., ST-6, Fig. 7).

According to Polonia et al. (2017), earthquake-triggered gravity flows originating from multiple sources may form amalgamated structures as stacked turbidite packages (Fig. 7). Therefore, an amalgamation of seismoturbidites in the Kumburgaz Basin may have produced stacked coarse layers without homogenite, since multiple gravity flows during a single earthquake would not have allowed the deposition of the suspended particle cloud, that forms the homogenite on the basin floor. Presence of amalgamated turbidites is detected on the core. In ST-7 (Fig. 7), three turbidite deposits capped with a homogenite layer suggest that these turbidites might be the result of subsequent slope failures during a single earthquake, as previously proposed for the Çınarcık Basin (Fig. 7) (Sarı and Çağatay 2006; Eriş et al., 2012; Drab et al., 2012).

The stacked layers within amalgamated unit are compositionally similar in coarse fraction which suggests multiple slides from the same sources. This is supported by similar trends in some elemental profiles (Fe/Ca, Ca and Sr) through the seismoturbidite layers (Fig. 7). The catchment areas of the two main feeder canyons on the northern shelf (NC and NEC; Figs. 1,2) are characterized by similar lithological composition (erosion products of Oligocene siliciclastic rocks; Görür and Okay, 1996; Okay et al., 2000; Adatepe et al., 2002), so it is not possible to distinguish the source of any particular seismoturbidite. It is possible that the observed seismoturbidite results from a unique major mass wasting event, or from the gathering of several slumps turning into coeval turbidites and channelized within three main canyons around the basin (Fig. 2).

6.3 Correlation of the turbidites with historical earthquakes and late Holocene Earthquake records from Kumburgaz Basin

According to the age-depth model, core CS-01 covers a period between ca. ~813 cal. a. BP and ~6116 cal. a. BP (Fig. 5), and includes 28 seismoturbidite (ST) units interrupting the marine hemipelagic sequence. The most recent important historical earthquakes (i.e.; AD 1766, 1509 and 1343) were not detected in this core, since the top ~2.5 m was not recovered. Nine of the seismoturbidites are within the ~2300 years-long historical period for which earthquake records are available in the published historical catalogues (e.g., Ambraseys and Finkel, 1991, 1995; Guidoboni et al., 1994, 2005; Ambraseys, 2002; Altınok et al 2011; Tables 2,3). Although the age range of some of the seismoturbidites correspond to more than one historical earthquake, we chose to select the relatively large magnitude earthquake within the age-model interval, with the epicenters closest to the Kumburgaz Basin (Fig. 5, Tables 2,3). It is important to note that historical earthquake catalogs can be incomplete in terms of several factors (i.e.; population, local intensity of the earthquake, political circumstances, wars, distraction from other natural disasters) usually affecting the records of the chronologists. Hence, we chose to rely on earthquakes that are documented in several historical catalogs.

ST-1 is dated between 1077 AD – 817 AD (mean age is ~964 AD), and may be correlated to a number of earthquakes that occurred during this interval; 1063 AD, 1010 AD, 989 AD, 862 AD are all documented in the catalogues as earthquakes affecting Constantinople (İstanbul) region (Ambraseys and Finkel, 1991; Ambraseys, 2002; Guidoboni et al., 2005). However, the 989 AD (7.2 Ms) and the 1010 AD (7.0 Ms) earthquakes are described to cause more significant destruction to Constantinople compared to the other earthquakes listed above and better mesh with the mean age of the ST-1. Guidoboni et al. (2005) mention that the buildings including several churches and specifically the Churches of Forty Martyrs and All Saints in Constantinople was damaged by the earthquake shocks of the 1010 AD. Records mention about aftershocks lasting for forty days following the main event. The 989 AD earthquake was reported to cause a larger scale destruction in Constantinople where houses, the

city walls and western side of the St. Sophia collapsed. [Guidoboni et al. \(1994\)](#) describe systematic aftershocks following the 989 AD earthquake. This earthquake set up waves in the sea between the provinces of Thrace to İstanbul described as tsunami waves in [Altinok et al. \(2011\)](#). Based on the destruction intensity reported in the historical records and the thickness of the ST-1 (the thickest in CS-01; ~ 50 cm), the 989 AD earthquake is the most likely event that can be correlated with this seismoturbidite unit. Sedimentary records related to the 989 AD earthquake are also documented in the Çınarcık Basin ([Drab et al., 2015](#)) (Table 3).

ST-2, with a calibrated age of 975 AD – 640 AD (mean: ~820 AD), can be correlated with the 989 AD, 869 AD, 862 AD, 796 AD earthquakes which affected Constantinople (İstanbul) and its surrounding areas ([Guidoboni et al., 1994](#); [Ambraseys, 2002](#)). Historical reports describe severe damages and fatalities in Constantinople during the 862 AD and the 869 AD earthquakes. The 869 AD was mentioned as an earthquake that lasted for forty days and forty nights (most probably aftershocks lasting 40 days); many churches collapsed including the St. Mary, killing many people inside it ([Guidoboni et al., 1994](#)). The 862 AD earthquake was reported to cause series of strong ground shakings bringing down the city walls of Constantinople. Statue of Victory at the Golden Gate and church of St. Anne collapsed during this earthquake ([Guidoboni et al., 1994](#)). The 862 and 869 AD earthquakes better fall in the range of the mean age of the ST-2 and most likely represent the closest epicenters to İstanbul based on the damages caused among the other earthquakes listed above.

ST-3 is within the age range of 963 AD – 608 AD (mean: ~796 AD). Within this interval, it may correspond to the 869 AD, 862 AD, 849-851 AD, 796 AD, 740 AD earthquakes, all documented within the Constantinople region ([Ambraseys and Finkel, 1991](#); [Ambraseys, 2002](#); [Guidoboni et al., 2005](#)). and one of the 869 AD and 862 AD earthquakes are most likely associated with the deposition of ST-2 thus we seek to understand the details of other events that are listed here. The 849-851 AD is mentioned as a moderate earthquake in the catalogues

and the 796 AD is reported with very few details. The largest earthquake within the age range of ST-3 is the 740 AD event with $M_s=7.1$ and $I=IX-XI$ (Guidoboni et al., 1994; Ambraseys, 2002; Altinok et al., 2011). Large scale destruction in İstanbul, İzmit and its surroundings, and a tsunami affecting the coastal areas of İzmit, were reported (Altinok et al., 2011). The aftershocks of this earthquake lasted almost a year (Guidoboni et al., 1994). The 740 AD may have caused the deposition of ST-3 also taking into account the good fit with mean age of ST-3. This event has also been observed as a distinct seismoturbidite unit in the sedimentary sequences of most SoM basins (McHugh et al., 2006; Çağatay et al., 2012; Drab et al., 2015) (Table 3).

ST-4 gives a wider age interval between 907 AD – 357 AD (mean age: ~658 AD) based on the age-depth model thus it may coincide with long list of historical earthquakes affected Constantinople region (862 AD, 796 AD, 740 AD, 557 AD, 554 AD, and 478-480 AD) (Guidoboni et al., 1994; Ambraseys, 2002). It is rather difficult to make a more precise correlation from the historical events within a ~600 age interval. Therefore, we chose to select events that fits better with the mean age of the ST-4 and neglect the ones already discussed for the previous seismoturbidite records. There are two major earthquakes (557 AD and 554 AD) in the region that may correspond to the deposition of ST-4. The 557 AD event is described in detail in many historical records as a terrible and devastating earthquake destructing many churches, houses, the city walls and killing many people in Constantinople (Guidoboni et al., 1994). Tremors felt for ten days and a tsunami was reported (Altinok et al., 2011). A wide region including Nicomedia (İzmit) and Nicea (İzник) were affected from this earthquake (Guidoboni et al., 1994). The 554 AD earthquake was felt in Constantinople (İstanbul) where houses, churches and part of the walls of Constantinople were damaged or collapsed during this earthquake (Ambraseys and Finkel, 1991; Guidoboni et al., 1994). ST-4 may correspond to either the 554 AD or the 557 AD earthquakes. However, the 557 AD is documented as a larger

519 earthquake and may be a closer epicenter to İstanbul. Sedimentary records of the 557 AD
 520 earthquake were also documented in the Central Basin (McHugh et al., 2014) (Table 3).

521 ST-5 is dated between 858 AD – 233 AD (mean age: ~578 AD) within the age-depth
 522 model. The 740 AD, 557 AD, 554 AD, 542 AD, 478 AD, 447 AD earthquakes all fall into the
 523 ~550 age interval (Ambraseys and Finkel, 1991; Guidoboni et al., 1994; Ambraseys, 2002).
 524 The 478 AD and the 447 AD (both events are considered as I: IX) are mentioned as major
 525 earthquakes that damaged Constantinople and the Marmara region in several catalogues
 526 (Ambraseys and Finkel, 1991; Guidoboni et al 1994; Ambraseys, 2002; Altinok et al., 2011)
 527 and Altinok et al. (2011) suggest occurrence of tsunami waves after these earthquakes. The 542
 528 AD is reported with less detail in Guidoboni et al. (1994), thus either of the 478 AD and the
 529 447 AD earthquakes may be the likely matches of the ST-5. There are sedimentary records also
 530 dated corresponding to the 478 AD earthquake in Çınarcık Basin (Drab et al., 2015) (Table 3).

531 ST-6 has an age range between 746 AD – 169 AD (mean: ~464 AD). The earthquakes
 532 documented in Constantinople region within this interval covers the 740 AD, 557 AD, 554 AD,
 533 478 AD, 447 AD, 437 AD, 407 AD, 358 AD earthquakes (Guidoboni et al 1994; Ambraseys
 534 and Finkel, 1991; Ambraseys, 2002). The 437 AD earthquake was described as a great
 535 earthquake lasting for four months; this event was reported from one reliable source in the
 536 history (Guidoboni et al 1994). The 407 AD earthquake destroyed many houses, caused
 537 damage and casualties in Constantinople particularly in the coastal districts. Sea waves are
 538 reported on the shores wrecking many ships (Ambraseys and Finkel, 1991). The Ottoman
 539 archives confirm that many ships sunk because of a tsunami caused by an earthquake (Altinok
 540 et al., 2011). There are several reports on the destructiveness of the 407 AD earthquake thus it
 541 is most likely that it may correspond to ST-6. Although the 358 AD event affected
 542 Constantinople, the majority of the damage was reported in the city of Nicomedia (İzmit) and

543 Nicea (İzmit). Sedimentary records are documented the 358 AD earthquake in Gulf of İzmit
 544 ([Çağatay et al., 2012](#)) ([Table 3](#)) supports the distance of this event from Istanbul.

545 ST-7 has an age range of 328 AD-43 BC (mean. ~135 AD). Few chronologically
 546 accurate events can be found in the historical catalogues within this time interval (the 180-181
 547 AD and the 120-128 AD earthquakes). The 180-181 AD earthquake was mentioned as the third
 548 catastrophe for Nicomedia (İzmit) describing a very destructive earthquake ([Guidoboni et al., 1994](#);
 549 [Ambraseys, 2002](#)). Records mention that the Emperor requested support for
 550 reconstruction of the damaged regions ([Guidoboni et al., 1994](#); [Ambraseys, 2002](#)). Another
 551 major earthquake reported to destroy the greater part of Nicomedia (İzmit) together with their
 552 respective districts in the 120-128 AD. The 120-128 AD and the 180-181 AD earthquakes are
 553 in agreement with the mean age value of ST-7 and can most likely be associated with this
 554 sedimentary record. Sedimentary traces of 180-181 AD earthquake are also dated in other cores
 555 from the Gulf of İzmit ([McHugh et al., 2006](#)) ([Table 3](#)).

556 The age of ST-8 ranges between 88 AD – 206 BC (mean: ~63 BC) and may be
 557 associated with the 69 AD and the 29 AD earthquakes documented in Constantinople and
 558 surrounding regions ([Guidoboni et al 1994](#); [Ambraseys, 2002](#)). The 29 AD and the 69 AD
 559 earthquakes are described as damaging the Nicea (İzmit) and the Nicomedia (İzmit) regions,
 560 respectively, which were the two major settlements in eastern Marmara (Bithynia) at that
 561 period. Therefore, one of those can be responsible for the deposition of ST-8.

562 ST-9 has an age range of 119 BC – 458 BC (mean: ~284 BC). The 427 BC earthquake
 563 described in the ancient catalogues damaging the city Perinthos (Marmara Ereğlisi), which was
 564 the main settlement at the time ([Guidoboni et al., 1994](#)). The 287 BC occurred in Lysimachia
 565 (around Şarköy) and mostly damaged Hellespont area (Dardanelles). It is difficult to match
 566 these events precisely with ST-9 since there were no major settlement in İstanbul at that time.
 567 Therefore, from this point forward the historical records provide limited information in terms

of damage intensities corresponding to wider areas. Either of the 287 BC and the 427 BC can be correlated with ST-9.

The remaining 19 seismoturbidites have mean values based on the age-depth model (Table 2, Fig. 5). Sedimentary section from CS-01 provide records of 28 seismoturbidite units within the last ~6116 yrs suggest an average recurrence time interval of. ~220 yrs. The interval between consecutive events ranges between 40 yrs to 425 yrs in Kumburgaz Basin. The average earthquake recurrence interval derived from CS-01 core from Kumburgaz Basin is compatible with the recurrence interval of 150-250 yrs of the NNAF based on historical records (Ambraseys and Finkel, 1991, 1995; Guidoboni et al., 1994, 2005; Ambraseys and Jackson, 2000; Ambraseys, 2002) and the geodetic and seismological studies (Reilinger, 1997, Straub et al., 1997, McClusky et al., 2000; Flerit et al., 2003; Pondard et al., 2007; Reilinger et al., 2006). The recent well known earthquake sequence of the 1999 AD, 1912 AD, 1894 AD, May 1766 AD, August 1766 AD, 1719 AD, 1754 AD and 1509 AD ($M > 7$) earthquakes are produced by the rupture of submerged segments of the NNAF (Fig.1) in the SoM (Ambraseys, 2001,2002; Barka et al., 2002; Parsons, 2004; Armijo et al., 2005; Pondard et al., 2007; Uçarkuş et al., 2011; McHugh et al., 2014), highlighting the consecutive earthquake cycle for the last 500 yrs and supporting the recurrence time interval of 150-250 yrs.

7. Conclusion

Basins of the SoM acts as recorders of sediment input fluctuations due to tectonic activity of the North Anatolian Fault. Thus, the study of seismoturbidite sequences is a critical tool to evaluate earthquake recurrence intervals on such a seismically active fault zone. Our multi-parameter study on a piston core (Core MRS-CS-01) from Kumburgaz Basin, is the first high resolution sedimentological and geochemical study revealing the seismoturbidites deposited over the last ~6.1 kyrs for this basin. Core MRS-CS-01 includes 28 turbidite units that are intercalated with hemipelagic sediments. Turbidite-Homogenite units are characterized by a

593 coarse laminated sandy-silty basal part, overlaid by a seiche controlled laminated part and a
 594 homogeneous mud (homogenite) cap. Based on the geochemical, physical and textural proxies
 595 together with ^{14}C dating, the most probable trigger is inferred to be earthquakes. Indications of
 596 earthquake triggering comprise deposition of thinly laminated deposits caused by oscillatory
 597 currents and deposition from multiple gravity flow deposits (amalgamated turbidites) triggered
 598 by the same or by subsequent events.

599 All 28 seismoturbidite units show similar detrital markers. Coarse laminated sand-silty basal
 600 parts show high magnetic susceptibility and gamma density values due to accumulation of the
 601 detrital elements (High Fe/Ca and K, low Ca and Sr content). Oscillations of current intensity,
 602 presumably related to seiche effects, caused the deposition of thin laminations that result in
 603 rapidly varying elemental compositions. Laminations are capped with a Ca and Sr increase
 604 which is caused by the accumulation of biogenic fragments at the top of the turbidite. The
 605 homogenite layer results from the deposition of the fine particle cloud sent in suspension by the
 606 gravity currents, and is dominated by the clay fraction (High K) with a gradually decreasing
 607 gamma density at its top. Mn/Ca anomalies are another important indicator, which is detected
 608 as one or several positive spikes at the base of the seismoturbidites. These Mn/Ca anomalies
 609 are interpreted as fossil redox fronts. Based on the multi-parameter analyses, we conclude that
 610 the seismoturbidites of the Kumburgaz basin differ from the typical turbidite description (e.g.
 611 Bouma sequence) and also presents some differences from turbidites of the other basins of SoM.

612 The seismoturbidite records from core CS-01 provide an average recurrence time interval of
 613 ~220 yrs for the last 6.1 kyrs which is in agreement with geodetic, seismological studies and
 614 historical earthquake records from the SoM. 9 out of 28 seismoturbidites from CS-01 can be
 615 associated with historical earthquakes reported in the last two millennia. These frequent long-
 616 term sedimentary traces (28 ST unit in ~6 kyrs) found in CS-01 suggest that the Kumburgaz
 617 Basin has been recording earthquakes as much as other deeper basins along the NNAF in the

SoM. The most recent part of the sedimentary record (ca. 1200 yrs to present) is missing from this core, thus it is still not known whether the 1766 AD, the 1509 AD or the 1343 AD earthquakes were related to Central High Segment or not. Further core recovery and sediment analysis are crucial to enlighten the correspondence of recent large earthquakes with this segment to make a more precise seismic hazard assessment for İstanbul.

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976 **Figure Captions**

977 **Fig 1.** Location of the study and tectonic setting. A) Inset map shows current tectonic setting of
978 Turkey and surroundings. B) High Resolution Multi-Beam Bathymetry Map of the Sea of

979 Marmara (CB: Central Basin, CiB; Çınarcık Basin, CH: Central High, GI: Gulf of İzmit, KB:
 980 Kumburgaz Basin, TB: Tekirdağ Basin, WH: Western High) (Revised from Uçarkuş, 2010).
 981 Black lines represent the faults. Yellow box indicates the location of the Kumburgaz Basin (Fig.
 982 2). Transparent lines represent Tekirdağ, Central High, Prince's Island and İzmit segments of
 983 the NNAF with blue, red, green and yellow colors respectively. Dashed black line represents
 984 the location of Constantinople.

985 **Fig 2.** Detailed bathymetry map of the Kumburgaz Basin and surroundings, showing locations
 986 of core CS-01 (yellow dot) and seismic reflection profile (Fig. 3) (red line). Faults are indicated
 987 with black lines. The main submarine canyons and depocenter in the basin are clearly shown in
 988 the inset map obtained by a slope gradient. (NWC: Northwestern Canyon, NC: Northern
 989 Canyon, NEC: Northeastern Canyon, WD: Western Depocenter, ED: Eastern Depocenter
 990 respectively).

991 **Fig 3.** Seismic reflection profile P02 from the Kumburgaz Basin, showing the main depositional
 992 units along the basin floor. Two different units are differentiated with different colors. Holocene
 993 marine unit and lacustrine unit are shown by blue and green color, respectively. Core CS-01
 994 penetrates the upper half of the Holocene marine muds based on the core-to-seismic correlation.
 995 The wedge out of the marine sediments is obscured at NNAF close to NE of the profile.

996 **Fig 4.** Generalized sedimentary log of core CS-01 and radiographic images, showing the main
 997 lithostratigraphy of the Holocene marine unit deposited during the last 6.1 cal kyrs BP (Fig. 5).
 998 According to visual sedimentological observation on the core, we differentiated 28
 999 seismoturbidite layers (ST-1 to ST-28), intercalating with hemipelagic/pelagic sediments. Red
 1000 color within seismoturbidite unit represents the basal coarse-grained part, blue colored layers
 1001 represent amalgamated turbidites, whereas yellow color is assigned to a homogenite part. Red
 1002 stars indicate the ^{14}C sample locations with calibrated ages.

Fig 5. Age-depth model for background sediment of the core CS-01 are reconstructed based on seven AMS ^{14}C ages by using Bacon.r Script. Red line represents the mean age of the iterations. Blue diamonds are the levels of the ^{14}C samples. Grayscale background indicates the iteration distribution. Black dash lines represent the position of the ST units.

Fig 6. Color image and radiography of the selected seismoturbidite layers (ST-4 and ST-13, 249 cmbsf and 957 cmbsf from base respectively) together with correlative plots of MS, gamma density, elemental profiles (Mn/Ca, Fe/Ca, Ca, K, Sr) and combination of grainsize parameters (sorting, skewness, ratios of clay, silt and sand). Secondary sorting profile is focused on the background sediment and homogenite transition.

Fig 7. Color image and radiography of the selected amalgamated seismoturbidite layers (ST-6 and ST-7, 336 cmbsf and 460 cmbsf from base respectively) together with correlative plots of MS, gamma density, elemental profiles (Mn/Ca, Fe/Ca, Ca, K, Sr) and combination of grainsize parameters (sorting, skewness, ratios of clay, silt and sand).

Fig 1

Fig 2

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Table 1. Summary of AMS radiocarbon dates obtained from core CS-01. Reservoir correction applied as $\sim 390 \pm 85$ yrs. according to [Siani et al. \(2000\)](#).

Sample Name	Depth in Core (mm)	Depth in background	Uncalibrated age (BP)	Calibrated age (BP)
Age 1	1300	725	1505 $\pm$ 30	974 $\pm$ 71
Age 2	4639	3526	2325 $\pm$ 35	1836 $\pm$ 103
Age 3	6535	5181	2640 $\pm$ 35	2223 $\pm$ 94
Age 4	10469	8584	3815 $\pm$ 35	3666 $\pm$ 113
Age 5	12539	10291	4115 $\pm$ 35	4041 $\pm$ 121
Age 6	13155	10848	4160 $\pm$ 35	4105 $\pm$ 123
Age 7	20910	17092	5780 $\pm$ 45	6100 $\pm$ 127

Table 2. Seismoturbidite age ranges based on age-depth model (Fig. 5).

ST number	Depth (mm)	Mean (AD/BC)
1	1200	964,8 AD
2	1780	820,5 AD
3	1899	796,7 AD
4	2495	658,6 AD
5	2870	578,4 AD
6	3367	464 AD
7	4605	135,9 AD
8	5390	63,5 BC
9	6510	284,3 BC
10	7119	420,4 BC
11	7950	701,4 BC
12	8624	982,9 BC
13	9577	1374,5 BC
14	10140	560,3 BC
15	10440	1658,4 BC
16	10965	1842 BC
17	11840	2060 BC
18	12505	2190,7 BC
19	13140	2308,4 BC
20	14185	2444,9 BC
21	14605	2517,6 BC
22	15320	2687,2 BC
23	16405	2957 BC
24	17490	3248,4 BC
25	18755	3576,5 BC
26	19645	3797 BC
27	20165	3915,2 BC
28	20875	4111,2 BC

Table 3. Distribution of historical earthquakes and seismoturbidites found in CS-01 in correlation with other seismoturbidite based studies in the SoM. Abbreviations: a) [McHugh et al., 2006](#), b) [McHugh et al., 2014](#), c) This study, d) [Drab et al., 2015](#), e) [Çağatay et al., 2012](#), respectively. Note that, assigned letters corresponds the ST units that have been correlated with historical earthquakes.

Central Basin	Kumburgaz Basin	Çınarcık Basin	Gulf of İzmit
		1894 AD (d)	
		1509 AD (d)	1509 AD (e)
1343 AD (a,b)		1343 AD (d)	
			1296 AD (e)
	989 AD (c) (ST1)	989 AD (d)	
860-865 AD (b)	869 AD or 862 AD (c) (ST2)		860-865 AD (e)
740 AD (a)	740 AD (c) (ST3)	740 AD (d)	740 AD (a,e)
557 AD (b)	557 AD or 554 AD (c) (ST4)		
	447 AD or 478 AD (c) (ST5)	478 AD (d)	
	407 AD (c) (ST6)		358 AD (e)
268 AD (b)			268 AD (e)
	120-128 AD or 180-181 AD (c) (ST7)		180-181 AD (a)
	29 AD or 69 AD (c) (ST8)		
	287 BC or 427 BC (c) (ST9)		427 BC (e)