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**Estimation of
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Estimation of successive co-seismic vertical offsets using coeval sedimentary events – application to the Sea of Marmara’s Central Basin (North Anatolian Fault)

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Abstract

In the deep part of the Sea of Marmara (Turkey), the sedimentation developing upon the North Anatolian Fault is strongly influenced by the associated seismic activity. Specific layers (homogenites-turbidites), representing individual sedimentary events, have been characterized along three giant piston cores retrieved from Çınarcık and Central (or Orta) basins. Analyzed sediments represent the last 12 to 17 kyr BP. For a 2 kyr-lasting interval, 11 events could be precisely correlated on both sides of the Central Basin's southern scarp. For each of them, based on the specific depositional process, the thickness difference between the two sites was considered as a direct estimation of the vertical component of a coeval co-seismic offset. The homogenite (upper) term accounts for the major part of the thickness difference. The 6 most significant values range from 36 cm to 144 cm and are likely representing dominantly normal throws, with estimated paleomagnitudes (M_w) ranging from 5.9 to 6.6.

1 Introduction

Since several decades, sedimentary archives, either marine or lacustrine, have been explored as potential paleoseismic records, beside previously well-developed onland approaches (in McCalpin, 2009). For the subaqueous records, two major groups of effects can be detected and analyzed: (i) in situ post-depositional disturbances (e.g.: Marco and Agnon, 1995; Ken-Tor et al., 2001; Rodriguez-Pascua et al., 2002, 2003), (ii) gravity-driven reworking and re-settling of large masses of unconsolidated sediments (e.g.: Adams, 1990; Strasser et al., 2006).

Two major questions arise for both groups: (1) how to ensure the earthquake-triggering, (2) how to identify the responsible active structure(s). For in situ disturbances, the first problem is generally solved; in particular, it benefits from analogical and/or numerical modelling (e.g. Moretti et al., 1999; Wetzler et al., 2010). For redepositional processes – which are envisaged in the present work – several recent catas-

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trophic events could be surveyed shortly after their occurrence (Thunell et al., 1999; McHugh et al., 2011; Lorenzoni et al., 2012); the results reinforced the earthquake-induced interpretation proposed for some “homogenite-type” layers (Chapron et al., 1999; Beck et al., 2007).

5 For historical and older events, the seismic origin of a specific layer can be established:

- directly, using intrinsic characteristics (texture, origin of components, overall geometry, etc., (see references in Beck, 2009, and Beck et al., 2007);
- indirectly, (i) on the basis of correlations with reported seismic events (for historical seismicity) (e.g. Siegenthaler et al., 1987; Piper et al., 1992; Chapron et al., 1999; Beck et al., 2012); (ii) when detecting the same paleo-event in a large area independantly from local setting (e.g. variable slope dip). This second approach is especially used for deep structures, as subduction (e.g.: Gracia et al., 2010; Moernaut, 2011; Poudoux et al., 2012), but, also in some cases, for surface-reaching major faults (e.g. Goldfinger et al., 2007);
- combining both types of arguments.

Direct relationships between an active structure and earthquake-induced sedimentary events are investigated for active faults reaching a sediment/water interface (sea- or lake-bottom), through high resolution imagery or/and coring. This favourable setting recently permitted detailed analyses of fault activity (offsets, slip rates) through adjacent sedimentation (Carrillo et al., 2006, 2008; Bull et al., 2006; Barnes and Pondard, 2010; Beck et al., 2012). The here-presented work was dedicated to one of these cases: the deep part of the Sea of Marmara (northwestern Turkey) developed along the North-Anatolian Fault.

25 As the sedimentological tools and approaches we used have been previously published (Sari and Çağatay, 2006; Beck et al., 2007, 2012; Uçarkuş, 2010; Çağatay et al., 2012; Drab et al., 2012; Eriş et al., 2012; Campos et al., 2013) only results (data and

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interpretations) implying paleoseismological aspects will be envisaged here. Detailed sedimentological aspects may be consulted in the above-mentioned publications.

2 Tectonic context and data acquisition

Being the gateway between the Black Sea and the Aegean Sea, with narrow shallow connections (Fig. 1), the Sea of Marmara has become the focus of paleoenvironmental investigations. In particular, Late Quaternary climatic cycles, and especially associated sea level changes, let a strong sedimentary imprint, in shallow parts as well as in deep basins (Çağatay et al., 2000; Major et al., 2006; Vidal et al., 2010; etc.). Different hypothesis (including catastrophic flooding) have been proposed for the last “re-connection” of the three realms through Bosphorus and Dardanelles (Çanakkale Straits) sills (Ryan et al., 1997, 1999; Aksu et al., 1999; Eriş et al., 2007; etc.). For our purpose, the age of the last non marine-to-marine shift of the Sea of Marmara is a key point, both for the chronological frame of recent seismo-tectonic activity and for the change of volume, composition, and behaviour of re-mobilized sediments (impact of water density and circulation).

2.1 Structural setting and recent seismic activity

The whole circum-Mediterranean areas represent complex and active plate boundaries where subduction and faulting are responsible for high seismic hazards (in Ambraseys, 2009). Among microplates located between the two major Eurasian and African plates, the Anatolian plate (Fig. 1 insert; McClusky et al., 2000; Flerit et al., 2003; Reilinger et al., 2006) is highly investigated as its boundaries have produced catastrophic earthquakes and represent a high permanent seismic risk. More precisely, the northern limit of the Anatolian Plate corresponds to the – right lateral strike slip – North Anatolian Fault (N.A.F. in the following), which northern branch follows the Sea of Marmara from the Izmit Gulf (East) to the Aegean Sea (West) (Barka and Kadinsky-Cade, 1988;

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Armijo et al., 2002; Polonia et al., 2004; McNeill et al., 2004; Gasperini et al., 2011; etc.). Beside the dominant strike slip displacement, the importance of normal faulting and fast subsidence has been underlined, especially for the Central and Çınarcik Basins (Cormier et al., 2006; Carton et al., 2007).

The migration of historical catastrophic ruptures along the N.A.F. has been intensively investigated aiming to understand past and present stress distribution, and to improve seismic risk assessment (Toksöz et al., 1979; Ambraseys and Jackson, 2000; Ambraseys, 2002; Hubert-Ferrari et al., 2002; Altunel et al., 2004; Aksoy et al., 2010; Fraser et al., 2011; Uçarkuş et al., 2011; Meghraoui et al., 2012; etc.). In particular, two destructive ruptured sections have been surveyed (offset and length) respectively West and East of the Sea of Marmara: (1) the M_w 7.4 1912 Ganos event, (2) the M_w 7.4 1999 Izmit event. As the deep basins of the Sea of Marmara are bounded or crosscut by the N.A.F. (Fig. 1), several offshore surveys have been dedicated to analyze its submerged section. Morphological and sedimentary impacts of major recent earthquakes have been searched using: seismic reflection with different resolutions and penetrations, multibeam and side scan sonar, different types of coring, and remote operating vehicles (R.O.V.) (Armijo et al., 2005). The different results concern: (1) deep fluids ex- plusion related to seismo-tectonic activity (Géli et al., 2008; Tary et al., 2012; Burnard et al., 2012; etc.), (2) mass wasting and creep (Zitter et al., 2012; Shillington et al., 2012; (3) deep sedimentation specificities (McHugh et al., 2006; Sari and Çağatay, 2006; Beck et al., 2007; Çağatay et al., 2012; Drab et al., 2012); (4) detection and dating of historical co-seismic scarps (Armijo et al., 2005; Uçarkuş, 2010). Historical tsunamis reports and modelling (Altinok et al., 2011; Hébert et al., 2005) complete these different data, taking into account the fact that these phenomena are not system- atically associated to earthquakes (Hornbach et al., 2010). Small size lacustrine basins aligned along the N.A.F. East of Izmit have also been studied for paleoseismicity (Aşar, 2013).

The Sea of Marmara, and especially its deep basins, represents a favorable setting for the search of past seismic activity, and, by mean, an essential data source for re-

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gional seismic hazards estimation (cf. Armijo et al., 2005). In the following, we will focus on the Çınarcık and Central basins' recent sedimentary fills, which we studied aiming: (1) to reconstruct a succession of earthquake-induced sedimentary "events", and, (2) to use part of this succession to analyze the activity of the fault zone corresponding to the southern limit of the "inner" Central Basin (as named by Uçarkuş, 2010).

2.2 Data acquisition and processing

The here-used data were collected during two cruises: (1) the MARMACORE survey (on R/V *Marion-Dufresne*), (2) the MARMARASCARPS survey (on R/V *Atalante*). Three types of cores were retrieved: giant gravity piston cores (CALYPSO device), classical Kullenberg-type cores, and very short cores (35 cm) visually picked using the VICTOR R.O.V.. In parallel, high resolution (3.5 kHz) seismic profiles were acquired, and a complete survey with the VICTOR R.O.V. was dedicated to a high precision multibeam bathymetric survey of different deep scarps (Armijo et al., 2005; Uçarkuş, 2010). The second and third types of cores have been analyzed and yielded paleoseismic information (Uçarkuş, 2010; Drab et al., 2012). A preliminary analysis of 7 Calypso cores (with length ranging from 22 to 37 m) and 3.5 kHz imagery has been achieved (Beck et al., 2007). 3 of them (MD01-2425 in Çınarcık Basin, MD01-2429 and MD01-2431 in Central Basin, location on Fig. 1) were chosen for later detailed laboratory sedimentological analyses on split cores (Eriş et al., 2012, and this work):

- sediment composition: microscopic observations, Carbon and carbonates contents (LOI) XRF profiles in selected portions (AVAATECH instrument); bulk magnetic content (BARTINGTON contact sensor with 5 mm measurement interval);
- layering and texture (grain array):
 - X-Ray pictures (SCOPIX device, Migeon et al., 1998)
 - detailed grain size analysis (MALVERN Mastersizer, 2000): base-to-top paths on binary diagrams for turbidites/homogenites layers (in Beck, 2009; Eriş

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et al., 2012); particle shape analysis for silt-clay fraction (SYSMEX FPIA-2100 device);

- Anisotropy of Magnetic Susceptibility profiles (2 cm interval) on selected portions (Campos et al., 2013), completed with Anhyseretic Remanent Magnetization (ARM) and Isothermal Remanent Magnetization (IRM) (AGICO MFK1-FA Kappabridge, SQUID and 2G 760R systems).

The chronology is based on AMS ^{14}C calibrated ages: previously published measurements performed in Woods Hole Oceanographic Institution (NOSAMS facility) (in Beck et al., 2007), and a set of new measurements performed at CEA-Saclay (CNRS-INSU ARTEMIS facility).

3 Recent sedimentation in the Çınarcık and Central basins of the Sea of Marmara

Cores MD01-2425, -2429, and -2431 (location on Fig. 1) were respectively retrieved at 1215 m, 1230 m, and 1170 m depths, with 31.30 m, 37.30 m, and 26.40 m respective lengths. They respectively represent about 17 kyr, 14 kyr, and 18 kyr BP of continuous deposition. The compositions, layering-types, and the general chronostratigraphy, appear very similar between the three cores, thus we will summarize the results obtained for Core MD01-2425 as a reference. They confirm and complete the investigations previously achieved by Eriş et al. (2012).

3.1 The post-LGM succession in the Çınarcık basin (Core MD01-2425)

Figure 2 summarizes the succession within which, especially in the lower (non marine) part, numerous turbidites, often associated to an overlying homogenite, are intercalated. For this reason, we will describe separately these instantaneous sedimentary “events” and the continuous (“back ground”) slow sedimentation. A neat subdivision into two successions appears (see also Eriş et al., 2012): (1) a lower part with a mean

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high sedimentation rate (about 5.4 mm yr^{-1}) due to abundant intercalations of coarser instantaneous terrigenous inputs; (2) an upper part with lower mean sedimentation rate (1.3 mm yr^{-1}) and few coarser intercalations. The limit (discussed hereafter) roughly corresponds to the transition from non marine (only connection with the Black Sea) to marine (connection with Aegean Sea and Black Sea) setting. The whole core corresponds to the Late Glacial–Holocene period.

3.1.1 “Back ground” sedimentation

It is represented in the whole core by a hemipelagic silty–clayey mud. Although the word “hemipelagite” should be restricted to marine/oceanic deposits, we also use it for the non marine succession as, in both cases, it is a mixture of clayey-silty terrigenous fraction (clay minerals, quartz, plagioclase, amphibole, pyroxene, fresh micas, opaques) and planctonic biogenic or bio-induced particles (carbonate and silica: calcareous nanoplankton, Diatoms). Additional authigenic particles are locally abundant (sulphides, calcite, aragonite, Mn oxides).

The bulk carbonate content ranges from 8 to 10 % in the upper marine part; it reaches 16 % at the limit non marine/marine. Organic Matter (weight % dried sediment) ranges from 4 to 6 % in lower part, and 7 to 14 % in the upper part. The highest values characterize the 1380–980 cm so-called “sapropelic” interval. This O.M. enrichment has been previously reported in the different basins of the Sea of Marmara, and in the shallower zone between Tekirdağ and Central basins (Çağatay et al., 2000; Reichel and Halbach, 2007; Beck et al., 2007; Vidal et al., 2010). The different proposed ages are in agreement and a 11-to-7.5 kyr BP period (cal ^{14}C without reservoir correction) can be attributed to this particular episode.

We include into the “background” sediments numerous silty–sandy laminated intervals present in the upper marine part. They are 1 to 3 cm thick and display millimetric parallel planar bedding, involving subtle changes in grain size (up to very fine sand) and mineralogy of detrital components. They have been observed in the three basins

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part of the succession (from about 16 kyr BP to the marine/no marine limit (our “reference layer”, Figs. 2 and 3)), homogenites + turbidites (HmTu) appear more frequent in Core MD01-2425 (Çınarcık Basin) than in Core MD01-2431 (Central Basin). This difference is also mentioned by Drab et al. (2012) for the last 2.5 kyr BP (marine section), based on short piston core; these authors also proposed several event-by-event correlations and attributions to historical earthquakes.

Despite the X-ray pictures resolution and sampling intervals of the different logs, we could not ensure an “event-by-event” correlation between Çınarcık and Central Basins along the whole non marine section. Conversely, an “event-by-event” correlation within the Central Basin could be proposed for the last 2 kyr preceding the main hydrologic change (blue rectangles on Fig. 3). Figure 4a and b shows the location of Cores MD01-2429 and MD01-2431 and the overall correlations previously proposed by Beck et al. (2007) and Eriş et al. (2012) based on 3.5 kHz seismic reflection profile.

4 Inferred co-seismic sedimentary events on both sides of the southern scarp of the Central Basin

The two analyzed sites are on both sides of the southern limit of the “inner” Central Basin (Fig. 4a) with a small relative depth difference (50 m at 1200 m b.s.l.). Figure 4b displays their position with respect to a major active fault scarp. Previous preliminary observations of these cores had demonstrated that the high difference of mean sedimentation rates between the two sites (Fig. 4b) was essentially due to the difference of instantaneous sedimentary events thicknesses (Beck et al., 2007).

Assuming the synchronicity of the “reference layer” in the two cores, a detailed analysis was later performed downcore, starting immediately below. For the fine-grained “back ground” sedimentation, because of its hemipelagic-type deposition, the same sedimentation rate was assumed at the two sites. The proposed layer-by-layer correlation (Fig. 5) is based on: (i) precise delimitation of hemipelagic intervals, with same thicknesses, (ii) similarities of subdivisions within HmTu composite layers. The cor-

relation could be achieved for a 2 m succession in Core MD01-2431 which appears equivalent to a 6.2 m succession in Core MD01-2429, the whole for a 2 kyr duration. 11 homogenite + turbidites events (HmTu) account for the difference. For the thickest ones (HmTu A, C, E, H, K) the homogeneous upper term accounts for about 90 % of the thickness increase in the deeper site. Assuming an earthquake origin for these sedimentary events, and the tendency of the associated suspension to settle in deepest areas (in Chapron et al., 1999), we consider the increased fills of the downgoing side as successive “seals off” of the created co-seismic scarps (Fig. 6 insert, case 2a). In the Lesser Antilles, Beck et al. (2012) described an active normal fault upon which the sea floor is maintained flat and horizontal, being each co-seismic offset quite exactly compensated by a coeval silty-sandy homogenite (Fig. 6 insert, case 2b). We tentatively applied their 2b model to the Central Basin events. 10 of the 11 events were plotted on an age vs. thickness difference log (Fig. 6). 6 of them led to significant values between 40 cm to 160 cm (Fig. 6).

Although the investigated sediments are recent with a reduced depth-in-core, a possible compaction effect has to be discussed as: (i) it concerns mainly clayey-silty material, (ii) the thickness of the homogenite term is up to ten times higher on the hanging wall with respect to the footwall. Based on this differential compaction, a 10 % maximum estimate is thus proposed for a correction of the thickness difference (leading to about 44 to 178 cm).

The inferred offsets were separated by variable time intervals (100 to 550 yr); if taking into account the 11 events, a mean 180 yr interval is deduced. The time distribution is in agreement with previously published paleoseismic results based on sedimentary record in the same area (Beck et al., 2007; Drab et al., 2012). In the present study, a precise rupturing site could be attributed to the sedimentary events.

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5 Discussion

The proposed use of homogenites + turbidites (HmTu) to analyze subaqueous active faulting along the inner Central Basin led to estimate a set of inferred co-seismic offsets, for a 2 kyr-lasting period. As it is a 2-D approach, the results only concern a vertical component (cf. Figs. 4 and 6). The latter may represent either the vertical component of an oblique slip displacement or a subvertical (normal here) one. West of the Central Basin, a historical scarp was observed and analyzed (Armijo et al., 2005; Uçarcuş, 2010) displaying locally low angle dipping slickensides. This site belongs to a NAF section with dominant strike slip behaviour. Applying such low angles displacements to account for our vertical offset values, especially the highest, would result in anomalously high lateral offsets (e.g. 15° dip and 144 cm vertical component). Otherwise, the here-analyzed site is considered as a limit of a pull apart basin (Armijo et al., 2005; Uçarcuş, 2010), and different investigations highlighted the importance of vertical component in Izmit Gulf and Tekirdağ Basin (Cormier et al., 2006; Carton et al., 2007). Based on tsunami modelling applied to the Sea of Marmara, Hébert et al. (2005) conclude to the importance of vertical offset related to faulting or to submarine landslides. In the following, we thus assumed that our estimated values represent dominant vertical throws, i.e. normal offsets.

With respect to an approach in terms of paleo-magnitude (M_w) of the earthquakes associated to estimated offsets, additional data are needed to propose an actual, complete, paloseismic approach: horizontal length and lower limit of rupturing. Nevertheless, we propose estimations for two inferred offset values (44 cm and 178 cm; Fig. 6; with compaction effect). We consider:

- a 70° mean fault dip as displayed by deep seismic reflection data from Laigle et al. (2008)
- two possibilities for the sea bottom rupture horizontal length: 8 km if considering the total length of the SW side of the Inner Central Basin “losange”, or 5 km if considering only the eastern continuous scarp (see on Fig. 4a)

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post-“reference layer” interval (the marine part) shows a 20 m “additionnal” thickness, leading to about 70 m of total vertical displacement (approx. 75 m slip with a mean 70° fault plane dip). This could correspond to a 6 mm yr⁻¹ mean normal offset, which distribution into creep vs. co-seismic increments has to be further discussed. Considering a relatively low number of sedimentary events in the Central Basin with respect to Tekirdağ Basin, Drab et al. (2012) underlined different explanation, including partial creeping along the Central segment. For a longer period, we observe a similar difference between Central Basin and Çınarcık Basin, with evidences of a specific behaviour of the southern limit of the former.

6 Conclusions

The detailed sedimentological analysis of a sedimentary accumulation bounding a subaqueous active fault confirmed the occurrence of co-seismic offsets through coeval specific events. It permitted to estimate their values and also confirms a dominantly co-seismic behaviour (null or negligible creep) at least for a 2 kyr time interval. With up to 1.8 m normal slip values, added to local structural and seismological data, this archive led to propose paleo-magnitude values (M_w between 5.9 and 6.6) compatible with historical data. These results bring additional arguments for seismic hazard assessment along the central portion of the N.A.F. (Sea of Marmara’s Central Basin).

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Table 1. Estimation of moment magnitudes M_w for the southwestern scarp of the Central Basin.

		brittle/ductile limit	Horizontal rupture length	
			5 km	8 km
3.0 10^{11} dyne cm^{-2} shear modulus	47 cm offset	12 km 20 km	5.9 M_w 6.1 M_w	6.1 M_w 6.2 M_w
2.5 10^{11} dyne cm^{-2} shear modulus	47 cm offset	12 km 20 km	5.9 M_w 6.0 M_w	6.0 M_w 6.1 M_w
3.0 10^{11} dyne cm^{-2} shear modulus	190 cm offset	12 km 20 km	6.3 M_w 6.5 M_w	6.5 M_w 6.6 M_w
2.5 10^{11} dyne cm^{-2} shear modulus	190 cm offset	12 km 20 km	6.3 M_w 6.4 M_w	6.4 M_w 6.6 M_w

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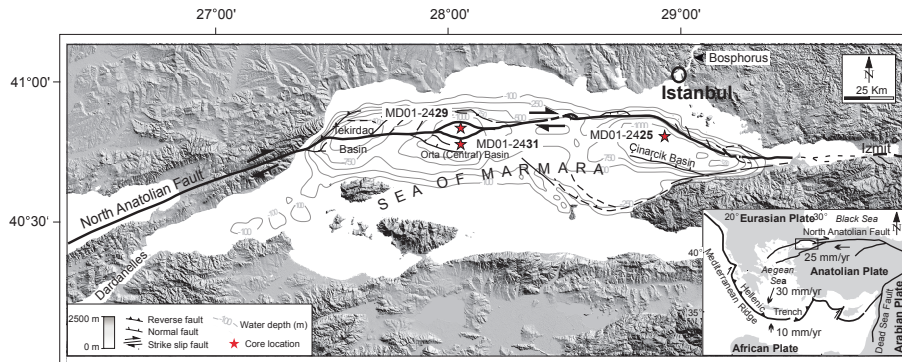


Figure 1. The Sea of Marmara and the North Anatolian Fault: simplified bathymetry and active structures. Location of analyzed core. NAF geometry simplified from Armijo et al. (2002, 2005); GPS kinematics from McClusky et al. (2000), Reilinger et al. (2006).

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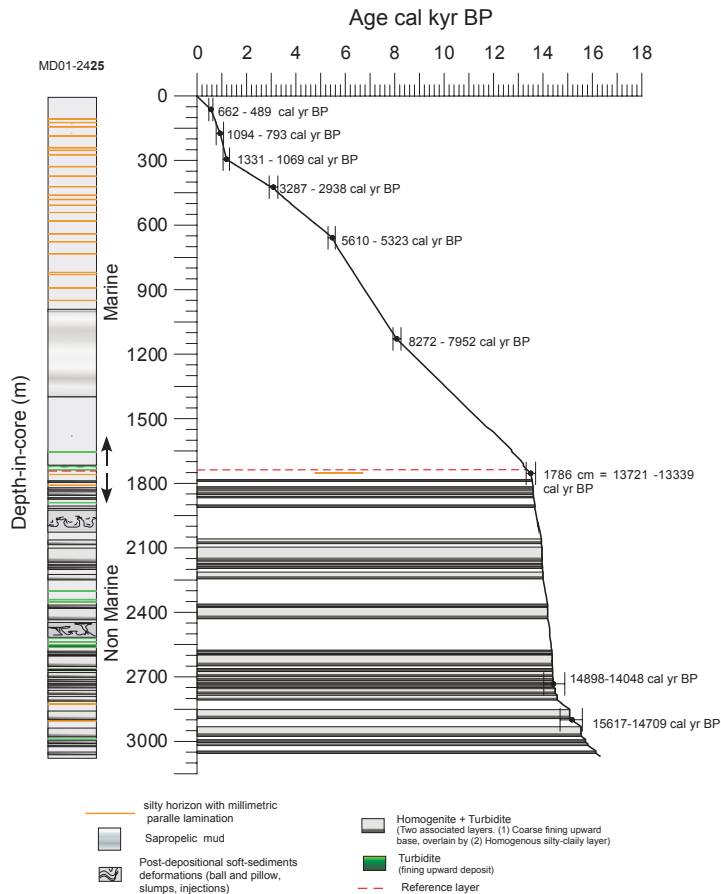


Figure 2. Age/depth curve of Core MD01-2425 (Çınarcık Basin) displaying major instantaneous deposits (homogenite + turbidite). Red dashed line indicates the limit between non marine (below) and marine sequences (reference layer displayed on Figs. 3 and 5); pLGH: pre-Late Glacial Homogenite (Beck et al., 2007).

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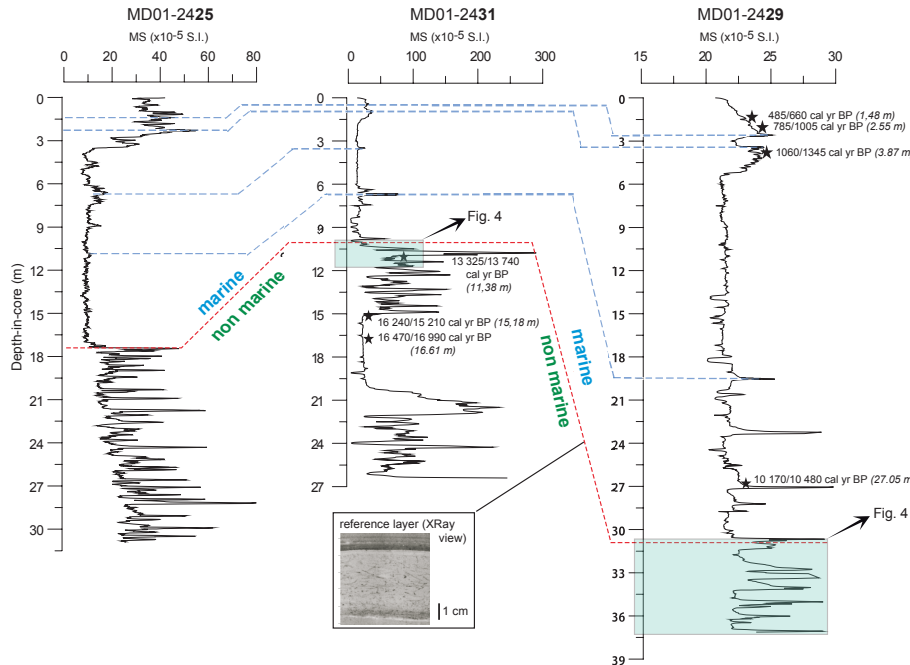


Figure 3. Chronostratigraphic correlations between the Çınarcık Basin (Core MD01-2425) and the Central Basin (Cores MD01-2429 and -2431). Blue rectangles correspond to close up and detailed correlation on Fig. 5.

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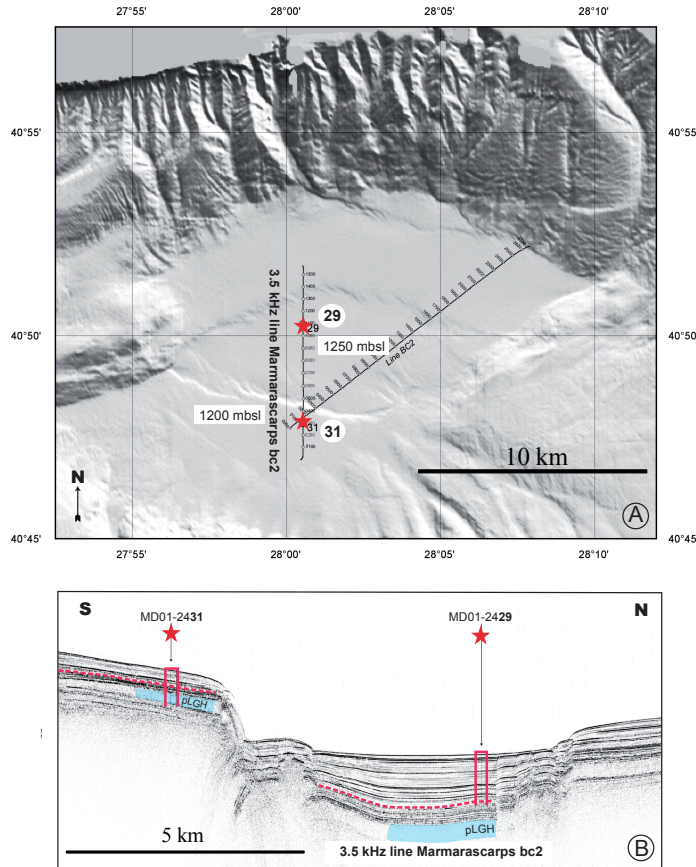


Figure 4. Detailed location of Orta/Central Basin’s long cores. **(A)** Bathymetry taken from Ranjin et al. (2001); **(B)** very high resolution seismic profile from MARMARASCARPS survey (Armijo et al., 2005; Uçarkuş, 2010). Red dashed line indicates the limit between non marine (below) and marine sequences (also underlined on Figs. 3–5).

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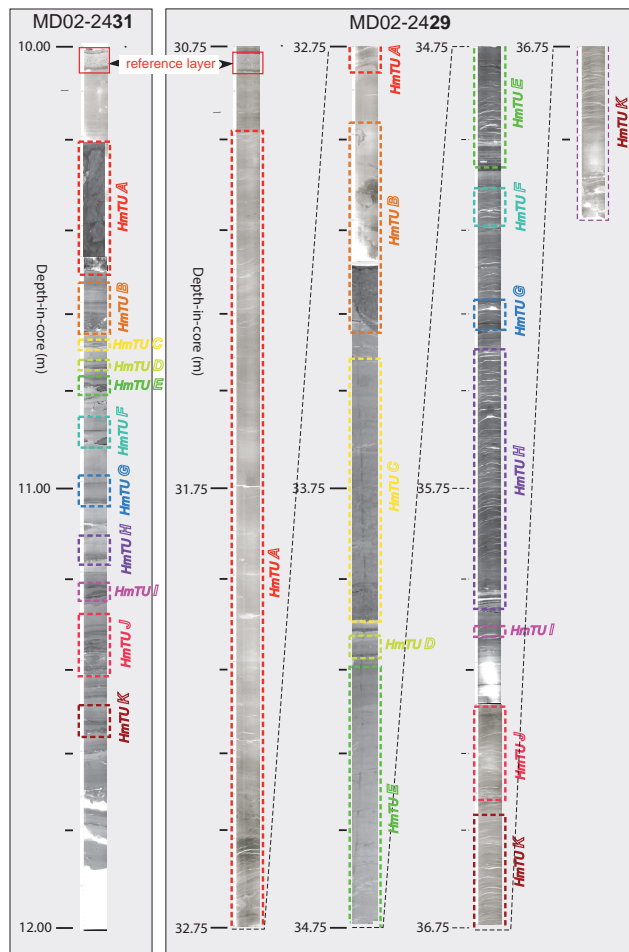


Figure 5. X-ray close up of two synchronous portions of Cores MD01-2429 and MD01-2431, displaying individually correlated sedimentary events (homogenite + turbidite).

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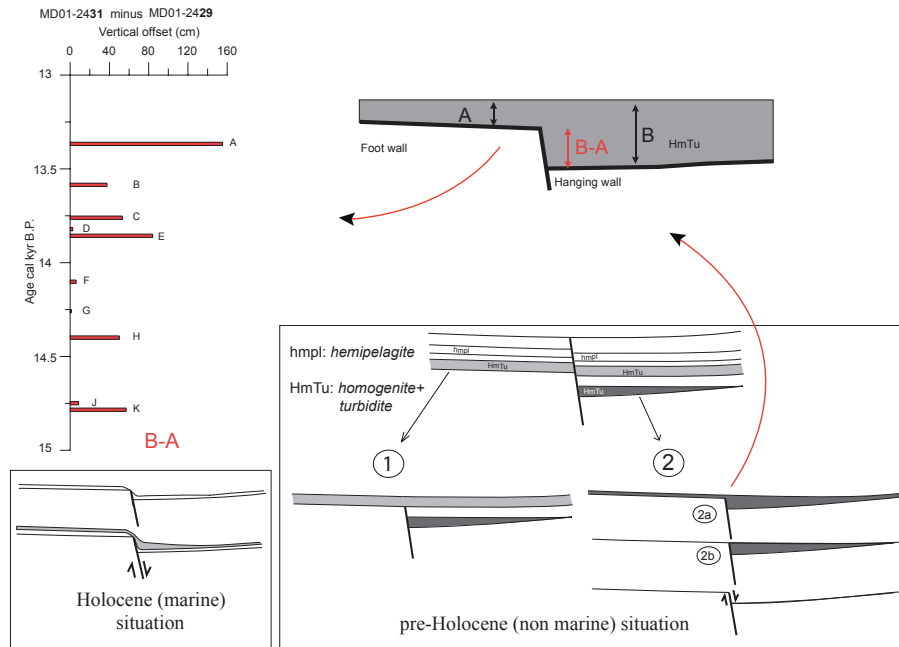


Figure 6. Successive inferred individual co-seismic offsets deduced from homogenite + turbidites (HmTu) thickness differences (insert sketch modified from Beck et al., 2012).

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