# Determination of probable underwater failures and modeling of tsunami propagation in the Sea of Marmara

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**Abstract.** In case of earthquakes or submarine failures in the Sea of Marmara, tsunamis may pose a real threat to densely populated coastal areas. In order to establish a base for mitigation studies, knowledge of the source region, generation mechanisms, seabed morphology, propagation, and coastal amplification of tsunamis should be known. The sea bottom characteristics have been investigated by a series of recent marine surveys. Since the underwater failures were most likely triggered by earthquakes, probable potential source regions, mainly along the continental slope, were defined. The generation of a tsunami offshore Yalova, in the east part of this inland sea, is simulated on the basis of an underwater landslide scenario. A mathematical model *Two-Layer* was used to define and discuss the propagation and distribution of maximum water surface elevations along the shores.

## 1. Introduction

Submarine mass movements such as underwater landslides or slumps are responsible for the generation of tsunamis. Understanding more about generation mechanisms of tsunamis with relation to submarine failures is becoming more important for the mitigation efforts on tsunami hazards. In this sense determining the source mechanisms and characteristics of past tsunamis forms an important part of the job. The surface waves generated by submarine failures are governed by different parameters describing landslide geometry and kinematics (Wiegel, 1955; Iwasaki, 1982; Heinrich, 1992; Watts, 1998; Grilli and Watts, 1999). Studies on numerical models for tsunami simulation and comparison of theoretical results with observations are useful for estimating future tsunamis expected in the seismically active areas (Nagano *et al.*, 1991; Shuto *et al.*, 1995). Imamura and Imteaz (1995) and Imamura *et al.* (1999) have recently developed and used a more realistic computational tool.

The sea of Marmara has high seismologic activity (Fig. 1a). Major earth-

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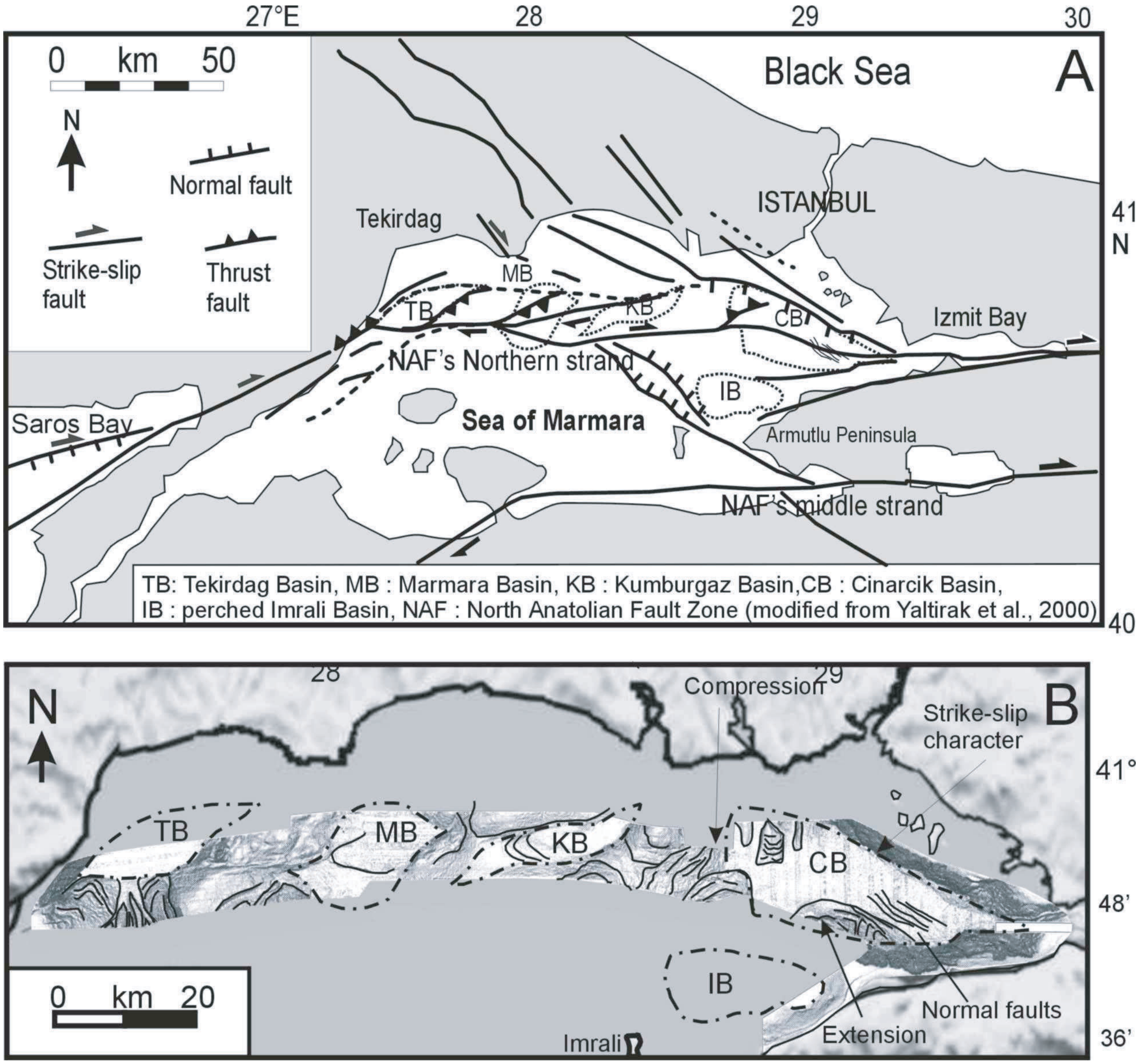



**Figure 1**: (a) Deep troughs of the Sea of Marmara within the tectonic frame. (b) Underwater failures along the unstable steep slopes, as prominent developments of sonar imagery almost enable the seafloor to be seen (modified from Alpar, 2000). Irregularities along the margins represent slumping.

quakes may trigger underwater failures, thus frequently causing tsunamis. More than 40 major tsunamis were reported (Altinok and Ersoy, 2000). Review of the available geophysical marine data suggests that the marginal slopes of deep basinal areas are probable tsunami source regions. The source will be a displacement caused either by faulting or sediment slumping. Eventually, the magnitude will depend on the source location, propagation of the waves, and run-up.

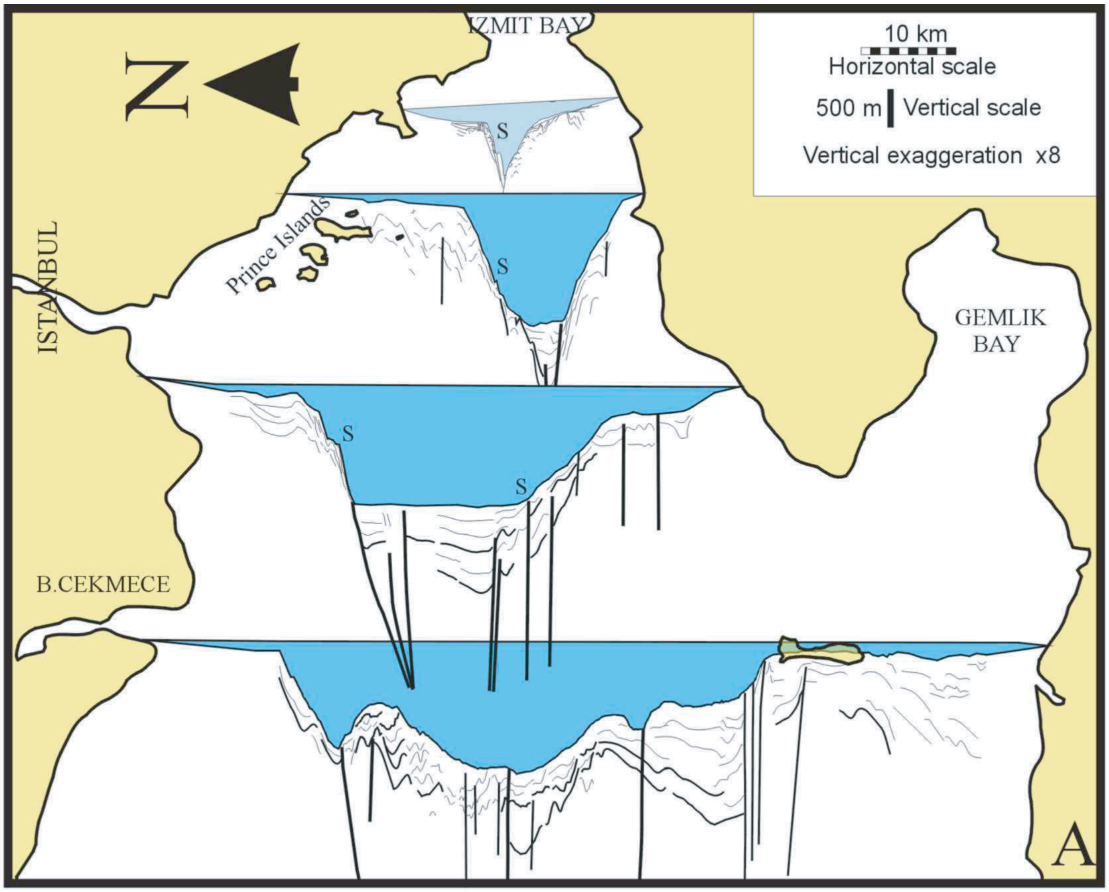
The ability to understand the potential tsunami sources, to develop effective models, and to carry out the risk assessment studies mainly depends on knowledge of the slope failures. Therefore, we will review slope failures on the basis of multibeam bathymetry (Fig. 1b) and seismic reflection profiles (Fig. 2a). Using a tsunami simulation model *Two-Layer*, which was used in some earlier studies for earthquake and landslide occurrences (Alpar *et al.*, 2000; Ozbay, 2000), the generation, propagation, and coastal amplifications of tsunamis related to underwater landslide scenarios are discussed.

## 2. Offshore Evidence for Tsunami Source

The Sea of Marmara is located on the right lateral strike slip of NAF's northern branch, which is along Izmit Bay, three deep Marmara basins (>1100 m), and Saros Bay (Fig. 1a). Even though sediment samples and hydrocarbon wells are scarcely distributed and cannot be easily utilized to assess tsunami risk, a wide range of swath bathymetric and seismic data have been acquired over most of this sea.

Narrow northern and wider southern shelves are separated by a structurally complex zone of rhomboidal transtentional deep basins (>1100 m) aligned along the NAF's northern strand (Fig. 1a) (Alpar, 2000). The Tekirdag Basin, westernmost of these steep-flanked basins (10°–30° slopes), is an elongate, SW-trending depression (Fig. 1b). The Marmara Basin is also an elongate depression, separated from the Kumburgaz Basin to the east. Cinarcik Basin is the easternmost and deepest (1270 m) submarine depression. It is the most important slump prone area in this sea (Fig. 1b). On seismic data, steep slopes, scarp areas, and slumps can be readily defined (Fig. 2a). Over the broad northern shelf, actual muds as thick as about 3 m on top of 110–140 m thick Plio-Quaternary terrigeneous sediments consists of potential slide horizons. The northern slope is rather steep, easing the engendering of underwater failures. Slumps can be observed on the 3 km wide steep (∼17° slopes) northern continental slopes. On the other hand, the shelf to the south of Cinarcik Basin is rather narrow. The thickness of the subhorizontally stratified Plio-Quaternary sediments ranges 20–30 m, much less if compared to the northern one. However, on seismic data, slumps are not so evident on the 4–6 km wide southern slope (∼7–10° slopes). Between the northern and southern slopes, which locally may be as steep as 30–40°, there are unconsolidated basinal sediments. They are thick and chaotic possibly due to slumped sediments (Fig. 2a).

In general, for the steep-flanked Cinarcik Basin, sediments exhibiting a high degree of mobility occur in areas where large normal faults exist. In



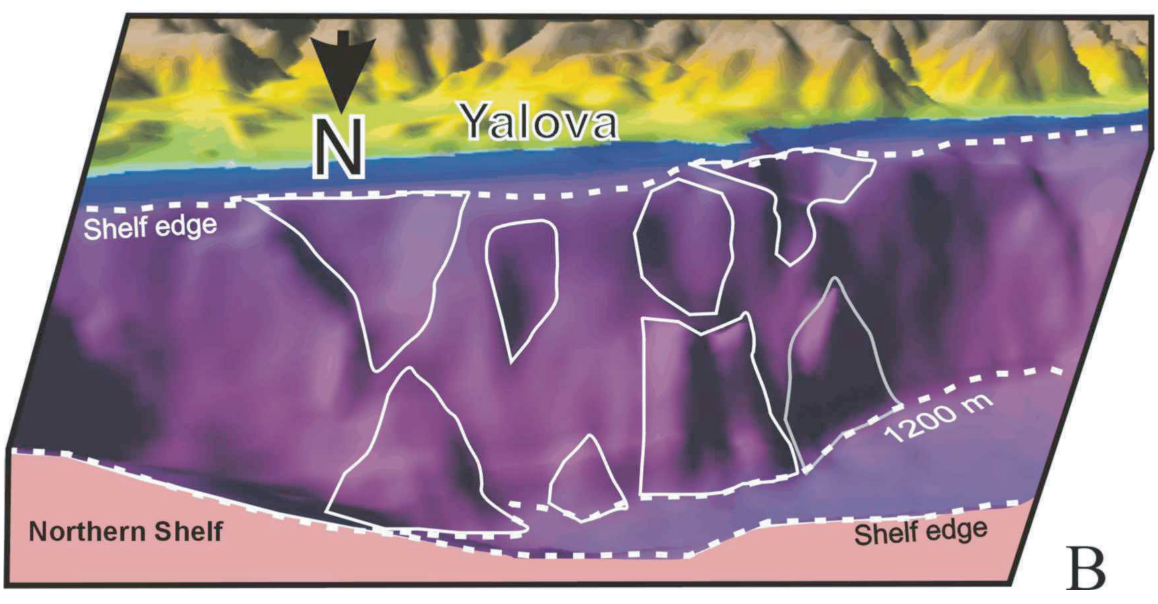




**Figure 2**: (a) Seismic block diagram in the Eastern Marmara (simplified from Alpar and Yaltirak, 2000). (b) Oblique 3D view looking toward the southern continental slope of the Cinarcik Trough over the Istanbul shelf (1500 m asl). NW-SE trending failures can be observed as irregularities on the multibeam data along the margin. Vertical exaggeration is 7 times. Level of detail (LOD) for digital elevation model is 13% and LOD for raster is 79% (Courtesy Berkarda Lab. of Istanbul University).

fact, the faults of the negative flower structure are integrated with the slopes. During the motion of strike-slip NAF's northern branch, these faults become active and cause slope failures, especially in the eastern sea of Marmara (Alpar, 2000). Beyond the slope gradient and occurrence of normal faults, the amount of sediment deposited, fluid content, and porosity control the degree of stability of sediments. The sediment type present in the basins and average sedimentation velocity are critical in estimating sediment stability in the context of earthquake shock. The average deposition rate is on the order of 0.4 mm/year at the continental shelf regions and 1–2 mm/year at the deep region of the basins, due to the depositional increment of mud layers in trenches transported by turbidity currents and underwater landslides (Alpar, 2000). On the basis of their morphology, probable risk areas for potential submarine landslides can be defined along the slopes. These areas are in good correlation with the basin bounding faults, implying that tsunamis in the region are generally engendered by coseismic landslide generations. Along the northern shores of the Armutlu Peninsula, the underwater landslides have characteristic scar morphology. Their headscarps, steep upslope regions at the top of the scar, seem to be well integrated with the shelf edge (Fig. 2b). Failed material at the base of these failures could not be clearly defined on the seismic sections, which are scarce.

On the other side along the eroded continental slopes of the Istanbul shelf, the slope failure deposits are cohesive landslides. Cohesive sediments are more tsunamigenic than non-cohesive. These landslides are associated with a particular scar directly up gradient. Their headscarps are also generally integrated with the shelf edge as very well defined on shallow seismic data (Fig. 2a). The average gradients of the scar slope and the area adjacent to failure are not so different, therefore not easily distinguished by the multibeam sonar data (Fig. 1b). Underwater failures engendered in weaker sediment, which are usually placed offshore drainage areas, tend to be somewhat larger (Fig. 1b). For example, in the Cinarcik Basin, the deposits slumped to the side of the basin reach down to the lowermost point of the slope where the 1150–1270 m deep flat base of the depression starts abruptly (Figs. 1b and 2b).

In order to define the degree of the tsunami threat along the coasts of the sea of Marmara, hydromechanical characteristics of the tsunami waves caused by underwater landslides should be investigated. In order to reach realistic conclusions and develop mitigation studies against possible hazardous effects, modeling is believed to be the most convenient tool.

## 3. Modeling

Until recently it was common to choose a water surface deformation as the initial condition for mathematical models for tsunamis. The models are based on the non-linear form of long-wave equations and proper boundary conditions. However, the kinematic characteristics of mass flows at the sea bottom due to landslides or slumps may cause different types of initial wave profiles. Therefore, it is important to include the movement of the sea bot-

**Table 1**: Characteristics of landslides selected for modeling of tsunami.

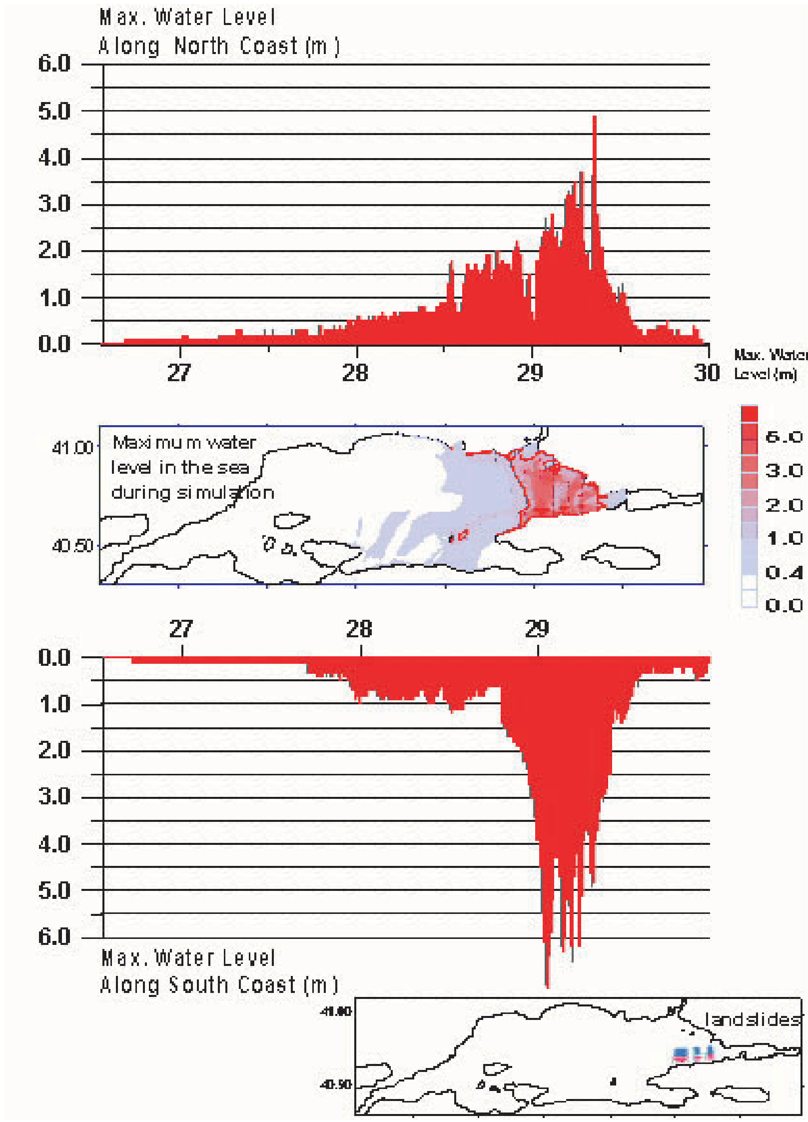
| | West landslide | Central landslide | East landslide |
|---|---|---|---|
| Assumed location of landslide | 29.05°E, 40.65°N | 29.17°E, 40.67°N | 29.27°E, 40.69°N |
| Water depth at the slided area | 250 m | 280 m | 300 m |
| Water depth at the deposited material | 700 m | 800 m | 600 m |
| Width (along EW direction) of the area of slided and deposited materials | 9 km | 4.5 km | 4.5 km |
| Length of slided area (along N-S direction) | 4.5 km | 4.5 km | 4.5 km |
| Length of deposited area (along E-W direction) | 9 km | 9 km | 9 km |
| Approximate height of slided material | 9 m | 9 m | 9 m |
| Approximate height of deposited material | 4.5 m | 4.5 m | 4.5 m |

tom in the theoretical approach for the tsunami generation mechanism. As a recent development of tsunami modeling, the model *Two-Layer* was created in Tohoku University Disaster Control Research Center in Japan (Imamura and Imteaz, 1995) and is used in this study. *Two-Layer* solves the sets of non-linear long-wave equations simultaneously within two interfacing layers with necessary kinematic and dynamic boundary conditions at the sea bed, interface, and water surface. Two interfacing layers are the water body in the sea and the moving mass at the bottom. After the sensitivity analysis for different input parameters such as the geometry of the basin, the volume and size of the slided mass, and the bottom slope by testing in a regular shaped basin (Ozbay, 2000), the model has been applied for a landslide generated tsunami scenario occurring in the eastern Sea of Marmara. The computation domain of the Sea of Marmara for this application is chosen as bounded by the longitudes 26.55° and 29.96° and the latitudes 40.2977° and 41.1066°. The grid size is taken as 300 m.

As a case study, a scenario of underwater landslides is assumed to occur at the southeast part of Cinarcik Basin, offshore the towns of Yalova and Cinarcik. The three-dimensional bathymetry of the area is known (Fig. 2b). Although the stability of slopes is uncertain, there are some interesting parts on this slope, which may be considered to fail partly with a triggering mechanism. In this study, three underwater landslides are considered and defined by their coordinates, water depth, width, length, and height of slided and deposited sediments (Table 1).

In the application of the model the simulation is taken as 90 min in real time. The sea state at different time steps, the water surface fluctuations at different selected stations, and the maximum water surface elevations are computed along the shores and stored in different files during simulation. The evolved initial wave and the distribution of maximum water surface elevations in the sea as a layout, and the distribution of maximum water elevations near the north and south shores are shown together in Fig. 3a. The distribution of arrival time of the maximum water surface elevation in the Sea of Marmara is plotted in Fig. 3b.

The results of the simulation imply that the arrival time of tsunami waves



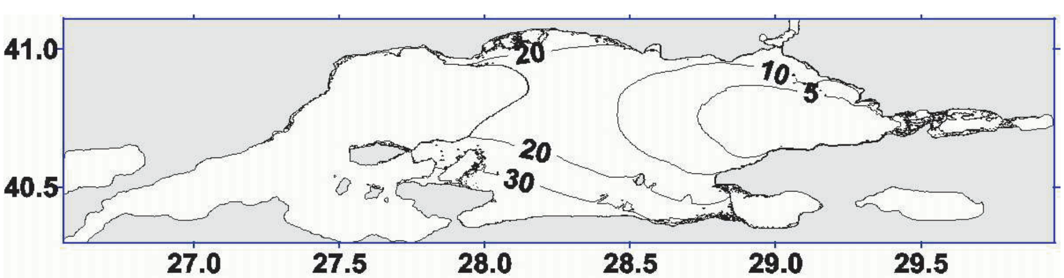




**Figure 3**: (a) Tsunami scenario according to the probable underwater landslides offshore Yalova. (b) Distribution of arrival time (minutes) of the maximum water surface according to the tsunami generation by probable underwater landslides offshore Yalova.

due to the scenario of landslides are less than 5 min to southern coasts and around 10 min to northern coasts (Fig. 3b). In addition, the water surface will exceed 3 m along approximately 15 km of coastline of the northern and southern shores (Fig. 3b).

## 4. Discussion and Conclusions

In order to determine the slope failure potential as a possible tsunamigenic source in the Sea of Marmara, the multibeam data, and the shallow and deep seismic reflection data of various marine surveys are analyzed. The deep basins in the Sea of Marmara with steep, unstable slopes are tsunami-prone areas. Coseismic landslide generation is the most common tsunami event in the Sea of Marmara. Even though some occasional tsunamigenic events not accompanied with an earthquake were reported, especially in Izmit Bay and the southern shores of the Prince Islands, they are still not defined due to the lack of instrumental data, e.g., mareogram records.

On the basis of these geophysical data, the underwater landslide and slump traces and potential landslide areas in eastern Marmara are pointed out in this study. A scenario of tsunami generation related to three landslides at the offshore region of the towns of Cinarcik and Yalova is selected. The model *Two-Layer* is applied to understand the propagation and coastal amplification of this tsunami in the region. According to the model study, the tsunami waves that may be generated offshore Cinarcik and Yalova can reach the nearest coastal area within 5 min. They can make high water surface elevations and strong currents at the shallower regions in eastern Marmara coasts which may be destructive at some localities depending on the coastal morphology at low lands and the existence of vulnerable facilities such as small craft harbors. We also point out the importance of further marine surveys for determining the stability of continental slopes. The seismic properties of the region and possible effects of a future tsunami should also be considered during the designing stage of coastal structures for the mitigation of the tsunami component of natural hazards.

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