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Submarine landslides and fault scarps along the eastern Mediterranean Israeli continental-slope

Oded Katz [a,*], Einav Reuven [a,b], Einat Aharonov [b]

[a] Geological Survey of Israel, 30 Malkhe Israel St., Jerusalem 95501, Israel
[b] The Institute of Earth Sciences, The Hebrew University, Edmond J. Safra Campus, Givat Ram, Jerusalem 91904, Israel

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ABSTRACT

The present work maps and studies the continental slope off the southeastern Mediterranean Israeli coast. Bathymetric grids with 15–50 m/pixel resolution were used to map over four hundred submarine landslides and numerous fault scarps exposed on the sea floor.

Landslide scars are found at water depth ranging between 130 m and 1000 m, where slopes exceed a critical gradient of about 4°–5°. Landslide surface areas range from 0.0024 km^2 to 91 km^2, where the observed size distribution has a peak (roll over) showing that the most probable landslide area is 1.6×10^{-2} km^2. In general landslides in the north of the studied area are smaller and occur at shallower depth than the southern ones. Landslides show a hierarchical pattern, resulting from sequential, retrograding, slope-failure events and are also observed to interact with a group of faults oriented sub-parallel to the coast. These faults are a result of salt tectonic related extension, their scarps forming elongated step-like morphological features rupturing the surface of the continental slope, as well as the deeper sea floor.

The morphology of the landslides as well as their cross cutting relation with the faults scarps, suggest that these landslide are recent, apparently younger than 50,000 years. The triggering mechanism is not clear yet, though several conditions which are known to promote slope instability prevail in the studied area: submarine slope gradients are close to the inferred critical slope angle; continuous sedimentation increases the load on the slope; active salt tectonic results in an overall extension and surface rupturing by normal faults; the studied area is merely 100 km away from seismogenic zones; and finally, apparent existence of gas close to the surface. Hence, it is suggested that submarine slope failure events in the studied area are also possible in the future.

1. Introduction

Submarine landslides are a result of submerged slope-failures, generating sediment transport from the continental shelf and upper slope toward the deep basins (e.g., Hampton et al., 1996; Mulder and Cochonat, 1996; McAdoo et al., 2000; Hutton and Syvitski, 2004; Lee, 2009). In general, landslides initiate as slope-material failure, followed by down-slope movements of coherent masses of sediment on discrete failure planes (Masson et al., 2006). Submarine landslides occur in many environments worldwide, such as oceanic volcanoes, river deltas, submarine canyons and open slopes (Lee, 2009), and are known in the Mediterranean Sea as well (Camerlenghi et al., 2010; Urgeles and Camerlenghi, 2013), where they occur in various passive and active margins settings.

Submarine landslides are recognized using bathymetric mapping and seismic profiling according to their distinct morphological (Masson et al., 2006; Bull et al., 2009; Chaytor et al., 2009) and structural indicators (McAdoo et al., 2000; Twichell et al., 2009; Camerlenghi et al., 2010; Frey-Martinez, 2010; Urgeles et al., 2010; Winkelmann et al., 2010). Submarine landslides are abundant even on very shallow slopes, and those that occur on open slopes tend to be the largest (Booth et al., 1993). The runout of landslides is highly variable: the mass may arrest soon after failure, it may creep, or it may turn into rapid debris or turbidity flows (Tripsanas et al., 2008), running up to hundreds of kilometers before arresting (Shaller and Smith-Shaller, 1996; Twichell et al., 2009). For this reason submarine landslides may endanger offshore submerged facilities (e.g., Locat and Lee, 2002; Thomas et al., 2010). In addition, rapid underwater landslides also endanger adjacent coastal areas by generating tsunamis (e.g., Longva et al., 2003; Sultan et al., 2004; Tinti et al., 2006; Tappin, 2010).

Given the hazard that submarine landslides pose, it is not surprising that they are the focus of numerous studies worldwide (e.g., Masson et al., 2006). In particular, the densely populated Mediterranean coast has been subject to intense study. Recently, Urgeles and Camerlenghi (2013 and reference therein) compiled a catalog of close to 700 late Quaternary submarine landslides around the Mediterranean, investigating landslide size distributions and triggering mechanisms. Urgeles and Camerlenghi (2013), found that landslides currently exposed on the Mediterranean sea floor were not necessarily triggered by

* Corresponding author.
E-mail address: odedk@gsi.gov.il (O. Katz).

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earthquakes, rather fluids play a major role in submarine slope instability (observed slope failure is often related to pockmarks and mud volcanoes). They also suggested that climate-induced stress changes (sedimentary load, sea level, bottom temperature effect on fluid flow, gas hydrate, and gas systems) during the last deglaciation phase, may have had a significant effect on submarine slope stability. However, the landslide catalog presented in the above works includes only the large size-range of landslides and is incomplete for landslides smaller than 1 km^3 (Urgeles and Camerlenghi, 2013). In addition, the landslides relation to submarine faults was not studied, perhaps because faults do not play as important role for large landslides as they do for smaller ones (this relationship will be addressed in the present work).

The present work focuses on medium to small underwater landslides, a size range that is rarely mapped underwater and was not mapped in the Mediterranean previously (Urgeles and Camerlenghi, 2013). We center our study on the continental slope off the southeastern Mediterranean Israeli coast (Fig. 1), and use newly released high-resolution bathymetric grids to map in detail landslides and fault. The resulting landslides catalog includes, for the first time around the Mediterranean, landslide size-range smaller than 1 km^3, and records the landslides spatial relation to submarine faults. The objectives of the work are: to map and analyze the landslide sizes and spatial distributions in the studied area, to study the mechanisms of submarine slope failure considering also its possible relation to the faults, to assess the time frame for the landsliding activity and then, to use these accomplishments to get a better understanding of the submarine landslide hazard relevant to the densely populated eastern Mediterranean shore.

The high-resolution mapping of submarine landslides and faults gives a unique opportunity to study how deep-seated salt tectonic affect temporally and spatially surface processes shaping passive margins. Another aim of global implications is mapping the population of small-to-medium sizes landslide in the Levant basin. This size range of landslides is not studied routinely, and we aim to characterize their unique locations, triggers, ages, activity, and distributions.

1.1. Regional setting

The studied coast (Fig. 1) is controlled by northward along-shore transport of sediments from the Nile Delta (Stanley et al., 1998; Brenner, 2003). During Pliocene–Quaternary a 1–2 km thick wedge of mainly Nile-derived clay-rich siliciclastic sediments accumulated in the eastern Mediterranean over sandy turbidities and Messinian evaporites (e.g., Gvirtzman and Buchbinder, 1978; Tibor et al., 1992; Ben-Gai et al., 2005). Recent sedimentation rates recorded on the studied continental slope (up to water-depth of 900 m), based on cores, are 25 cm/ky to 130 cm/ky (Luz and Perelis-Grossowicz, 1980; Schilman et al., 2001; Hamann et al., 2008; Kuhnt et al., 2008; Almogi-Labin et al., 2009). Sedimentation rates recorded for the deeper part of the SE Mediterranean (beyond the continental slope) are significantly lower, <5 cm/ky (Calvert and Fontugne, 2001).

The current submarine offshore morphology in the study area consists of up to 200 m deep shelf that is up to 20 km wide in the south and narrows northwards. Slope gradients on the shelf are generally small, not more than 2° (see Fig. 2 for water depths and slope gradients). Further to the west, on the continental slope, between 200 m and 1000 m water depth, the slope steepens to 4° or steeper values in some locations. The continental slope consists of two lateral provinces (Fig. 1): The submarine canyons province in its northern part (north of Latitude 32.75°N) (not studied here), and the open slope province, hereafter the studied area, further south of this Latitude.

Two main types of mass movements are observed along the open slope: The first type consists of very large slumps, over 1 km thick, with their primary sliding-plane located within the Messinian evaporites (Almagor and Garfunkel, 1979; Almagor, 1984; Cartwright and Jackson, 2008). The internal deformation within these landslides, also known as 'disturbances' (Garfunkel, 1984), consists of landward block rotation on listric growth faults rooted at the underlying evaporites. Two sites across the studied continental slope are believed to reveal this kind of very large gravitational collapse (Figs. 1, 2): the Palmahim and Dor Disturbances (Mart et al., 1978; Almagor and Garfunkel, 1979; Garfunkel et al., 1979; Roter, 2011). Other similar disturbances are known to the south, namely the Bardawil and Gaza (Garfunkel, 1984).

The second type of submarine mass movements along the open slope consists of small to medium size landslides ($<10^{-2}$–10^1 km^2), which were identified previously off coast Israel (Almagor and Garfunkel, 1979; Frey-Martinez et al., 2005), but were not comprehensibly mapped or studied previously, there or elsewhere in the Mediterranean (Urgeles and Camerlenghi, 2013). These small to medium submarine landslide are the subject of the current work. In addition, north–south elongated morphological step structures are also seen to outcrop on the sea floor in the studied area. The structures are recognized as surficial scarps of growth faults that are a result of subsurface salt tectonic related to the buried Messinian evaporitic sequence (Garfunkel, 1984; Baudon and Cartwright, 2008; Gvirtzman et al., 2015). This subsurface salt tectonic results in extensional deformation of the overlaying Pliocene–Quaternary sequence near the continental slope (Ben-Avraham, 1978; Gradmann et al., 2005; Mart and Ryan, 2007; Cartwright and Jackson, 2008; Cartwright et al., 2012).

1.2. This work

Our work consists of several steps: First we map submarine landslides on the Israeli continental slope from newly available bathymetric maps, focusing on the small to medium landslides. The large number of identified landslides allows us to perform analysis of their statistical

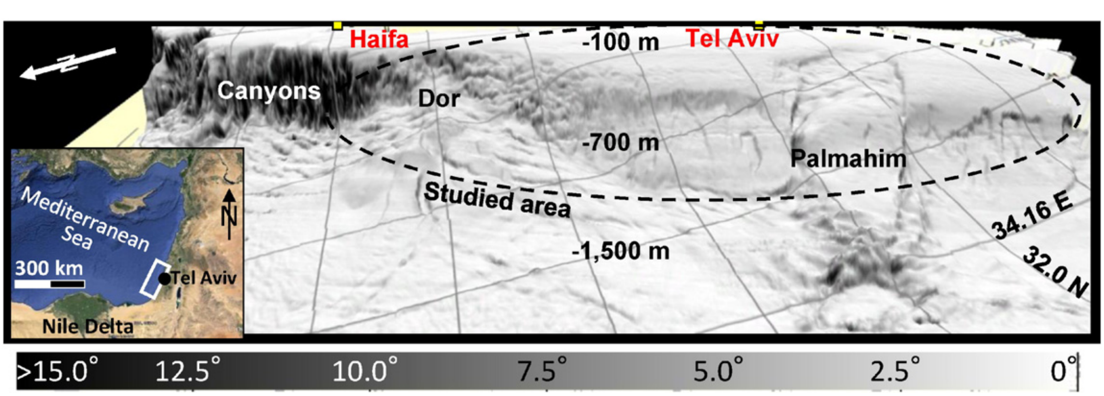

Fig. 1. Perspective view of the studied area (studied area is marked by a dashes ellipsoid). Gray coloring is the slope angle based on 50 m bathymetric grid (legend is shown below the figure). Location is shown in the inset, where the studied area is marked by a white rectangular.