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Discussions

Interactive comment on "Characteristics and frequency of large submarine landslides at the western tip of the Gulf of Corinth" *by* Arnaud Beckers et al.

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Comments from Referee 1: The paper presents the interpretation of landslide deposits from different sets of single- channel seismic reflection profiles across the Gulf of Corinth. From a hazard perspective, evidence of mass transport complexes is important, particularly if these can be linked to the preconditioning and triggering factors. In this area, recurrence rate of landslides appears significant, and as landslides can generate destructive tsunamis, assessing the source areas, causes and consequences are important. This is a well- written paper, with a good data set and logical structure, even though the content is largely descriptive. There are nevertheless a few points

that I am missing from the paper: Whereas identifying landslide deposits and obtaining the volumes involved are essential in a geohazard perspective, there is also a need to better define the land- slide processes and consequences. - I am somewhat surprised to see that the source areas from the different landslide events remain very poorly constrained, despite the fact that some of the landslide deposits are quite large, and cover a significant part of the basin.

Author's response: Considering this question of the reviewer and some of the following ones, we realized that part of the context regarding the geohazard landslide perspective is missing. First, we talk about earthquakes and landslides triggered by earthquakes, but did not provide a fault map. We presently add a new set of figures labeled Figure 1. At the top of Figure 1, we now display the active faults with the high resolution bathymetry obtained by Nomikou et al. (2011). Second, another element was also missing. Readers without previous knowledge of the submarine context of the Gulf of Corinth would not realize that very large amount of uncompacted sediments are available in steep submarine delta slopes, which is a preconditioning factor. In the setting (line 70-74) we mention that "the western gulf is bordered to the south by 400 m high Gilbert deltas built by the Erineos, Meganitis and Slinous river, and at its north-western end, by the fan delta of the Mornos River.... The delta fronts are highly unstable (..". But the comments of the reviewer show that a more precise context is necessary.

Author's changes in manuscript: We now show in Figure 1 in addition to the active faults and the submarine bathymetry, which evidences the steep and wide delta fronts, the morphosedimentary map of Holocene deposits and the isopach maps of the Holocene and the previous glacial-interglacial period.

Author's response: The isopach maps evidence the very large volume of sediments accumulated on steep unstable slopes that is available for mass transport. Most landslide deposits documented in paper have sources in these steep overloaded delta fans located along the southern coast and at the north-western end of the Gulf. So in fact the source areas are broadly very well defined. However given that there are high quality multi-beam data available but only a high-resolution raster map of the bathymetry by Nomikou et al. (2011) it is not possible to define in more details the source areas.

Author's changes in manuscript: We change the setting section in the following way to provide clearer indication about the morphological setting and the inferred source areas located in steep slopes surrounding the flat basin. " The western Gulf of Corinth is characterized by a relatively flat deep basin dipping gently to the east. Featuring a narrow canyon in the west, it widens in the east (Delphic Plateau, Fig. 1). It is bordered by steep slopes on all sides (Fig. 1) To the north, it is limited by the Trizonia scarp with slopes ranging from 25° to locally more than 35° and the associated Trizonia Fault (Nomikou et al., 2011); these slopes are mostly devoid of sediments which are trapped in the bay areas to the north (Fig. 1B). To the south, the western Gulf is bordered by 400m high Gilbert deltas built by the Erineos, Meganitis and Selinous rivers that lie in front of the active Psathopyrgos, Kamari and Aigion Faults running along or near the coastline. Delta fronts have 15° to 35° slopes incised by gullies (Lykousis et al., 2007; Nomikou et al, 2011) and consist of a thick pile of fine grained sediments. The delta-front sediments accumulated over the Holocene and the previous glacial-interglacial period have thicknesses, respectively, larger than 50m and 100 m (Fig. 1B and 1C; Beckers, 2015; Beckers et al, 2016). At the north-western end of the Gulf, lies the largest fan-delta of the Mornos River that drains 913 km2 and is by far the largest watershed among the rivers flowing toward the westernmost Gulf of Corinth (Fig. 1A). The delta fronts are highly unstable (Ferentinos et al, 1988; Lykousis et al., 2009), which favours frequent submarine landsliding (Stefatos et al., 2006; Tinti et al., 2007; Fig. 1B). During the last centuries, submarine landslides have been triggered by earthquakes and by sediment overloading on steep slopes (Galanopoulos et al., 1964; Heezen et al., 1966). Numerous debris-flow deposits and mass-transport deposits (MTDs) have thus accumulated at the foot of the deltas (Ferentinos et al., 1988; Beckers et al., 2016; Fig. 1B). Alongside these gravity-driven sedimentary processes, contour-parallel bottom-currents also influenced sediment transport in this area (Beckers et al., 2016)."

We also have clarified the section 5.2. Sediment sources in the following way: "5.2 Sediment sources

According to the mapping of the thickness of the deposits, large sliding events in the westernmost Gulf of Corinth mainly result from slope failures in, or close to, the Gilbert-type fan-deltas. Large sediment volumes were trapped in these deltas during the Holocene. As shown in Figure 1, Holocene foreset beds reach 40 to 60 m in thickness on average in the Eroneos and Meganitis fan-deltas, and sediment accumulation during the Holocene exceeding 100 m have been observed locally in between. These are the sources of MTD 10 in sliding event C and MTD 14 in sliding event D. The remarkable amount of sediments delivered to the gulf of Corinth during the Holocene probably results from large volumes of sediments stored onland during the last glacial period that were mobilized from river floodplains and colluvial deposits to rivers deltas. Widespread soil erosion resulting from human deforestation and agriculture during the second half of the Holocene also contributed to increase sediment fluxes in this period. Similarly, the previous period considered here spanning $\sim$130 ka to $\sim$11 ka is also characterized by a large sediment accummulation with a pile of 60 to 100 m forming the delta fronts of the Erineos and Meganitis delta (Fig. 1). These sources are one of the main source of MTD 10 in sliding event F."

Comments from Referee 1 : The preconditioning and triggering factors remain uncertain. I note that the point (abstract) of dramatic changes in water depth and water circulation at 10-12 ka is only applicable to a some of the cases.

Author's response: The preconditioning and triggering factors are discussed at length in the paper with section 5.4 and 5.3. Some of the context about the preconditioning factors (i.e. quantity of sediments available on slopes for mass transport), and triggering factors (fault maps, and relation between fault map and sediment accumulation on slopes) was missing and is presently displayed in Figure 1. In addition we have clarified the section 5.2. Sediment sources (see above).

Comments from Referee 1 : Landslide dynamics and the tsunami potential are briefly mentioned but not really addressed. Such assessment would re- quire modelling, but also information about the soil properties, the source areas, etc. Not all landslides will create tsunamis (see Løvholt et al., 2017).

Author's response: We fully agree that assessment about landslide dynamics and tsunami potential is not fully addressed, because it is beyond the paper scope and would require modeling. In addition, it would require a precise knowledge of the landslide source area that we have not. We only have a first order estimate of most of the source areas (i.e. Erineos delta fan).

Comments from Referee 1 :The authors report landslide volumes, calculated from a (sparse) grid of seismic reflection profiles. The authors should mention the method used to obtain these values (e.g., gridding algo- rithm) as well as adding a statement about the uncertainty, particularly considering the line spacing of the seismic lines, and the lack of 3D seismic data. Can we be sure that the spatial extent mapped is a realistic impression of the failures or can they be over-estimated, due to the gridding and missing out areas where there are no deposits (but not evidenced because of the lack of data). This should be added as a key point under 5.1 Limitations of the analysis.

Author's response: We report landslide volumes and were extra careful in the mapping. The gridding algorithm was specified in the text: line 100-102 "an inverse distance weighted interpolation between thickness data points was used to derive isopach maps of the deposits and estimate their total volume". For the small size MTD of SED A, the comparison with other volume evaluation shows that our volume evaluation is adequate. For MTD with a large size, the volume would be adequate because of the large surface area sampled by numerous seismic profiles. We are uploading Figure 2 that show the mapping of the MTDs with the seismic grid, but we are not considering to include the seismic grid in the published version of figure 2 because it would be difficult to read it with the grid.

Author's changes in manuscript: We would include the seismic grid in the figure 7 showing the largest MTDs (MTD 10, MTD 14 and MTD 17). The figure 7 uploaded thus now shows the seismic grid and the inferred mapping that took into account the geomorphological and topographical constraints: MTD10, 14 and 19 to the north were constraints by the Trizonia scarp.

Author's response: Two versions of Figure 2 were uploaded: one as we want to include it the paper and the other with the seismic grid in response to the reviewer comment. We prefer to indicate the seismic grid in Figure 7 and not in Figure 2, because it was more difficult to read figure 2 with the grid.

Comments from Referee 1: What is the onshore-offshore relationship of the landslides?

Author's response: There is a priori no relationship. All submarine landslides originate from the submarine delta-fans. Landsliding is documented onshore on the northern coast and along the Psathopyrgos scarps, but it has no influence on the submarine landslides documented. The new figures 1 added now provide the necessary context for a better understanding to readers

Comments from Referee 1: In the interpretation, the authors repeatedly refer to blanking but they do not really illustrate what is it and what the causes may be. Author's response: We agree with the reviewer that we do not illustrate what is it and what the causes may be. So we add some more details and differentiate more clearly in the text the different blanking areas and stratigraphy that have unclear origin. First, blanking occurs below the Holocene and in two distinct spots. In the Mornos Canyon, a wide blanking area exists at a depth of about 50 to 70 m below the sea floor, a few meters below reflector 1, in direct continuity with the fan delta of the Mornos River. The origin of the blanking is unknown, but it is a low-stand related feature related to the Mornos Delta and it might correspond to coarse grained, organic rich sediments. Another area with blanking occurs at the junction between the Mornos Canyon and the

Delphic plateau at the foot of the Erineos foreset beds, at a depth similar to SE F (MTD 19); it is associated with strongly disturbed sediments forming mounds. Its origin is unknown, but it might be related to a MTD. Finally there are uncertainties regarding the southward extension of MTD 14. It extends into a zone of chaotic reflections and very disturbed seismic stratigraphy of unclear origin. Our estimate of the volume of MTD 14 was thus conservative and is considered as a minimum.

Author's changes in manuscript: To clarify the statements, we have rewritten the paragraph line 199- 207 dealing with the blanking and uncertain area in the following way. "In some zones (Fig. 2), the existence or the geometry of MTDs is difficult to evaluate because of seismic blanking and strong chaotic reflections affecting some stratigraphic intervals. Above reflector 1, the stratigraphy is clear except regarding the southern extension of MTD 14 in SE D. The low amplitude, almost transparent reflections characterizing the MTD deposit extends until a more chaotic and thicker deposit associated with surface mounds (Fig. 5). We could not decipher if the chaotic reflections that disturb the seismic stratigraphy was associated with MTD 14 in SE D or in relation with sediment remobilization from the underlying sliding event F (Fig. 4). So the mapped extension of MTD 14 in Fig. 2E is conservative and considered as a minimum. Below reflector 1, the amplitude of the reflectivity sharply decreases, which is a characteristic of lowstand deposits in the Gulf (Bell et al., 2008), and blanking occurs in two areas .In the Canyon area, a wide blanking area exists at a depth of about 50 to 70 m below the sea floor, a few meters below reflector 1, in direct continuity with the delta of the Mornos River. Blanking is thus a low-stand related feature and might correspond to coarse grained, organic rich sediments of the Mornos River. Consequently, the stratigraphy of MTDs between reflectors 2 and 1 is well established only below the Delphic Plateau. The other area associating with blanking and strongly disturbed sediments forming mounds occurs at the junction between the Canyon and the Delphic plateau at the foot of the Erineos foreset beds, at a depth similar to SE F. Its origin is unknown, but it might be related to an MTD deposit in relation with MTD 19."

Comments from Referee 1: Likewise, the authors refer to coarser grained material in a deformed mass transport deposit, but there is no evidence for this. I doubt that one would be able to observe this from sparker data, as the masses are essentially deformed. Maybe speculation?

Author's response: We evidenced that the MTD are usually lenticular bodies of low-amplitude, incoherent reflections.

Author's changes in manuscript: We removed the sentence referring to coarse-grained deposits line 140: "which would make them different from the coarse-grained deltaic deposits that are known to fail relatively frequently along the southern coast." The text is now explicit about the limit of the interpretation of the MTD facies: "In the Delphic Plateau basin (eastern part of the deep flat basin), most MTDs are imaged as lenticular bodies of low-amplitude, incoherent reflections (Fig. 3 and 4). They generally have a flat upper surface and pinch out on their margins. Their thickness ranges between a few meters, which is the minimal thickness for a MTD to be imaged with the seismic system used, and 53 meters. The geometry and seismic facies indicate subaquatic mass-flow deposits (e.g. Moernaut et al., 2011, Strasser et al., 2013). The seismic facies of many MTDs also suggests a fine-grained lithology. However, this statement must be viewed cautiously considering the uncertainties on the interpretation of seismic facies in terms of grain-size, especially for reworked sediments. For instance, failure of coarse-grained deltaic deposits commonly result to their total disaggregation and transformation into grain flows and turbidity currents, whereas finer grained deposits evolve as landslides and cohesive debris flows (Tripsanas et al., 2008)."

Author's response: But in the next paragraph (line 145-149), we still want to evidence that some MTD display a different facies with high-amplitude reflections and coherent layering, which could be related to coarse-grained sediments.

Author's changes in manuscript: We change the sentence, to evidence that it was a possible interpretation: "In the Canyon basin (western part of the deep flat basin), the MTDs present the same general characteristics but the reflector pattern is more variable (Fig. 4). Some high-amplitude reflections and coherent layering are observed in some MTDs, revealing suggesting coarser-grained sediments and locally preserved stratigraphy."

Author's response: So in the section 5.2. Sediment sources, we are discussing the observation about the two types of seismic facies observed regarding the MTD. We are also providing more information about the fact that the foresets are made of a thick accumulation of stratified fine-grained sediments and that are not made of coarse grained sediments.

Author's changes in manuscript: The text as been corrected as followed: "The seismic facies of most large MTDs also implies that they are likely composed mainly of fine-grained sediments, and seismic profiles across fan-delta area have shown that the pro-delta foresets are locally made of a thick accumulation of stratified fine-grained sediments . These fan-delta sediments are probably the main source of sediments for the largest MTDs (MTD 10, 14 and 19). However, some smaller MTDs seem to be made of coarser-grained sediments according to the seismic character (e.g., in SEs A and B in the Canyon basin), suggesting failure also occurred in coarser-grained parts of the fan-deltas located at the junction between the topset and the foreset (e.g., the 1963 slide in the Erineos fan-delta)."

Comments from Referee 1: Smaller comments: I would recommend making the seismic profiles with the same vertical exaggerations or same scales to facilitate comparison. Likewise, please add an indication on the figures where the seismic lines cross.

Author's response: We purposely chose to show the seismic profile with different vertical exaggerations, in order to be able to evidence the different features we wanted to illustrate. We purposely chose not used the same scale or vertical exaggeration for all seismic profiles because our goal is to illustrate deposits and structures that have very different sizes, from 1 to ∼10 km in length and from ∼4 to ∼40 m in thickness. If we

choose the same vertical scale for all profiles, small-scale evidences will not be visible.

Comments from Referee 1: Terminology is in places confusing. I understand from this paper that landslide event actually refers to a certain interval in time (not specified) during which various landslides (with different source locations) may occur. Thus, different landslides compose a landslide event.

Author's response: Yes your understanding is correct, but because the terminology was confusing we choose to further clarify our statements.

Author's changes in manuscript: We change the related paragraphs: The stratigraphic position of MTDs in the Canyon and in the Delphic Plateau basins is not random. Most of them are clustered and are defining multi-MTDs temporal "events", based on common un-deformed underlying or overlying reflections that can be followed across the basin. Such correlations suggest that six clustered events of large submarine mass wasting occurred over the last 130 ka. Two sliding events (SE) are represented by clustered MTDs located between reflectors 2 and 1 (SE E and F). The four others occurred during the Holocene: SE D comprises MTDs deposited just on top of the reflector 1, SE C is located in the middle of the Holocene sequence, SE B somewhat higher, and finally SE A includes MTDs that outcrop at the sea floor. …. The definition of sliding events reflects a clustering of submarine landslides in a relatively short period of time. It does not necessarily imply a synchronous occurrence of all submarine landslides included in one event. Indeed, the accuracy of the correlation between separated MTDs that are interpreted to belong to the same sliding event is in the order of one or two reflections in the seismic data. Deciphering the exact MTD chronology within a sliding event was not possible because of the discontinuous character of many reflections and the relatively large distance that separates some MTDs (up to 8.5 km). This "stratigraphical" uncertainty corresponds to ∼1-2 meters of sediment so, based on sedimentation rate estimates, sliding events represent a set of MTDs that occurred over a period of 300 to 1000 years (Lykousis et al., 2007).

Comments from Referee 1 :The map should contain all geographical references used in the text. This is currently not the C2 case.

Author's response: Geographical references have been added to the new figure 1.

Comments from Referee 1 :On Figure 1, I would recommend adding a colour-coded (shaded relief or so) topographic/bathymetry map and slope map, as both are important to understand the processes. The maps should ideally cover the onshore and offshore part. Note that the "grey lines" referred to are not only the seismic grid but also bathymetric contour lines. Add the location of the Delphic Plateau, and the "Canyon".

Author's response: A new Figure 1 has been added to provide needed context taking into account remarks from the reviewer; a shaded topography was also added. The old figure 1 is now figure 2.

Author's changes in manuscript: New Figure 1 taking into account the remarks of referee 1.

Comments from Referee 1 : There are a few typos in the text - Figure 2: explain the horizons [1] and [2].

Author's response: We explain them now.

Author's changes in manuscript: In the caption of figure 2, we now state: "Figure 2. E-W Sparker seismic profile showing the mass transport deposits imaged in the Delphic Plateau basin. See the location of the profile in Fig. 1. Horizon [1] indicates the beginning of the last post-glacial transgression, at 10.5-12.5 ka and horizon [2] the marine isotopic stage 6 to 5 transgression, which occurred at ca. 130 ka (Cotterill, 2006; Beckers et al., 2015; 2016)"

Comments from Referee 1: The term "outcrop" suggests that something was eroded on top. This may not be the case for the youngest landslide deposits. Consider using exposed as the seafloor

Author's response: We took into account this comment.

Author's changes in manuscript: line 197-198: SE A includes MTDs that outcrop at the sea floor was change to SE A includes MTDS at or near the seafloor responsible for the present-day hummocky topography of the seafloor line 219: Sliding event A: Eight MTDs that outcrop at the sea floor have been identified. was changed to Sliding event A: Eight MTDs at or near the seafloor have been identified.

Comments from Referee 1 : Figure 6 is too small, and ideally, the maps should all use the same area, to facilitate comparison. This would be a good place to add the various source areas.

Author's response: We took into account this comment.

Author's changes in manuscript: We enlarge Figure 6 and use the same area to facilitate comparison. We also place the different source areas.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-371/nhess-2017-371-AC2-supplement.pdf

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-371, 2017.

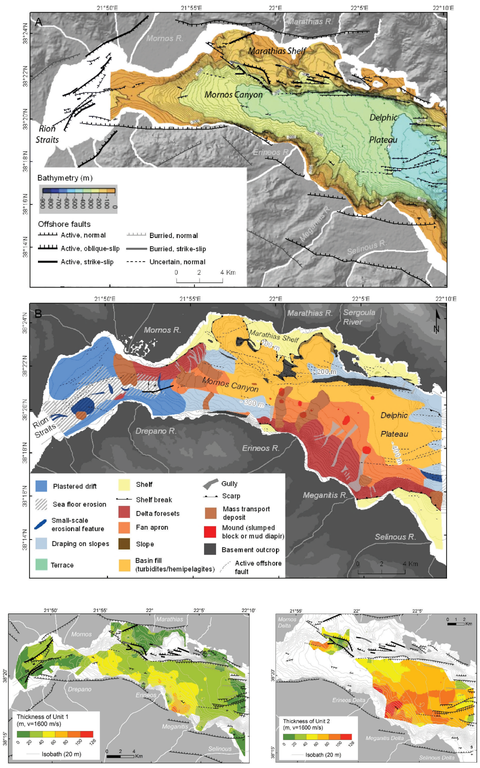

Fig. 1. New Figure 1

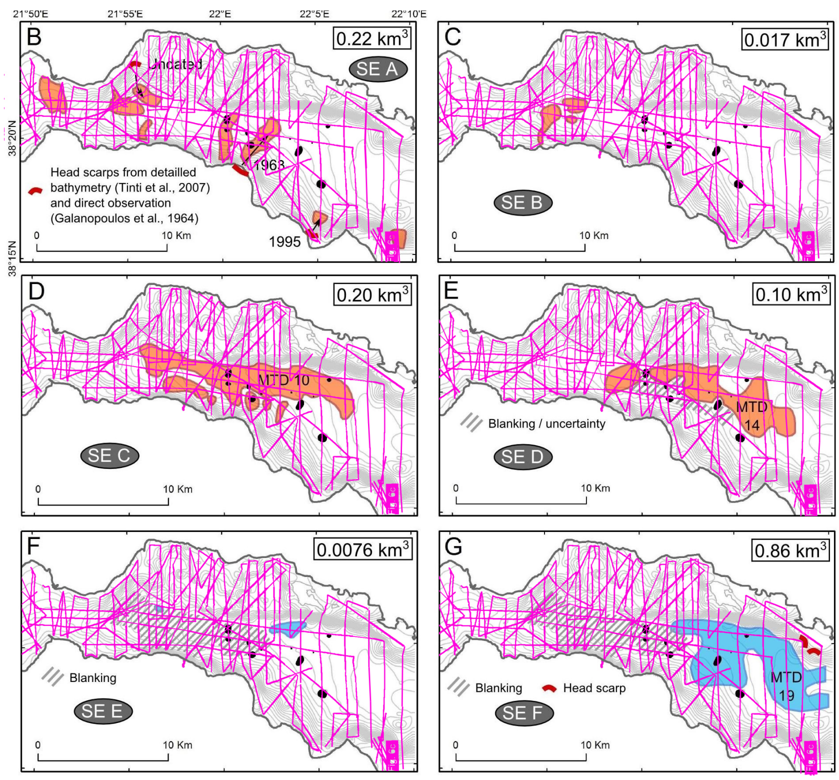

Fig. 2. Figure 2 with grid

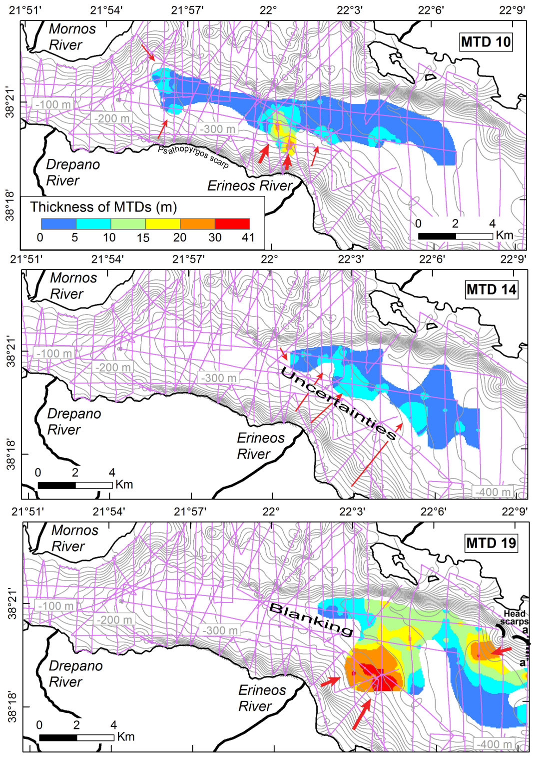

Fig. 3. New Figure 7 with grid