

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

Arnaud Beckers et al.

aurelia.ferrari@ulg.ac.be

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Comments of referee 2: Overview The paper describes the frequency and characteristics of small volume submarine landslides in the Gulf of Corinth over the past 130 ka. The landslides have the potential to generate hazardous tsunamis, with one historical event recorded. Potential landslide preconditioning and triggers are discussed. Six major landsliding events are recognised, of which three are relatively large volume. The age of the events are dated by their relationship to two regional seismic horizons interpreted as major flooding events and dated at 130 and 10-13ka. Most slide events (four) are identified as Holocene, with two others older than 10 to 12 ka.

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Although the volumes of most slides are quite small (largest 1km³) one, in historical times (1995), generated a significant tsunami. Author's response: Note that there was another significant tsunami generated during historical times by one of the slide we have mapped: the 1963 tsunami was generated by a submarine landslide on the Erineos prodelta. Moreover, numerous other historical tsunamis have been reported in the western Gulf of Corinth: 1996, 1984, 1965, 1888, 1887, 1861, 1817, etc. (the full list is in Papadopoulos, 2003, Natural Hazard; summary in Beckers et al., 2017, Marine Geology)

Comments of referee 2: The paper is a dense read, because of the number and complexity of the landslide failures and the relationships to triggering mechanisms and preconditioning.

Comments of referee 2: The strengths of the paper are in the seismic data and its interpretation. The weakness is the lack of sample data to identify the sedimentology of the slides and their ages, which are based on the slides relationships to the two regional horizons. As with all submarine landslides, earthquakes are proposed as the most likely trigger. Earthquake records (from sediments) are confined to the past 17 thousand years, with frequencies of 400-500 years for the period 12-17ka in the central Gulf of Corinth and in the western Gulf (from palaeoseismology) 200 to 600 years. Preconditioning factors are identified from events in other regions outside the western Gulf.

Author's response: We fully agree with the referee about the paper weakness. There are no long coring across the western gulf of Corinth, to establish a relationship between MTDs, their sedimentological imprint and an earthquake catalogue.

Comments of referee 2: Focussing on the science, I am surprised that the dated regional horizons are not used more fully to understand sedimentation rates and the potential rates of sediment recharging in the western basin. These might better inform on the local differences between the glacial and post glacial environments that would

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influence slide failure.

Author's response: We have now added new data in figure 1 showing isopach 1 of the Holocene and of the previous glacial interglacial period in answer to referee 1, but we have not fully exploited the data to discuss the potential influence of sediment recharging in the western basin. In the discussion, we now stress that there is a large difference regarding the sediment recharging between the Holocene Period and the previous 130-12kyrs one. Considering the spot between the Erineos and the Meganitis delta-fans (See Fig. 1) where we could have a reliable record of sediment accumulation over the last 130 kyrs, up to ~ 100 m were accumulated over the last 10.5 to 12.5 kyrs and up to 125 m were accumulated over the previous ~120 kyrs period. So there is an order of magnitude difference in sediment recharging between the Holocene and the previous period. We are now discussing these facts in the text.

Author's changes in manuscript: Change in the Discussion section 5.5 Other potential triggers and pre-conditioning factors

...Overall, these data suggest that the Last Glacial probably experienced the largest sedimentation rates over the last 130 ka in most of the Gulf of Corinth. This inference is however not valid at the western tip of the Gulf. The comparison between isopach maps of the Holocene and the anterior 130-12 kyrs period evidences a large Holocene increase in sedimentation accumulation rate (Fig. 1). In the Delphic plateau basin, average sedimentation rate (excluding the thickness of MTDs) reaches ~2.4 mm/yr for the Holocene and ~ 0.4 mm/yr for the previous 120 kyrs. This is in line with the fact that only one large sliding event F was recorded during the ~60 ky-long Last Glacial. Increased sedimentation is thus a pre-conditioning factor of landsliding in the western Gulf.

Comments of referee 2: I am also surprised that there is not more consideration of the major difference between the glacial and Post glacial sea levels in the context of the slides and their headscarps. Consideration of Figure 1 suggests that lowering

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sea level by 60 metres makes a major difference in some regions that may influence sedimentation and sliding. Whether the difference in sea levels is important or not, it would be informative to see the effects on a figure.

Author's response: We agree that the lowering sea level might make a difference in some part of the Gulf but not a major one regarding the delta-front bordering the southern edge of the western Corinth Gulf. The new figure 1 showing the high resolution bathymetry of Nomikou et al. (2011) clearly show that the isobaths -100 is located close to the shoreline all along the faulted southern coast west of Aigio, and that the foreset beds extend to isobaths -300m. So the submarine slopes where submarine landslides can initiate are not significantly different between the Last Glacial Period and the postglacial period, they might be a little more restricted during the Last Glacial Period.

Author's changes in manuscript: The following clarification was included in the Discussion section and the subsection 5.5 Other potential triggers and pre-conditioning factors ... During this lowstand period, the extent of submarine slopes where submarine landslides can initiate were not significantly reduced, because the foreset beds of the Erineos and Meganitis that are the largest source of mass wasting sediments for the Delphic plateau extend down to the ~300 m isobaths. The steepest slopes of these two prodeltas are located above isobaths -100m and between isobaths -150m and -200m according to the slope map of Nomikou et al. (2011), so unstable slopes above -60m that were submerged only in the postglacial period cover a restricted area.

...

Comments of referee 2: It would also help the reader if some of locations of data which underpin the interpretations, which are outside the area were identified on a map. These include the Philious Basin (Page 13, lines 457-458) and the Alkyonides basin (Page 113, Line 467). Identifying the location of these would identify their relevance.

Author's response: We fully agree with the reviewer that the reader needs to know were

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the locations of data, which underpin the interpretations need to be added. However the paper is already long with 9 figures and we did not want to include a new one. So we choose to indicate clearly in the text the relevant information regarding the location of the data with respect to the Gulf of Corinth.

Author's changes in manuscript: in the Discussion section and the subsection 5.5 Other potential triggers and pre-conditioning factors Regarding the location of the Alkyonides Basin, we add the clarification that it is located at the eastern tip of the Gulf in the following way: "Collier et al. (2000) suggest that the denudation rate at the eastern end of the Gulf in the Alkyonides Basin" Regarding the location of the Philious Basin we did the same: "Fuchs (2007) presents the evolution of sedimentation rates in colluvial deposits on the southern shoulder of the Corinth Rift, in the Philious Basin, . . ."

Comments of referee 2: The interpretation of the earthquake triggering of the landslides is undoubtedly reasonable, but the evidence is very sparse. It seems that only the 1995 earthquake triggered the MTD at the foot of the Meganitis fan, but this is hypothetical. What was the trigger of the 1963 landslide which caused a major tsunami, was it just sediment loading? The following discussion of the relationships between earthquake frequency and landsliding is also question able, because it is assumed that the earthquake frequency for the glacial period is the same as for the Holocene (page 12, lines 416-418) which seems to me to be unlikely. This is quite a jump in the interpretation as it underpins much of the subsequent discussion on triggering and pre-conditioning – but that is always the problem with MTDs. I guess it doesn't invalidate the interpretations too much.

Author's response: There are no relationship between the earthquake frequency and climatic changes. The earthquake cycle is linked to loading on faults due to geodynamic processes at depth independent of surface processes. So indeed we assumed that earthquake frequency is nearly constant. There are still some potential effects on the seismicity due to the rapid water level changes at the beginning of the Holocene, which would have change the stress field and the pore pressure. But nobody has mod-

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eled it, and its effects on the fault system in the Gulf of Corinth are unknown. Any lengthly discussion about it would be very speculative. We still include a short sentence to take into account the referee remark.

Author's changes in manuscript: in the Discussion section and the subsection 5.5 Other potential triggers and pre-conditioning factors

"The deposition of SE D occurred at 10-12 ka, when the water level started to increase in the Corinth Gulf. Water level change might change the stress field and pore pressure potentially affecting the earthquake cycle. Water level increase and bottom current initiation would also.."

Author's response: The earthquake frequency might also have changed because of change in the geodynamics of the rift over the 130 kyrs timescale. Previous studies (i.e. Ford, M., et al. "Rift migration and lateral propagation: evolution of normal faults and sediment-routing systems of the western Corinth rift (Greece)." Geological Society, London, Special Publications 439.1 (2017): 131-168) suggest a rapid evolution with respect to fault growth and linkage. Demoulin et al. (2015) also evidenced an Holocene acceleration of the strain rates using fluvial morphometry and we also found a large increase in Holocene subsidence rate compared to the previous period probably linked with an acceleration of the deformation (Beckers, A., 2015, Late quaternary sedimentation in the western gulf of Corinth: interplay between tectonic deformation, seismicity, and eustatic changes, PhD thesis, pp. 260), but these later finding will be independently published in a peer-review journal. Given the uncertainties about the earthquake frequency, we choose not to have an extended discussion about the topics, because it would be too speculative. We still have included the following changes in the text

Author's changes in manuscript : in the Discussion section and the subsection 5.4. The possible role of large earthquakes "This high Holocene frequency compared with the ~120 kyrs anterior period may be attributed to two factors. First it might be a

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bias, because the seismic reflections corresponding to the last glacial period (110-12ka) are less clear (lower amplitude and lower continuity) than the reflections from the Holocene interval. Consequently, medium-sized landslides such as those detected in SEs A and B might have been missed in the seismic unit between reflectors 2 and 1. Second, it could be attributed to a change in earthquake frequency due to a Holocene acceleration of the strain rates that was evidenced by fluvial morphometry (Demoulin et al., 2015) and subsidence markers (Beckers, 2015)."

Comments of referee 2: Regarding my comment on the complexity of the paper, I make some suggestions. There are geographical names mentioned in the text, which are not on the figures, e.g, Delphic Plateau, Canyon basin, possibly others.

Author's response: We made modifications to mention the names in the figures already for referee 1.

Comments of referee 2: With regard to the organisation of the paper, I found it hard to understand the full setting of the GoC from the background sections because background material is distributed later in the paper. Other material which should be presented early on in the Background includes; the stratigraphic framework (Page 2 lines 90-95) and the palaeolake levels (Page 13 lines 477-485). Including these would provide a broader picture to background the environmental changes over the 130 ka time period.

Author's response : We already change the setting section to provide a clearer picture according to the remarks of referee 1, but we now include a new paragraph in the setting to provide more information also regarding the stratigraphic framework and the palaeolake levels.

Author's changes in manuscript : The following paragraph was added to the setting section: The shallow sedimentary infill of Gulf of Corinth infill consists of a distinct alternation between seismic-stratigraphic units with parallel, continuous high-amplitude reflections and units with parallel, continuous low amplitude reflections to acoustically

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transparent seismic facies (e.g. Bell et al., 2008; Taylor et al., 2011). Generally, the semi-transparent units are thicker than the highly reflective units (e.g. Taylor et al., 2011). These alternating seismic-stratigraphic units have been observed throughout the Gulf of Corinth and have been interpreted as depositional sequences linked to glacio-eustatic cycles (Bell et al., 2008; Taylor et al., 2011). Because of the presence of the 62 m deep Rion Sill at the entrance of the Gulf, the Gulf of Corinth was disconnected from the World Ocean during Quaternary lowstands and was thus a non-marine sedimentary environment. The marine and non-marine environments are associated with different climatic regimes (e.g. Leeder et al., 1998). During glacial stages, the sparse vegetation cover was more favourable to erosion than during interglacials, so high quantities of sediments were routed towards the Gulf (Collier et al., 2000). These lowstand deposits appear as thick, low-reflective units. The thin, high-reflective units are interpreted to represent the marine highstand deposits. The last lacustrine-marine transition has been sampled in different sedimentary cores (Collier et al., 2000; Moretti et al., 2004; Van Welden, 2007; Campos et al., 2013).

Conclusions Apart from my above comments, this is an interesting paper identifying the potential hazard from submarine landslides in an enclosed basinal area, where future events, if of sufficient volume would be a tsunami hazard. It is well organized and well written. The remote data set is good, the temporal controls on the events are weak, but the innovative approach, using the (sparse) data applicable to this, results in a plausible story which should be published with some modification.

Please also note the supplement to this comment:

<https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-371/nhess-2017-371-AC1-supplement.pdf>

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

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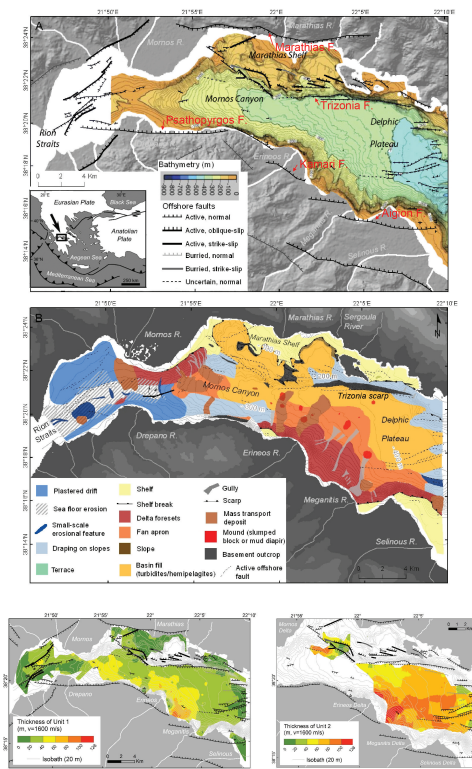


Fig. 1.

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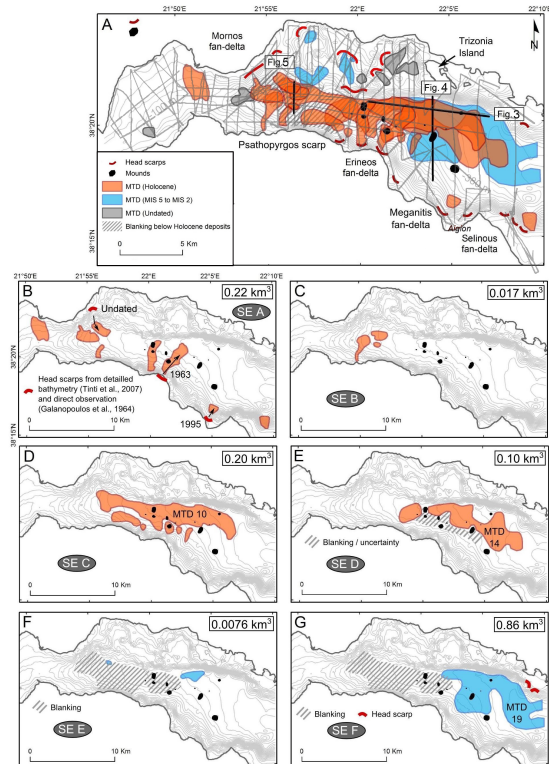


Fig. 2.

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