Reply to comments of reviewer #1:

Dear reviewer,

Thanks for the thorough and constructive comments to our submission. The integration of these suggestions will definitely help to further improve our manuscript. In the following we will address each of the comments separately (author replies in blue). All references to line numbers are based on the revised version with track changes.

Dear Editor and authors, the work by Brill et al. presents an insight into the Typhoon Haiyan's sedimentary record in coastal environments of the Philippines and its palaeotempestological implications. I commend the authors on a well-written and interesting manuscript. The authors addressed a topic with particular societal relevance due to the consequences of these catastrophic events for coastal areas. In this case, it is particularly relevant to say that the authors conducted extensive fieldwork and were also able to complement that with results derived from the application of some sedimentological proxies (grain-size, XRD and magnetic susceptibility). The data set gathered seems to be solid and very interesting from a scientific point of view. Overall, the manuscript has a clear structure and aims. However, in my opinion, several aspects should be addressed by the authors before the manuscript is accepted for publication, please see details below.

Although most of the issues I raise (please see below) are minor, I would like to stress that the authors need to be more consistent in terms of the vertical datum that they used. They should rewrite some of the numbered lists and make the text easier to follow.

All height information are presented in meters above mean sea level in the revised manuscript version. The respective sections have been rewritten for clarification (see also replies to specific comments below for more details).

They need to address more clearly the differences between tsunami and storm deposits and they should discuss transport modes and its implications for the depositional signature of the Typhoon Haiyan's sedimentary record in coastal environments of the Philippines (Jaffe et al., 2012 - Sed Geol).

We added some more explanations concerning potential features that may allow to differentiate between tsunami and storm deposits in the discussion section of the revised version. There, we provide sufficient details on potential tsunami and cyclone indicators (and the problematic that all of them are dependent on local setting) to allow the reader to follow our argumentation (page 17, line 16 to page 18, line 6). However, in our opinion this discussion has already occurred in a large number of publications, and we therefore will also refer to the respective literature for more information (we will provide more references dealing with this topic) instead of going too much into detail.

We also enlarged the discussion of transport modes for the different storm signatures reported (page 14, line 10-21; page 14, line 29 ff). In agreement with observations on the deposits of other tropical cyclones (e.g. Williams, 2009 at the US coast), we mainly attribute the formation of the slightly normally graded sand layers to settling from suspension during an early stage of the storm surge (at least at sites HER and TOL this initial flooding of the back-barrier areas was supported by infra-gravity waves). On the other hand, the laminated washover fans are interpreted to be the result of bedload transport over the coastal barrier, related to distinct storm waves during a later stage of the storm surge.

On top of this, they should stress that although local settings and sediment source are fundamental aspects that control storm deposit bed formation, there are a group of common features between the studied sites and that they share characteristics with deposits elsewhere (maybe adding a table summarizing these sedimentological features would help to the reader).

We have highlighted this aspect in both the discussion section (page 17, line 31 ff) and the conclusions (page 18, line 31). This does also include a new figure (figure 14) listing the characteristics of the different storm features (including comparison with features of other storms and tsunamis) as suggested by the reviewer.

Abstract

The abstract is clear and well written. However, the authors need to clarify if they are studying 3 or 4 sites (they mention 4 sites here but mention 3 sites on page 3 line 10).

We aligned the information on the number of locations in the manuscript to 4 sites: Hernani (Samar), Tacloban (Leyte), Carbin/Molocaboc (Northern Negros), and Bantayan.

I also suggest that the authors need to provide more comparisons with palaeotsunami data to sustain their sentence in line 20. In my opinion, that sentence should end "(...) typhoon signatures that can be used for palaeotempestological studies." the rest of the sentence should be deleted unless discussion is enriched with further topics on the comparison between tsunami and storm depositional signatures.

We slightly enlarged the discussion of tsunami signatures in the revised version of the manuscript (see reply to comment above) and, thus, will leave the sentence as is.

Introduction

Page 2, line 18, once we started talking about using geological record for several millennia we should also mention (and take in consideration) sea-level changes especially when we are using just a few specific study sites.

We absolutely agree with the reviewer that sea-level changes (and changes in palaeogeography) since the time prehistoric tsunamis or storms made landfall have to be considered when interpreting their geological records. We added a short section to highlight the importance of this aspect (page 2, line 21).

Page 2, line 25 - "natura are" - spelling mistake

Was corrected.

Page 2, line 27 - suggest you delete text up to line 30... "Here, we report..."

We deleted the part of the mentioned section referring to a previous study on coastal boulders from the same area (May et al., 2015). However, we think the sentence concerning the potential relevance of the presented data for a general discrimination of tsunami and storm deposits is necessary and should not be deleted, since we believe that sediments of exceptional typhoons such as Haiyan definitely contribute to this discussion.

Page 3 - I believe you should clarify or stress again the aims of your work, in particular at the end of the Introduction.

We stress the aims of our study at the end of the introduction to make this aspect clearer for the reader (page 3, line 4-10). The revised section reads: “The major aims of this study are to (i) document Haiyan’s impact on the sedimentology and geomorphology of heavily affected coastal areas by recording onshore and intertidal sedimentation, coastal erosion and geomorphological changes. Based on these data, sedimentary and geomorphological typhoon signatures typical for the study area shall be established. In addition, (ii) the spatial variability of these typhoon signatures due to site-specific characteristics such as the local topography, bathymetry, geology, and hydrodynamics as well as the exposure to the typhoon track shall be investigated. Finally, (iii) the potential of these modern typhoon deposits will be evaluated in respect of possible implications for the identification of prehistoric cyclones in the geological record."

Study area

Page 3, line 10 - "three study areas"???

We changed to "four" to be in accordance with the information given earlier (see reply to first comment).

Page 3, line 28 - when you refer to Samar please make reference to Figure or provide some clues about the specific location.

We added a reference to Figure 1a, where the track of Typhoon Haiyan as well as the location of Samar are indicated.

Page 4, line 5 - "three distinctive wave pulses" - Three sets of waves? How was this established? Was it measured? What was the Hs difference between the different pulses? Where any of these pulses related with infra-gravity waves?

These three pulses of flooding with periods much longer than those of wind waves are based on eye-witness observations, so their heights (or the differences of heights between the pulses) are not well constrained. As mentioned on page 4, line 4, numerical models suggest that they may be the result of seiches (i.e. standing waves) in the semi-enclosed San Pedro Bay (Mori et al., 2014).

Page 4, line 10 - i) and ii) and iii) - numbered lists were used intensively in this manuscript. I do not think they were used properly. Each numbered topic is very extensive and the reader is not guided properly. I suggest you rewrite all parts in the manuscript were you used numbered lists. Either you simplify the topics or you should write them as different sentences and start the sentences with "on the other hand" or "moreover" or etc.

We changed the structure of this section according to the reviewer's suggestions.

Page 4, line 11 - "model-predicted". Throughout the manuscript you mention several times this but provide no details about modeled data. I strongly suggest you do that! Which model was used? What was the source data? What equations were used to calculate Hs, etc? etc, etc?

There are a number of different models that have been used. The data presented by Bricker et a. (2014), Mori et al. (2014), Cuadra et al. (2014), May et al. (2015b), Roeber and Bricker (2015), Kennedy et al. (2016), and Soria et al. (2016) are all based on models with different specifications. Although we agree that knowledge of models and parameters is important to evaluate the model output, providing all specifications in the manuscript would be a lengthy description that in our opinion would rather distract the reader. Since we refer to the original literature wherever we mention modelled data, interested readers can easily consult these articles for further information.
While the detailed specifications of the models are in our opinion not required to understand the presented data, there are two main types of models that have been used to predict flooding levels, and which to discriminate is indeed important for the interpretation of our data: (1) numerical storm-surge models combined with <u>phase-averaged</u> wave models are routinely used to model surge heights for larger areas (Bricker et al., 2014; Cuadra et al., 2014; Mori et al., 2014; May et al., 2015; Soria et al., 2016); (2) numerical surge models with <u>phase-resolved</u> (boussinesq-type) wave models are required to reproduce the interactions of waves with the local topography, which may generate infra-gravity waves (Roeber and Bricker, 2015; Kennedy

et al., 2016). So while we think it is sufficient to refer to the original literature for detailed model specifications, we explicitly included the discrimination of phase-averaged and phase-resolved wave models in the revised version of the manuscript (page 4, line 9-22).

Page 4, line 13 - throughout the paper you refer to, at least 3, height (vertical datum) units (atl, msl, above mean low water and depth below surface). This makes it really hard for the reader. I strongly suggest you convert all to m above mean sea level!

We agree with the reviewer that the use of different height levels might be confusing for the reader. To allow for comparability between all sites, we now provide all height references for data presented in this research (topography, sediments, flood marks, etc.) in meters above or below mean sea level (above/below msl). However, since the same values relative to mean sea level may – depending on the elevation of the ground – have completely different implications for sedimentation, we also provide the flow depth in meters above ground level in case of the measured flood marks. For describing the stratigraphies of sediment profiles, we will stick to meters below surface, since here a relation to sea level would be rather confusing. We state this information explicitly in the methods section of the revised version (page 5, lines 27-28).

Page 4, line 24 - please provide reference after "Philippine plate".

We added Rangin et al. (1989) as a reference.

Page 4, line 29 - suggest you replace "originating" with "originated" and add "denser" to make the sentence ..."darker and denser minerals..."

The sentence was changed accordingly.

Page 4, line 31 - Please see comment to page 4, line 10.

The structure of this sections was changed according to the reviewer's suggestions.

Methods

Page 5, line 12 - "along-shore perpendicular transects". So, cross-shore? What was the space between consecutive profiles? Did you created a DEM?

Due to the limited time available at each study location during the survey, we measured only a single transect at most of the sites. Only on Carbin Reef (6 transects) and at BAN B (3 transects) several transects were measured (all of them are documented in the respective figures). Consequently, no DEMs were created as well.

Page 5, line 16 - heights - Please see comment to page 4, line 13.

As already mentioned in our reply to page 4, line 13, all heights are provided in meters above mean sea level in the revised version. Flow depth (so meters above ground surface) is provided additionally in case of flood marks.

Page 5, line 21 - please replace "was" with "were".

Was corrected.

Page 5, line 23 - this is a relevant aspect of the manuscript. Here, you suggest that in some locations you only used one core? Do you think this is enough for well supported interpretations? Especially, when later you refer to all local specific conditions and lateral variations of the deposit!!

We indeed analyzed only a single sediment core for site BAN A. For all other locations (HER, TOL, BAN B), several samples collected at different distances to the shoreline were analyzed. We agree that there are lateral variations in terms of granulometry and faunal composition at the individual sites, which are of course not covered by the single core at BAN A. However, at site BAN A the lateral extension of the deposit is only ~10-20 meters. We checked the lateral structure by means of trenches and the section sampled by BAN 4 is assumed to be representative for the entire washover fan. Especially for the comparison of BAN 4 with other sites the lack of lateral data should be negligible, since the differences between sediments from different sites are much more pronounced. Although some limitations must be expected for granulometry and faunal composition that vary laterally, we therefore assume that the results of this single core (i) represent the typical sediment composition at BAN A quite well, and (ii) can already document the main differences compared to the other locations.

Page 6, line 13 - suggest you compare your approach with Quintela et al. (2016 – Quaternary International) methodology to identify allochthonous Foraminifera species within high energy deposits.

The methodological aspects of foraminifer determination, counting and taphonomy classification used in our study should be similar to those applied by Quintela et al. (2016). Particularly the argument that higher percentages of broken foraminifer tests are the result of high grain density in the traction-transport dominated parts of high energy flows may be of importance for discussing our foraminifer assemblages, and is considered in the discussion section of the revised version (page 14, line 19-21).

Results

Page 6, lines 19, 26, 27, 28 - heights - Please see comment to page 4, line 13.

All heights are provided in meters above mean sea level and (additionally) as flow depth above surface.

Page 6, line 23 - please refer to Figure 2 (?).

A reference to figure 2 was added.

Page 7, line 3 - I believe you should provide/describe more grain-size data information. I suggest you add information on the D10, D90, sorting and unimodal or bimodal character of your samples.

We complemented the grain-size information for all sites, and provide data on mean, sorting, and modality for each site.

Page 7, line 9 to 13 - I feel that in the discussion you should refer to the relationship between reworking and sediment concentration. Did you detected more reworked material in the basal sector of the storm layer or on the top? How was this correlated with grain-size?

In case of HER 10, no clear vertical trend in foraminifer taphonomy or species composition could be detected. There is rather a slight correlation between coarser grain size and stronger reworking (Fig. 4). This is similar for core BAN 4, where strong reworking correlates with larger grain size as well (Fig. 12). However, since sediments first tend to become coarser towards the top of BAN 4 and fine afterwards, reworking is highest in the central section of BAN 4.

Page 7, line 23 - again, the heights...what vertical datum did you used this time?

All heights are provided in meters above mean sea level and, in case of flood marks, (additionally) as flow depth above surface.

Page 8, line 2 - please refer to Figure.

We inserted a reference to figure 6.

Page 8, line 29 - I guess you should cite it as personal communication.

We now cite the observation as “personal communication”.

Page 8, line 30 - heights - Please see comment to page 4, line 13.

The heights are provided in meters above/below mean sea level.

Page 9, line 16 - Rsubt was collected at approximately what depth?

The sample was collected at 0.5 m below mean sea level. We added this information in the revised manuscript.

Page 10 - line 14 to 17 - the fact that the basal sector is slightly finer than the middle section is not just a consequence of the more erosive character of the initial stage of the event? The following phases benefited from a lowered coastal sector thus were capable of transporting coarser sediments farther inland.

The proposed mechanism is a very plausible explanation for the observed stratigraphical pattern at this location, because both units are assumed to be deposited by similar processes, i.e. wave swash overtopping the coastal barrier. We briefly address this aspect in the discussion section of the revised version (page 15, line 11-16).

Page 11, line 16 to 19 – this just reflects the dominance of the original (2nd cycle) sediment source.

We agree that the mineralogy and geochemistry mainly indicate the differences between limestone and volcanic environments. We already address this topic in the discussion section (page 15, lines 15 ff in the original version of the manuscript).

Page 11, line 20 - I believe it is the first time you refer to principal components analysis, I suggest you refer to it in full.

The abbreviation PCA is already mentioned in the methods section. However, we agree that referring to it in full at this position might facilitate reading.

Line 12 - line 13 - this strongly suggests this area as the main sediment source.

That is how we interpret this data in the discussion section as well. To make this implications already clear in section 4.5, we added a brief explanation.

Discussion

Page 12, line 27 - again the numbered list.

We removed the numbering to facilitate reading.

Page 12, line 30 - "normally graded or massive layers of sand". This implies totally different sediment transport modes (suspended grading and traction). I believe you should add a sentence here to comment on this and discuss reasons for the differences observed.

This should read “normally graded to massive layers of sand”. While slight normal grading could be detected for thicker layers (close to the coast) and especially those analyzed for vertical grain-size variations in the laboratory, the small thickness of the sand layers further inland did not allow for unambiguous identification of grading. We assume that even the thinner parts of the sand sheets might be normally graded. But since we cannot prove this (macroscopically their structure could be both massive and slightly graded), we prefer to describe them as “normally graded to massive”.

Page 13, line 3 - I suggest you add references from one of the several works conducted by Donnelly et al. or Liu et al. in the eastern coast of the US.

We added Donnelly et al. (2006) as a reference from the US coast.

Page 13, line 8 - I believe you should also mention infra-gravity waves.

Actually, the mentioned “long-wave phenomena” already include infra-gravity waves that can result e.g. from surf beat. To make this clearer, we explicitly use the term “infra-gravity waves” at this position.

Page 13, line 13 - very very interesting but why? Can you add a comment on this?

The deposits described by Williams (2009) have actually a very similar structure as those described on the Philippines: a finer, graded sand layer formed during the initial inundation of the back-barrier plains, topped by washover deposits during a later stage of the storm surge. We therefore assume similar transport modes for our deposits, i.e. suspension settling for the graded sand sheet and bedload/traction for the formation of the washover lobes. The role of long-wave phenomena for the deposits presented in our study (infra-gravity waves at HER and seiches at TOL) is probably a contribution to higher and more extensive flood levels, but not significantly different sedimentation processes.

Page 13, line 16 - now it is important to know at what depth was your sample (Rsubt) retrieved!!

As mentioned before, the sample was collected at 0.5 m below mean sea level. It contrasts significantly in terms of faunal composition from the storm deposits, while the littoral reference samples from BAN reveal a similar granulometry and faunal composition with the typhoon deposits.

Page 13, line 25 to 29 - I suggest you rewrite this sentence.

We changed the structure of this section to make it clearer for the reader.

Page 14 - line 1 - you must refer, for example, to the work of Komar and Wang (1984) or Komar (in Mange, 2007).

We added Komar and Wang (1984) as a reference for density sorting.

Page 14, line 6 to 9 - Agree with interpretation.

Page 14, line 18 to 20 - I accept your interpretation but I think formation of ridges implies a "continuum in time" more suitable with normal storm regime and a succession of events.

We agree that ridges might form during several successive events rather than single storms. In fact, we state the possibility of ridge formation by several typhoons (with significant growth of a pre-existing ridge during Haiyan) further down in this section.

Page 14, line 21 - please see comment to page 4, line 10.

We removed the numbering.

Page 14, line 27 and 28 - I think this partially contradicts statements above. I suggest you rewrite it

Since our evidence is not unambiguous without robust age data, we have to provide both possible explanations for the ridge formation. Of course these explanations partially contradict each other, because only one of them can reflect reality. We rewrote the section to clarify this aspect.

Page 15, line 3 - please quantify the "remarkable amplification".

In the central part of the bay, water levels of more than 8 m above sea level were recorded, which is much higher than in Haiyan-affected areas not subject to infra-gravity waves (HER) or raised water levels related to shore configuration (TOL). We added the value in the revised manuscript.

Page 15, line 4 - which models?

Here we refer to storm surge models combined with phase-averaged wave models (for details we refer to the original reference by Bricker et al., 2014) that do not account for the effects of infra-gravity waves (phase-resolved wave models). We added this information in the revised version.

Page 15, line 8 to 14 - Reasoning perfectly reasonable

Page 15, line 15 - in fact, you can add that sediment source is always a decisive factor.

We now explicitly mention sediment source as a further decisive factor.

Page 15, line 24 to 27 - please rewrite this sentence.

The sentence was rewritten.

Page 15, line 28 – is backwash really relevant for depositional imprints in storm events? Against gravity?

Usually backwash is probably of minor or no importance during storms. However, sample HER 10 was collected close to a fluvial channel, where the backwash was not against gravity.

Page 16 - line 4 to 7 - here, you acknowledge that site-specific limits extrapolations of your conclusions. I agree and it really is hard to overcome this but, in my opinion, this field of science will progress will a multitude of sites, settings and events being studied. Maybe you can add a sentence regarding future work.

We agree that the value of case studies is their contribution to the database of locally and regionally differences of storm and tsunami deposits. We already tried to address this aspect later in this section. However, we modified our statement to highlight this message.

Page 16, line 20 - you need to add a comment on the different settings studied by Hawkes et al. (2007) and Goto et al. (2011).

The settings mentioned here are wide coastal plains or beach-ridge plains with a low topography that does not hinder lateral inundation and sediment transport due to steep slopes. Indeed, this is not true for the sites investigated by Hawkes et al. (2007), so we replaced the reference with observations on 2004 Tsunami deposits from a beach-ridge plain in Thailand by Jankaew et al. (2008). While most of the sites presented here have a steeper topography and are therefore not directly comparable, similar conditions are given at TOL. Nevertheless, in spite of high surge levels >5m, sand transport is limited to not more than ~300 m (although the topography of the coastal plain would allow for much more extensive deposition).

Page 16, line 20 to 27 - your conclusions are somewhat constrained because you did not compared tsunami and storm deposits in the same locations (e.g. Kortekaas and Dawson, 2007).

We agree that the conclusions are limited due to this fact. However, by comparing with tsunami deposits from sites with similar settings (similar flood levels and similar topography), we think our findings nevertheless add to the observation that sediment extent tends to be a discriminative feature.

Page 16, line 28 to 31 - 2 units by one event is totally different from 2 units by more than one!! You need to discuss this!!

We agree that both interpretations would have completely different implications. But since we are not able to prove one of the two possibilities (the formation of the washover fans at TOL could neither be proved by eyewitnesses nor by satellite images), we have to present both options for this location.

Conclusions - Page 17, line 2 - "local factors"... After so much work, it is important to stress the relevance of local conditions. In fact, I suggest you provide a geomorphological sketch (conceptual) model that describes accurately the initial pre-event conditions and the deposit after the event.

The idea to present the main outcomes of the study in a conceptual figure is very reasonable. We decided to merge this figure with the table summarizing the characteristics of the storm features presented in this paper (see reply to an earlier comment). This figure (figure 149 includes schematic sketches for the formation of each storm feature (coral ridge, sand sheet, washover fan). It, however, does not provide a separate figure on the pre-event situation. This is poorly constrained and, thus, cannot be documented with sufficient detail.

References

I suggest you add the above mentioned references.

The mentioned references will be included.

Figures

The figures have very good quality, are well-designed and are informative.

Supplementary material

Useful.

I believe that in scientific terms the authors developed quality work that clearly deserves publication in NHESS, subject to very few minor changes. Regards Pedro J. M. Costa

Reply to comments of reviewer #2:

Dear reviewer,

Thanks for the thorough and constructive comments to our submission. We think integration of these suggestions will help to further improve our manuscript. In the following we will address each of the comments separately (author replies in blue). References to lines always refer to the revised version with track changes.

Dear Editor and authors,
The research presented in this paper is a valuable contribution to the documentation of the sedimentary record of storms. Documenting the sedimentary record of Haiyan is critical because it is a very large storm and there is a need for data on erosion and deposition for extreme storms. The scope of the field investigation is impressive and the wide variety of laboratory analyses performed create a large data set that can be used to discriminate storm deposits from tsunami and other high-energy deposits. The figures are informative and well done. I recommend that this paper be published after revision. I suggest possible ways to improve the paper below.

Main comments:

Perhaps because of the amount of data presented I found the paper hard to follow. I suggest two things to help the reader: (1) a table summarizing all the sites visited and their important characteristics [source sediment available for transport, topography, etc.] and Haiyan deposit metrics [inland extent, maximum thickness, number of layers, grain size, etc.],

The suggested compilation of the most important storm deposit characteristics at each investigated site is very reasonable. This was also suggested by reviewer 1. We now provide this summarizing information as a new figure 14, which combines information in table form with conceptual figures for the generation of the different sediment types (i.e. sand sheets, washover fans, and coral ridges).

and (2) adding text in the introduction, or in a new section, about published reports on geometries and thickness/grain size trends for storm and tsunami deposits to give context for Haiyan deposits.

To provide more context for typical storm and tsunami signatures we added references for the geometry, grain size, thickness and sediment sources of well-investigated, modern analogues in the introduction section (page 2, line 24-29): “Although all potential discrimination criteria have been observed for both tsunami and storm deposits from a global perspective (Shanmugam, 2012), local comparisons assign several decimeter thick, laminated deposits with inland extents of a few tens to hundreds of meters that often show foreset bedding and tend to thin and fine landwards to typical storm signatures, while tsunami deposits tend to be rather thin, are composed of a few layers with massive or normally graded structure, and may extend inland for several kilometers (Tuttle, 2004; Morton et al., 2007; Switzer and Jones, 2008; Goto et al., 2011).” Likewise, in response to a comment of reviewer 1, we added information on discrimination criteria between tsunami and storm deposits in the discussion (section 5.3).

I am not entirely sure, but it appears that all the figures use distance along transect rather than distance from the shoreline. This is supported by the text on Page 6, Line 24, “shallow reef outcrops occur at 180 m transect length.” I also measured the distance along transect at Tolosa (Fig. 5). TOL14 is about 120 m inland from the shoreline, but is plotted at about 145 m in Figure 3 and 5. I measured the distance along transect at Tolosa to be about 140 m. Do all the figures use distance along transect rather than distance from the shoreline? If so, they need to be corrected. Distance along transect is meaningless because a change in transect orientation results in a different distance along transect for the same distance from the shoreline, the physically meaningful parameter.

The trenches are indeed plotted against distance along transects in all figures (only flood marks at TOL are already plotted with distance to shoreline). Since we agree that the distance perpendicular to the shore is the physically meaningful parameter, we adjusted all distances in figures 2, 3, and 5 to be consistent with distance to shoreline. The new numbers for distance to shoreline have also been implemented in the text.

I disagree with the statement on Page 1, Line 20 in the Abstract that Haiyan deposits, "might also function as a benchmark example for a general discrimination between storm and tsunami deposits." The Haiyan deposits are part of a spectrum of possible storm deposits; however, because of the presence of surf beat creating a tsunamilike bore they may not be typical. If so, although valuable to illustrate the spectrum of possible storm deposits, they may be more atypical than typical and therefore not a "benchmark example for a general discrimination between storm and tsunami deposits."

We agree that the expression "benchmark" example might be misleading. What we want to express is that the deposits formed by Haiyan describe an extreme case of storm deposition that should be considered for the discrimination of cyclone and tsunami deposits. A similar observation was made for boulders along the coast of Samar that were moved during Haiyan (May et al., 2015): due to the exceptional hydrodynamic conditions related to Haiyan's storm surge (i.e. the generation of surf beat), much larger boulders than typically related to storms could be moved, which is a valuable information for the discrimination of storms and tsunamis in the geological record, although Haiyan might rather be an atypical example. We modified the section to: "As these sediments and landforms were generated by one of the strongest storms ever recorded, they not only provide a recent reference for typhoon signatures that can be used for palaeotempestological and palaeotsunami studies in the region, but might also increase the existing spectrum of possible cyclone deposits. Although a rather atypical example for storm deposition due to the impact of infragravity waves, it nevertheless provides a valuable reference for an extreme case that should be considered when discriminating between storm and tsunami deposits in general" (page 1, 19-23).

A discussion of preservation potential of the Haiyan deposits would provide insight into whether the deposits observed in this study would be found in the geologic record. Instead of using "geological imprint" in the first sentence of the Conclusions (Page 17, Line 2) use "deposits" because preservation of the deposits is not addressed. Preservation of storm deposits in environments investigated in this study is a rather large topic and worthy of another paper. But, although it might seem like semantics, the "geological imprint" is unknown at this time because whether the deposit will be preserved is unknown and how it will be altered as time passes is also unknown. Same comment about using "geological legacy" in the next sentence (Page 17, Line3). I suggest using "deposits" again.

The reviewer is of course right. The terms "geological record" or "legacy" imply information on the preservation of the deposits that we do not – and within the frame of this paper cannot – present. Meanwhile we collected some data about the preservation of some of the documented deposits, but including this new data and discussing it would be too much for a single paper. Therefore, we strictly use the term "deposits" in the revised version of the manuscript.

Also in the conclusion is the statement, "the sandy onshore deposits left by Haiyan are very similar to those generated by tsunamis." Rather than give a qualitative qualifier of "very similar", which means different things to different people, list the similarities.

At this point we will only list the major similarities between Haiyan induced sand sheets and washover fans on the one hand, and the respective tsunami features on the other hand: sedimentary structure, sediment sources, and granulometry (page 19, line 11-12). For more details we refer to the new overview figure (Fig. 14), which summarizes the main characteristics of each type of deposition during Haiyan, and refers to references reporting similar deposits generated by tsunamis.

In the Abstract (Page 1, Line 3) and Conclusions (Page 17, Line 4) it would help the reader if you clarified what "Extended onshore sand sheets"/"extensive sand sheets" mean. Is there an inland distance that a sand sheet extends inland that you classify as "extended"/"extensive"? Perhaps it would be better to specify how far inland the sand sheets extend. How readers define extended/extensive will vary and it is better to be specific.

We agree that the description is subjective and should be replaced by a number. We replaced the phrase by “Onshore sand sheets reaching 100-250 m inland…” in the revised version of the manuscript.

Shell fragments are present in the Haiyan deposit at some locations. Grain size is measured by laser diffraction and Camsizer and does not account for particle density or shape, both of which would be quite different for shells than other components and affect their settling velocity and transport in suspension. I suggest discussing how the presence of shells affect your interpretation of the grain size data. Woodruff et al. (2008) address the differences between settling velocities of shells and siliciclastic particles. Figure DR2 in the data repository summarizes their results. The citation for Woodruff et al. (2008) is: Woodruff, J.D., Donnelly, J.P., Mohrig, D., Geyer, W.R., 2008. Reconstructing relative flooding intensities responsible for hurricane-induced deposits from Laguna Playa Grande, Vieques, Puerto Rico. Geology 36, 391–394.

Shell fragments settle significantly slower compared to siliciclastic particles of the same size. Thus, larger shell fragments are found in a matrix of siliciclastic sand with much smaller grain diameter. This will make deposits with a large percentage of shells (i.e. parts of the deposits at BAN) appear coarser than they would be for siliciclastic grains only, without being related to any changes in flow dynamics. For storm deposits at TOL (no carbonates) and HER (nearly 100% carbonates without platy shell particles) no significant effects are expected. We address this aspect in the methods section (page 6, line 10-12) by adding “It should be noted that both approaches do not consider differences in particle shape and density, which significantly influence the settling velocity of the grains (Woodruff et al., 2008). This is particularly important for the interpretation of granulometric variations in storm deposits with a significant percentage of shells”. In addition, it is addressed when discussing the granulometry of storm deposits at BAN in section 5.1.1 (page 15, line 11-16): “On the other hand, the coarsening trend could just be an artefact of the reduced settling velocity of platy shell fragments, which are particularly abundant in this section of BAN 4 (Fig. 7), compared to more spherical grains (Woodruff et al., 2008)”.

A fining trend in modal grain size is reported for Hernani (page 7, lines 2 and 3; Figure 3). However, the mean grain size trends of Hernani are more complicated. If trends in modal grain size are reported, please discuss how mean grain size trends are different and justify why you assign a “fining landward” trend based on modal grain size.

We added a description of the trend in mean grain size to allow comparison. Since a definition of landward fining based on modal grain size is indeed not common, we changed the sentence to read “While mean grain size does not show any fining trend in the deposit, modal grain size decreases from 1.3 cm to 220 µm along the same section (Figs 3, 4a)”. Although it may not be adequate to assign a fining trend based on modal grain size, the mode data at least indicate that there are changes in particle size along the transect (even though these do not affect the mean).

Are the statistics in Figure 3 for grain size for the entire deposit? That is, are they averages for all the grain size data for deposit? Please clarify for the reader.

The data presented in the original version of the manuscript are based on mean grain size and sorting for the entire storm deposit. We adjusted the figure to show both average data for the deposit, as well as trends for individual units where appropriate. All trend lines will be labeled accordingly.

Please explain further how it was determined that sediment from the foreshore and deeper water are part of the Haiyan deposit (Page 132, Line 16). Are there grain sizes present in the Haiyan deposit that are not from the beach? Can this be sediment picked-up landward of the beach? Were there samples collected from the foreshore and nearshore close in time to when Haiyan impacted the Philippines that have grain size data?

Unfortunately, reference samples were only collected and analyzed from the beach. Additional samples from the foreshore, deeper water, and terrestrial environments were not collected.

The interpretation that minor proportions of the Haiyan deposits are derived from sources different from the beach are based on the differences between the beach reference samples and the typhoon deposits in terms of granulometry and faunal composition (species and abrasion). These other sediment sources could in principle be areas seaward of the littoral zone, but also areas landward of the storm deposits. In response to this comment and a similar comment made by reviewer 1 we changed the section (page 14, line 16-21) to read: "Nevertheless, obvious differences in the granulometry and faunal composition of the sand sheets and modern beach sand (Fig. 8b, S4) may indicate also minor contributions of sediments from other source areas (the foreshore, deeper water, or landward areas), as reported by Pilarczyk et al. (2016) for deposits of Typhoon Haiyan from Tanauan (Leyte) and Basey (Samar). Alternatively, at least the differences in foraminifer taphonomy may reflect alteration of the sediments due to wearing and fracturing of foraminifer tests during transport in high energy flows (Quintela et al., 2016)."

What is meant by "a rather normally graded structure of these sand sheets" (Page 13, Line 9)? This is important because grading of deposits may be a discriminator of storm versus tsunami deposition. Were the Haiyan deposit suspension graded, as has been observed for deposits formed by several recent tsunamis and for paleotsunami deposits? (for an explanation of suspension grading see: Jaffe, B.E., Buckley, M.L., Richmond, B.M., Strotz, L., Etienne, S., Clark, K., and Gelfenbaum, G., 2011, Flow speed estimated by inverse modeling of sandy sediment deposited by the 29 September 2009 tsunami near Satitoa, east Upolu, Samoa, Earth-Science Reviews, v. 107, p. 23-37, doi:10.1016/j.earscirev.2011.03.009.)

This should read "mostly normally graded structure". While slight normal grading could be detected for thicker layers (close to the coast), the small thickness of the sand layers further inland did not allow for unambiguous identification of grading. We assume that even the thinner parts of the sand sheets might be normally graded, but cannot prove this by measurement data. However, regardless of normal grading can be observed or not, it is hard to say if they are suspension graded or not. Particularly, since the assignment of most normally graded sections within sand sheets is not based on laboratory analyzes (because they were not sampled in higher resolution). Only at BAN B sand sheets were sampled by pushcores and high-resolution data are available. Although the grain size distributions are not multimodal, improved sorting with decreasing grain size cannot be observed. A clear assignment of suspension-grading is therefore not possible.

Missing reference for Haiyan surf beat: Roeber, V and Bricker, J., 2015, Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan, Nature Communications (6), DOI: 10.1038/ncomms8854.

The missing reference was included in the paper and reference list.

<u>Other comments:</u>

Page 2, Line 8- Suggest changing "coastal disasters in the immediate past" to "recent coastal disasters".

Okay, was changed accordingly.

Page 2, Line 15- Suggest ending the sentence after "records" and change the next part of the sentence to a new sentence "This discrepancy is great because cyclones usually follow an inverse power law (Corral et al., 2010).

Okay, was changed accordingly.

Page 2, Line 18- Suggest changing "even events of the highest magnitudes" to "large events".

Okay, was changed accordingly.

Page 2, Line 25- Suggest changing "are particularly" to "are".

Okay, was changed accordingly.

Page 3, Line 16- Suggest changing "the significance of seasonality" to "seasonal variability".

Okay, was changed accordingly.

Page 4, Lines 10-18 and later in the paper as well- (i), (ii), (iii) are not needed and are distracting.

All numberings were removed in the revised version of the manuscript.

Page 4, Line 31- Suggest changing "typically shows" to "is characterized by".

Okay, was changed accordingly.

Page 4, Line 31- Again, (i), (ii), (iii) are not needed in this paragraph.

Okay, see reply to comment above.

Page 4, Line 32- The fetch over the Pacific, not the narrow shelf, is the reason that Eastern Samar has high swell waves.

We agree that the fetch is clearly the dominating factor for swell generation. Therefore we deleted the narrow shelf as an additional argument in the revised version of the manuscript.

Page 5, Lines 13 and 14- The times of day for the DGSP are not relevant and should be omitted.

We agree that this information is not required to understand the presented data. We deleted it in the revised version of the manuscript.

Page 5, Line 15- Suggest changing "were recorded by levelling" to "were documented by measuring elevations of".

Okay, was changed accordingly.

Page 5, Line 20- Suggest deleting "directly".

Okay, was changed accordingly.

Page 5, Line 23- Define what you mean by representative. Typical thickness? Typical sediment grain size? Typical structure?

Push cores were taken from deposits with sedimentary structures typical for the respective sites. This was supposed to guarantee sampling of all stratigraphical units documented at a site (and documentation of the differences between units). Since grain size and thickness of individual units vary in lateral direction, the push cores can only reflect part of this spectrum.

Page 5, Line 27- Chemical formula contain subscripts for the number of atoms for elements

We checked this. The formula are shown with correct formatting now.

Page 6, Line 17- Is Barangay capitalized?

Okay, is written in capital letters in the revised version.

Page 6, Line 19- Suggest changing "the two tropical storms/depressions recorded between Haiyan and this field survey on January 19th and February 1st respectively" to "the two tropical storms/depressions hitting the Philippines on January 19th and February 1st, respectively, which is after Haiyan and before this field survey".

Okay, was changed accordingly.

Page 7, Line 6- Are the values for grain size in ")"thinning and fining landward from 8 cm and a mean of 570 _m at 130 m from the shoreline (HER 8) to only 3 mm and a mean of 223 _m at 260 m (HER 3) (Fig. 3)." for the mode or mean? It appears from Figure 3 that they are for the mode, but I am not sure because this for Unit 1 and it is not clear what is shown in Figure 3.

The values are indeed for the mode, which is as well shown in figure 3. We clarified this in both text (replace mean by mode) and figure 3 (state the respective units grain size trends are plotted for) in the revised version of the manuscript.

Page 7, Line 21- Delete "According to".

Okay, was changed accordingly.

Page 7, Line 22- Suggest changing "bushes, Haiyan" to "are evidence that Haiyan".

Okay, was changed accordingly.

Page 7, Line 30- Suggest changing "Pre and post-typhoon" to "Pre- and post-typhoon".

Okay, was changed accordingly.

Page 8, Line 9 and later in the text- The use of the word "profiles" is not standard. Suggest changing "profiles TOL 7-14" to "trenches TOL 7-14". This suggestion applies everywhere in the text where "profile" is used to describe a trench.

Okay, was changed accordingly.

Page 8, Line 15- Specify what "slightly inclined" means.

The laminae are dipping landwards with an angle of ~10-15°. We added this information in the revised version of the manuscript.

Page 8, Line 21- What is meant by "moderate flooding". I have no idea what is moderate. Please be specific by giving a spatial extent and/or a water depth.

Since information on flooding was inferred from eyewitness observations, exact (i.e. measured) values for flooding extent and water levels cannot be provided. However, based on the observations, estimations for flooding extent (not more than a few 10s of meters) and water levels (not more than ~3 m above msl) are stated in the revised version of the manuscript.

Page 8, Line 25- How thin are the sand patches?

The documented sand deposits do not exceed a maximum thickness of 10 cm; most of them are in the range of 1-3 cm thickness.

Page 9, Line 1- Delete "single". It is not needed.

Okay, was changed accordingly.

Page 9, Line 1- Suggest changing "in either direction" to "crest elevation".

Okay, was changed accordingly.

Page 12, Line 30- Suggest changing "show comparably large inland extents exceeding 100 m" to "extend at least 100 m inland".

Okay, was changed accordingly.

Page 13, Line 13- Suggest changing "dedicated" to "attributed".

This section was changed in response to a comment of reviewer 1. In this context the mentioned expression was removed anyway.

Page 16, Line 21- Suggest changing "confined" to "indicated".

Okay, was changed accordingly.

Page 25, Figure 3- Be consistent with line types in each panel. Sorting is a different line type for HER 3-9 than for TOL 3-14 and BAN 1-3. A minor point, but why not make it easier on the reader to compare panels? Also, a solid line is used for both the mode and mean in different panels. Why not use a solid line for the mean and another line type for the mode?

We agree with the reviewer that a consistent style for all panels would facilitate reading the figure. The line styles for mean, mode and sorting were homogenized in the revised version of the manuscript.

Page 25, Figure 3- Why does the thickness scale for TOL 3-14 start at -2? This makes it difficult to determine the thickness of the more landward deposits. Why not start the scale at 0 to make it easy to determine the thickness of landward deposits?

We see the point and adjusted the scale for thickness.

Page 25, Figure 3- Why is there a vertical dashed line at 40 m in the TOL 3-14 panel? Please explain this line in the caption.

The vertical line is a drawing artefact that has no important meaning and was deleted.

Page 25 Figure 3 caption- The mean grain size of HER 3-8 doesn't monotonically fine landward. See earlier comment on mode versus mean and description/definition of landward fining.

It is true that the fining trend at TOL is restricted to the mode but does not apply to the mean. We adjusted the figure caption to match this observations.

Page 29, Figure 6- For consistency, add the column that indicates grading by the shaded triangles.

Okay, is added in the revised version.

Page 29, Figure 6 caption- The transect is not coast-perpendicular.

The figure caption was changed to read "Transect illustrating the succession of typhoon deposits in landward direction".

Page 33, Figure 10 caption- The transect is only shore-perpendicular for trenches 1 and 2, not 3.

The figure caption was changed to read "onshore sediments of Haiyan were investigated in three trenches (MOL 1–3) along a landward transect (T1)".

Typhoon Haiyan's sedimentary record in coastal environments of the Philippines and its palaeotempestological implications

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Abstract: On November 8th 2013, category 5 Supertyphoon Haiyan made landfall on the Philippines. During a post-typhoon survey in February 2014, Haiyan-related sand deposition and morphological changes were documented at four severely affected sites with different exposure to the typhoon track, and different geological and geomorphological settings. Onshore sand sheets reaching 100-250 m inland are restricted to coastal areas with significant inundation due to amplification of surge levels in embayments or due to accompanying long-wave phenomena at the most exposed coastlines of Leyte and Samar. However, localized washover fans with a storm-typical laminated stratigraphy occurred even along coasts with limited inundation due to waves overtopping or breaching coastal barriers. On a recent reef platform off Negros in the Visayan Sea, storm waves entrained coral rubble from the reef slope and formed a several 100 m long, intertidal coral ridge when breaking at the reef edge. As these sediments and landforms were generated by one of the strongest storms ever recorded, they not only provide a recent reference for typhoon signatures that can be used for palaeotempestological and palaeotsunami studies in the region, but might also increase the general spectrum of possible cyclone deposits. Although a rather atypical example for storm deposition due to the influence of surf beat, it nevertheless provides a valuable reference for an extreme case that should be considered when discriminating between storm and tsunami deposits in general. Even for sites with low topography and high inundation levels during Supertyphoon Haiyan, the landward extent of the documented sand sheets seems significantly smaller than typical sand sheets of large tsunamis. This criterion may potentially be used to distinguish both types of events.

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Keywords: typhoon; tropical cyclone; storm deposit; storm versus tsunami; sand sheet; washover fan; coral ridge; Philippines

1. Introduction

On November 8th 2013, Typhoon Haiyan (local name: Yolanda) made landfall on the Philippines reaching category 5 on the Saffir-Simpson Hurricane scale. By crossing the archipelago Haiyan caused more than 6000 casualties, affected more than 16 million people, and damaged more than 1 million houses (NDRRMC, 2014; Lagmay et al., 2015). Its destructive power resulted from exceptional surface winds reaching sustained velocities of up to 315 km/h (1-minute averaged data), gusting even up to 380 km/h, in combination with massive storm surge flooding with water levels up to 9 m above tide level (IRIDeS, 2014). Based on recorded wind speeds and core pressure, Haiyan was not only an exceptional event for the Philippines but one of the most powerful tropical cyclones ever recorded. Against the background of the ongoing controversial discussion on the influence of climate change on cyclone frequencies and magnitudes (Knutson et al., 2010; Pun et al., 2013), Typhoon Haiyan could be both an exceptional low-frequency event and/or a precursor of a new normality.

The need for robust data that provide information about long-term typhoon risk in affected areas is highlighted by the lack of awareness and preparedness of many inhabitants regarding Haiyan (Engel et al., 2014; Lagmay et al., 2015). Similar to other recent coastal disasters, such as the 2004 Indian Ocean Tsunami (Brückner and Brill, 2009) or Cyclone Nargis in 2008 (Fritz et al., 2009), studies of occurrence patterns and effects of past flooding events with exceptional magnitude have been lacking in the Central Philippines. Although previous catastrophic typhoons with similar tracks have been historically documented, e.g. in 1897 or 1984 (PAGASA, 2014; Soria et al., 2016), their disastrous effects have not been taken into account properly. This was at least partly due to limited comprehension of the term "storm surge", which people mainly associated with the moderate flooding of typical typhoons in the area (Engel et al., 2014; Mas et al., 2015). This discrepancy between real risk and perceived risk results from an underrepresentation of local high category typhoons in instrumental and historical records. This discrepancy is great, because cyclones usually follow an inverse power law (Corral et al., 2010).

Geological imprints of cyclones may be used to enhance existing historical and instrumental records, as they potentially cover periods of several millennia and, thus, document even large events in statistically significant numbers (Hippensteel et al., 2013; May et al., 2013, 2015a). However, using geological archives to extend tropical cyclone histories requires the identification of tropical cyclone traces, reliable dating of event layers, as well as a careful consideration of potential changes in paleogeography and/or sea level. In particular the discrimination of similar depositional events such as tsunamis is challenging (Shanmugam, 2012). In this regard, modern event deposits offer the possibility to establish (locally valid) event-specific criteria that indicate prehistoric events in the geological record (Nanayama et al., 2000; Kortekaas and Dawson, 2007). Although all potential discrimination criteria have been observed for both tsunami and storm deposits on a global perspective (Shanmugam, 2012), local comparisons assign several decimetre thick, laminated deposits with inland extents of a few tens to hundreds of meters that often show foreset bedding and tend to thin and fine landwards to typical storm signatures, while tsunami deposits tend to be thinner, are composed of a few layers with massive or normally graded structure, and may extend inland for several kilometres (Tuttle, 2004; Morton et al., 2007; Switzer and Jones, 2008; Goto et al., 2011). Likewise, modern analogues may help to evaluate reliable age (Bishop et al., 2005; Brill et al., 2012) and magnitude (Brill et al., 2014) reconstructions of palaeoevents. Since sedimentary signatures of cyclones are influenced by local factors (Schwartz, 1982; Matias et al., 2008), Haiyan's geological footprint will primarily be useful to establish criteria for inferring past typhoons from geological records found in the same areas. However, as one of the strongest storms ever recorded, Haiyan might increase the spectrum of possible cyclone features and, by this, add to the discussion on discriminating between tsunamis and extreme cyclones in general.

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Here, we report on sandy sediment data from four different Haiyan-affected coastal areas, collected during a post-typhoon field survey on the Philippines in February 2014, i.e. three months after Haiyan made landfall. The investigated areas comprise different geologies with carbonate and volcanoclastic coasts, as well as different geomorphological settings including steep cliff platforms, low coastal plains and coral reefs. The major aims of this study are to (i) document Haiyan's impact on the sedimentology and geomorphology of heavily affected coastal areas by recording onshore and intertidal sedimentation, coastal erosion and geomorphological changes. Based on these data, sedimentary and geomorphological typhoon signatures typical for the study area shall be established. In addition, (ii) the spatial variability of these typhoon signatures due to site-specific characteristics such as the local topography, bathymetry, geology, and hydrodynamics as well as the exposure to the typhoon track shall be investigated. Finally, (iii) the potential of these modern typhoon deposits will be evaluated in respect of possible implications for the identification of prehistoric tropical cyclones in the geological record.

2. Study area

The Philippine archipelago is located in the western Pacific Ocean between 5° and 20° northern latitude. Field work was carried out in four different areas (Fig. 1): (i) at the east coast of Samar between Llorente and General MacArthur (Fig. 1b); (ii) at the northeastern coast of Leyte between Tacloban and Dulag (Fig. 1b); (iii) on several islands northeast of Northern Negros (Sagay); and (iv) on Bantayan (Fig. 1c). All four study areas were significantly affected by Typhoon Haiyan, but are characterized by a different exposure to the typhoon track and by particular geomorphological and geological settings.

2.1 Climate and typhoon activity

2.1.1 General climatic and hydrodynamic conditions

The Philippine islands are characterized by a subtropical climate influenced by monsoon winds and the ENSO system. While the west of the archipelago experiences seasonal variations in rainfall and temperature with a dry period from November to April and a wet season during summer monsoon, seasonal variability gradually decreases towards the east reaching all-season wet conditions along the eastern coast (PAGASA, 2011). Hence, the study areas on Leyte and Samar show no pronounced annual rainfall variations. Northern Negros and Bantayan are influenced by weak monsoon seasonality. The highest swell waves occur during the winter monsoon and along the Pacific coast, while wave action during the summer monsoon and within the Sea of Visayas is generally moderate (Fig. 1e, Navy METOC, 2014). Tidal variations are in the range of 0.8–1.8 m. In addition, the entire Philippine territory is located in the corridor of east-west moving typhoons. On average, 21 tropical cyclones hit the Philippines annually, whereas the occurrence probability increases markedly towards the north (Fig. 1d, PAGASA, 2014).

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2.1.2 Haiyan's path over the Philippines

Starting as a tropical depression on November 3rd 2013 over the northwestern Pacific, Haiyan continuously gained intensity, turning into a tropical storm on November 4th, and a typhoon on November 5th. On November 6th Haiyan reached category 5 on the Saffir-Simpson Hurricane scale and finally made landfall on Samar on November 8th (IRIDeS, 2014) (Fig. 1a). After its first landfall near Guiuan (Eastern Samar) at 4:40 am, Haiyan crossed the archipelago in a western direction without reducing its strength below category 5 (Fig. 1a). On its path over the Philippines, Haiyan made landfall on northern Leyte at 7:00 am, on northern Cebu at 10:00 am, on Bantayan at 10:40 am, and later on Panay and Palawan (NDRRMC, 2014).

Depending on the exposure to the typhoon track, wind speeds, storm surge levels and wave heights varied significantly between the study sites. Additional variations are determined by differences in local bathymetry, fetch and shape of the coastline (see section 2.2). In general, coastal flooding rapidly reached peak levels that lasted for approximately two hours and was characterized by inflowing waves with periods of several seconds (Mas et al., 2015; Morgerman, 2014). The resulting flooding levels at the affected coastlines could mostly be reconstructed by means of combined storm surge and phase-averaged wave models (Bricker et al., 2014; Mori et al., 2014; Cuadra et al., 2014) (details concerning the specifications of each model presented in this paper are provided in the respective references). However, around Tacloban, significant amplification of storm surge levels to values of up to 8 m were measured (Mas et al., 2015), and three distinct flooding pulses were observed by eyewitnesses (May et al., 2015). Furthermore, along the coast of Eastern Samar surprisingly high values of run-up and flow depth were documented during post-typhoon surveys (Tajima et al., 2014; May et al., 2015b). While the exceptional water levels in the semi-enclosed basin of the San Pedro Bay can be explained by the funnel-shaped topography and seiches using combined storm surge and phase-averaged wave models (Mori et al., 2014; Bricker et al., 2014; Soria et al., 2016), the inundation pattern along the open coast of Eastern Samar can be attributed to the impact of infra-gravity waves due to an interaction of wind waves with the coral reef, if phase-resolving wave models are applied (Roeber and Bricker, 2015; Kennedy et al., 2016).

The exposed coast of Eastern Samar is characterized by a large fetch and a steep offshore bathymetry. Hence, it experienced maximum wind speeds with the highest model-predicted storm waves of up to 20 m, but only a limited wind-driven surge (Bricker et al., 2014). Field evidence documents run-up of approximately 12 m above mean sea level (a.s.l.), and up to 800 m inundation distance (PAGASA, 2014; Tajima et al., 2014; May et al., 2015b). Also the northeastern coast of Leyte was still exposed to the full strength of the storm winds, since the landmasses to the east are too narrow to significantly reduce Haiyan's intensity. However, due to the shallow water and the resonance effects in the enclosed embayment (Mori et al., 2014), storm-water levels were dominated by a surge setup, while model-predicted wave heights were <5 m (Bricker et al., 2014). Field evidence shows that the storm surge reached run-up levels of nearly 8 m a.s.l., and inundation of several hundred meters inland (Mas et al., 2015, Tajima et al., 2014). On the other hand, smaller surge levels and moderate wave heights were modelled for Northern Negros and Bantayan (Bricker et al., 2014), due to a shallow bathymetry, low tide at the time of landfall and the

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sheltering landmasses of Samar, Leyte and Cebu to the east. Likewise, eyewitness accounts document maximum onshore flooding levels of only ~2 m a.s.l. (Cuadra et al., 2014).

2.2 Geology and geomorphology

The Philippine islands are formed by a complex geological structure of north-south running volcanic arcs, tectonic basins and fragments of continental crust reflecting subduction and collision processes between the Eurasian and the Philippine plates (Rangin et al., 1989). As the main tectonic structures, the Philippine and Manila trenches confine offshore subduction zones to the east and west of the archipelago, while the Philippine Fault crosses the archipelago in an axial position from north to south (Fig. 1a, Rangin et al., 1989). The associated volcanoes and ophiolites form islands dominated by steep, cliff-lined coasts that are bounded by fringing reefs and are occasionally intersected by flat alluvial lowlands and pocket beaches. The clastic beaches are characterized by either white sand of coral reef origin, or darker and denser minerals derived from volcanic provinces (Bird, 2010).

The rocky carbonate coast of Eastern Samar is characterized by steep headlands with cliffs formed of Pleistocene coral limestone and occasional pocket beaches bordered by fringing reefs (HER, Fig. 1b). Since the fetch over the Pacific is not restricted, Eastern Samar is exposed to high swell waves especially during the winter monsoon (Fig. 1e) (Bird, 2010). On the other hand, the northeastern coast of Leyte is dominated by alluvial plains, sandy beaches and beach-ridge plains (TOL, Fig. 1b, Dimalanta et al., 2006), while rocky promontories and fringing coral reefs are scarce. Water depths in the shallow, funnel-shaped San Pedro Bay between Leyte and Samar do not exceed 30 m (Bird, 2010). In contrast to this, the northeastern coast of Negros is characterized by wide coastal plains bordered by mangroves and extensive coral reefs (Rangin et al., 1989). Within the shallow water of the Visayan Sea to the north (water depths mainly <50 m) numerous coral islands occur (CAR and MOL, Fig. 1c). The island of Bantayan represents the northeastern limit of the coral islands. The raised limestone formations making up the island are completely surrounded by fringing reefs that partly border steep rocky coastlines, but are also associated with sandy beaches (BAN A and B in Fig. 1c, Bird, 2010).

3. Methods

The topography of all studied locations was documented along transects by means of a Topcon HiPer Pro differential global positioning system (DGPS). To reconstruct flooding characteristics of Haiyan's storm surge, indicators for onshore flow depth and run-up height were documented by measuring elevations of debris lines, grass or floated debris in trees and bushes, as well as impact marks in the bark of palm trees relative to the sea level. All altitudes are given in meters above mean sea level (msl), and – in case of flood marks – additionally in meters above ground surface. Onshore flow directions were deduced from oriented grass and trunks using a compass. In addition, comparison of rectified pre- and post-Haiyan satellite images were used to estimate inundation areas. Sediments and depositional landforms generated by Typhoon Haiyan were documented both onshore and in the intertidal zone. This included sandy deposits as well as coral-rubble ridges. Shore-perpendicular trenches

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Gelöscht: (iii)
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Gelöscht: shore-perpendicular
Gelöscht: at 14 Feb at ~4 pm (TOL), 17 Feb at ~4 pm (HER), 23 Feb at ~10 am (BAN A), and 23 Feb at ~3 pm (BAN B)
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were used to describe and document the stratigraphy of sandy deposits in the field. For detailed sedimentary and faunal analyses, sediment from Haiyan's deposits and reference environments was taken in the form of bulk samples from each stratigraphical unit at different distances from the shoreline, as well as push cores from at least one storm deposit with representative sedimentary structure at each investigated location.

To deduce transport processes, mode of deposition, and source environments of the storm deposits, we analysed fine-grained samples in terms of their granulometry, geochemistry, mineralogy and faunal composition at the Institute of Geography, University of Cologne. Grain-size analyses were performed with a Laser Particle Analyser (Beckman Coulter LS 13320) for material <2 mm after pre-treatment with H_2O_2 and $Na_4P_2O_7$ to remove organic carbon and to avoid aggregation. In case of samples with grain size >2 mm, the granulometry was determined on dried sediment using a Camsizer (Retsch Technology). It should be noted that both approaches do not consider differences in particle shape and density, which significantly influence the settling velocity of the grains (Woodruff et al., 2008). This is particularly important for the interpretation of granulometric variations in storm deposits with a significant percentage of shells. Statistical parameters (mean, sorting, skewness) of grain-size distributions were calculated with the GRADISTAT software (Blott and Pye, 2001) using the formulas of Folk and Ward (1957). Further information about flow directions and mode of deposition was obtained by visually interpreting sedimentary structures in µCT scans with 50 µm voxel resolution (using myVGL 2.1 software) performed on two selected push cores (BAN 4 and TOL 8) at the University of Ghent, Belgium.

The chemical characterization of deposits includes determination of organic carbon by means of loss on ignition (LOI) measured after oven-drying at 105 °C for 12 h and ignition in a muffle furnace at 450 °C for 4 h. Carbonate contents were measured gas-volumetrically using the Scheibler method. The bulk-mineralogical composition was determined by X-ray diffractometry (XRD) on powder compounds performed on a Siemens D5000 using a step interval of 0.05° and a dwell time of 4 seconds. A fixed 1° divergence and antiscatter slit was used at diffraction angles from 5 to 75° 2theta. The Cu K-alpha radiation source was operated at 40 keV and 40 mA. The data were analysed with DiffracPlus Eva software package (Bruker AXS, Berlin, Germany).

Magnetic susceptibility (MS) was measured with a Geotec MSCL core sampler. To apply microfaunal composition as an indicator for sediment source and mode of transportation (e.g., Brill et al., 2014; Pilarczyk et al., 2016; Quintela et al., 2016), samples were sieved to isolate fractions >100 and <100 µm. At least 100 foraminifers were identified to species level, if possible, and counted under a binocular microscope. States of reworking were assessed semi-quantitatively on the basis of test taphonomy and classified as no, low, medium, or strong reworking. To select appropriate parameters for interpreting transport processes and sediment source areas, we carried out principal component analysis (PCA) using PAST software (Hammer et al., 2001) after removing foraminifera species with insignificant abundance (i.e. <5 individuals in all samples) and correlating parameters based on Spearman's rank correlation coefficient (≥0.95).

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4. Results – Sedimentary and geomorphological structures

4.1 Eastern Samar – Hernani (HER)

At Barangay Batang, municipality of Hernani (HER, Fig. 1b) the Pleistocene reef retreats to a position more than 200 m from the shoreline, resulting in a gently inclined sandy coast (Fig. 2). For Haiyan, local residents report complete inundation of the lower coastal plain with water levels of several meters above msl, while Agaton and Basyang – the two tropical storms/depressions hitting the Philippines on January 19th and February 1st, respectively (Fig. S3), which is after Haiyan and before this field survey – caused no significant flooding (Tab. S1 in online supplement).

Starting at the shoreline behind a 550 m wide intertidal reef lagoon and destroyed mangrove stands, the landward transect crosses a sandy beach ridge with a crest height of 2.2 m above msl at 50 m from the shoreline. Landwards, the tree-covered back-barrier depression is crossed by a shore-parallel channel before shallow reef outcrops occur at 120 m from the shoreline. After a second depression cultivated with rice fields (160–220 m), the transect ends at the inactive cliff of the elevated Pleistocene reef platform at 230 m inland and 2.8 m above msl. While swash lines document maximum inundation that exceeded the inactive cliff, floated grass and litter in trees indicate water levels of at least 2.5 m above msl (equal to a flow depth of 1.5 m above surface) at 100 m, up to 5.0 m above msl (3.7 m flow depth) at 170 m, and heights of 2.6 m above msl (1.4 m flow depth) at 220 m (Fig. 2).

Erosion was the dominant process seaward of the beach ridge, which is marked by an erosive scarp. Behind the barrier, sedimentation of sand and coral rubble was documented (HER 3–10), reaching its landward limit at the foot of the inactive cliff (Fig. 2). A sharp contact separates the light brown sandy layer covering the dark brown, densely rooted pre-Haiyan soil (Figs 4b, c). The thickness of the deposit decreases rapidly landwards, from 20 cm directly behind the beach ridge (HER 9) to only 2 cm at 110 m (HER 7) and a few mm at 210 m (HER 3). Coarse coral clasts at the surface (up to ~20 cm) occur as far as 100 m inland. While mean grain size does not show any fining trend in the deposit, modal grain size decreases from 1.3 cm to 220 µm along the same section (Figs 3, 4a).

Two different sedimentary facies units can be distinguished: Unit 1 was not encountered in HER 9 but comprises the entire typhoon deposit in HER 3–8 and 10 (Figs. 4a, b). It is characterized by normally graded to massive (HER 3-7) or slightly laminated (HER 8, 10), poorly sorted (3.4-7.3), unimodal fine-medium sand (mean of 85-230 µm). While sorting and mean grain size remain more or less constant, unit 1 is thinning landward from 8 cm at 90 m from the shoreline (HER 8) to only 3 mm at 210 m (HER 3). At the same time, the modal grain size decreases from 570 µm to 220 µm (Fig. 3). Unit 2 is characterized by a bimodal grain-size distribution that is significantly coarser than unit 1 (modes at 1.2 mm and 2.7 cm). It is only present at HER 9 (Fig. 4c), where it forms a 15 cm thick layer with steeply landward inclined layering and numerous angular coral fragments (constituting 77% of total mass). Both units are dominated by carbonates (nearly 100% Mg-calcite and aragonite). The foraminifera assemblage (determined for HER 10) is dominated by *Calcarina* sp. (41%), *Amphistegina* sp. (21%) and *Baculogypsina sphaerulata* (12%) that show significant reworking (<8% fresh tests, >50% strongly reworked). Vertical

Gelöscht: b…rangay Batang, municipality of Hernani (HER, Fig. 1b) the Pleistocene reef retreats to a position more than 23…0 m from the shoreline, resulting in a gently inclined sandy coast (Fig. 2). For Haiyan, local residents report complete inundation of the lower coastal plain with water levels of several meters a.s.l. ...

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Gelöscht: the two tropical storms/depressions recorded between Haiyan and this field survey on January 19th and February 1st respectively (Fig. S3)

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Gelöscht: 5… m (HER 7) and a few mm at 216… m (HER 3). Coarse coral clasts at the surface (up to ~20 cm) occur as far as 100 m inland. While mean grain size does not show any fining trend in the deposit, modal grain size decreases from 1.3 cm to 220 µm along the same section Along the same section, a fining trend from a modal grain size of 1.3 cm to 223 µm is observed ...

Gelöscht: 570 …30 µm). While sorting and mean grain size remain more or less constant, unit 1and…is thinning and fining …andward from 8 cm and a mean of 570 µm …t 913… m from the shoreline (HER 8) to only 3 mm and a mean of 223 µm …t 216… m (HER 3). At the same time, the modal grain size decreases from 570 µm to 220 µm (Fig. 3). Unit 2 is characterized by a bimodal grain-size distribution that is significantly coarser than unit 1 (modes at 1.2 mm and 2.7 cm). It and …s only present at HER 9 (Fig. 4c), where . At HER 9 ...

variations of species composition and taphonomy within HER 10 follow no clear trend. They rather roughly correlate with changes in grain size, showing a higher percentage of abraded and broken tests for coarser sediment sections (Fig. 4d).

4.2 Northeast Leyte (Tolosa)

Flood levels in Tacloban and in the coastal barangays to the south (Fig. 1b) reached >6 m above msl and locally inundation extended up to 1 km inland (Tajima et al. 2014). The typhoon was accompanied by strong wind damage with uprooted trees, heavy beach erosion and onshore sedimentation. Due to the position to the typhoon centre – winds and surge are strongest to the right of the typhoon track – water levels, beach erosion and sedimentation continuously decreased towards the south.

Although – according to surge levels – thickest onshore deposits are to be expected in Tacloban and directly south of it, we report on the storm impact on the nearshore area of Tolosa's beach-ridge plain (TOL, Fig. 1b), since the northern areas are more densely populated and unaltered typhoon sediments were hard to find three months after Haiyan. Floated grass found in trees and bushes are evidence that Haiyan overtopped the 2.2 m high beach ridge (above msl) and inundated the marshy back-barrier depression with water levels of at least 4.7 m above msl (3.5 m flow depth) at a distance of 70-90 m from the shoreline (Fig. 5). At the landward end of the transect, 300 m from the shoreline, water levels of at least 3.2 m above msl (1.8 m flow depth) have been recorded and satellite images for the Tolosa area document a landward flooding extent of up to 800 m during Haiyan (Fig. 5a). However, since sandy deposition stopped even more seaward, any further documentation was beyond the scope of this survey. The direction of onshore flooding is indicated by grass bent down in a NW-NNW direction, a westward collapsed north-south running wall structure, and the NW orientation of floated palm trunks (Figs 5b, c).

An erosive scarp at the seaward slope of the beach ridge indicates coastal erosion by Typhoon Haiyan that had already partially recovered in February 2014. Pre- and post-typhoon satellite images show a shoreline retreat of 25–30 m (inset in Fig. 5b). Between 30 and 130 m inland, a sheet of dark grey sand was deposited (TOL 3–14, Fig. 6). While 5–10 cm of sediment were accumulated on top of the beach ridge (TOL 3–4), the maximum thickness of 10–20 cm is reached directly leeward of the barrier (TOL 5–8). Further landward, the thickness rapidly declines, reaching 2–5 cm at 70–90 m from the shoreline (TOL 9–11) and only a few millimetres landwards of TOL 11 (TOL 12–14) (Fig. 6).

Investigations of trenches TOL 5 and 7 reveal the complete absence of carbonate components and microfauna in the storm layer. Instead, the composition is dominated by a mixture of feldspar (30–70%), amphibole (20–40%) and a minor percentage of quartz (5–30%). Magnetic susceptibility and LOI help to discriminate typhoon deposits from the underlying soil, but have constant values within the storm layer (Fig. 6c). However, in the stratigraphy of TOL 7 (Fig. 6b) and in the µCT scan of TOL 8 (Fig. 7), a normally graded unit 1 with scour marks at the base is clearly discriminated from the successive horizontally laminated unit 2 within the Haiyan deposits.

Unit 1 forms a slightly normally graded to massive layer of unimodal fine to medium sand at the base of trenches TOL 7–14. It covers the pre-Haiyan soil and, at several places, bended stems of grass. In trenches TOL 9–14, unit 1 constitutes the entire

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event deposit and is covered by a thin mud cap (Fig. 6a). While it is well-sorted (1.5–1.7) throughout the entire transect, its thickness decreases in a landward direction from 3–5 cm behind the beach ridge (TOL 7–10) to <1 cm at TOL 11–14. A landward fining trend from 240 µm to 130 µm has been noted as well (Fig. 3). Unit 2 comprises a well-laminated layer of unimodal medium sand (Figs 6, 7) and makes up the upper part of the storm layer in the proximal part of the transect (TOL 3–8). Sorting is similar to unit 1 (1.5–1.6), but the mean grain size (245–328 µm) is slightly coarser. The lamination is due to alternating concentrations of pyroxene (dark) and quartz (light) (XRD results, Fig. 8a). In TOL 5, the laminae are slightly inclined landwards (10-15°) and show repeated coarsening and fining sequences that superimpose a vertical coarsening upwards trend from ~260 µm to 320 µm (Fig. 6c). Unit 2 forms a washover fan at the landward slope of the beach ridge. While no clear trend in the thickness of the deposit was found – values range between 5 cm at the top of the beach ridge (TOL 4) and the landward edge of unit 2 (TOL 8), and ~20 cm directly behind the ridge (TOL 5) – it slightly thins landward (Fig. 3).

4.3 Northern Negros

All visited coral islands north of Negros (Carbin, Molocaboc, Suyac, Fig. 1c) were affected by moderate flooding reaching a few tens of meters inland and water levels less than 3 m above msl. Wind and wave directions changed from NNE before to WSW after the passage of Typhoon Haiyan's centre (Tab. S1, online supplement). Substantial beach erosion associated with onshore transport of sediment was observed directly after Haiyan. While coral rubble ridges were formed in the intertidal zone of Suyac and Carbin (CAR), onshore deposition was restricted to thin sand patches (few centimetre) and small coral boulders or parts of sea walls (main axis <2 m) in the proximal coastal zones of Molocaboc (MOL) and Suyac.

4.3.1 Carbin Reef (CAR)

On Carbin Reef, a coral rubble ridge along the western edge of the reef platform is visible at low tide (Fig. 9), but entirely submerged at high water. According to local fishermen (personal communication), the ridge did not exist in its present form prior to Haiyan (Tab. S1, online supplement), which means that it had either been absent or significantly lower (Reyes et al., 2015). The average crest height of the more than 300 m long section of the ridge measured during the field survey is 0.20 m below msl (boulders reach heights of 0.45 m above msl) without a significant trend in crest elevation. The basal width is 10–20 m, and lobe structures at its landward side cover corals in living position that must have been alive prior to the typhoon. Morphology and sediment – the ridge is mainly composed of centimetre to decimetre large coral fragments – allow the discrimination of two units: lobes of greyish, algae-covered coral rubble extending up to 20 m landward (unit 1), and light, freshly broken coral branches that form steep lobes or patchy coverings extending not more than 10 m from the reef edge, on top (unit 2). While both units are present along the entire 300 m long section, they significantly broaden from 10 m to 20 m width along the northern section (Fig. 9).

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4.3.2 Molocaboc Island (MOL)

At Molocaboc (Fig. 10), the coastal zone behind the 550 m wide intertidal platform of the fringing reef is formed by a beach ridge with a crest height of 2.4 m above msl, followed by a shallow back-barrier depression densely covered by acacia shrubs at 2.0 m above msl. Behind the beach ridge, fresh sandy deposits that rapidly thin landwards from 10 cm at 20 m shoreline distance to only 1 cm at a distance of 45 m have been recorded. The unimodal, medium to coarse (mean = 600–680 µm), moderately sorted (1.7–1.8) sand shows no apparent sedimentary structures and a calcareous composition (>90% Mg-calcite and aragonite); the Foraminifer assemblage is dominated by *Calcarina* sp. (58%) and strongly reworked tests (<18% fresh). The storm deposit contrasts with the underlying soil which is likewise unimodal, but slightly finer (mean of 390-410 µm), poorly sorted (3.4–4.7) and shows elevated contents of organic matter (4–7%) and reduced carbonate concentrations (70–80%). A reference sample from the shallow subtidal (R_{subt}) at 0.5 m below msl is unimodal, slightly finer (mean = 310 µm), moderately sorted (2.4), and dominated by different foraminifera (*Quinqueloculina* spp. [18%], *Peneroplis pertusas* [17%], *Elphidium* sp. [14%], *Ammonia beccarii* [12%]) with moderate reworking (74% fresh).

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4.4 Bantayan

Eyewitnesses report limited storm surge elevations with moderate waves and peak flooding arriving at low tide for the entire east coast of Bantayan (Tab. S1, online supplement). However, while onshore deposition is restricted to sand sheets of a few centimetres in coastal areas directly behind active beach ridges, beach erosion of several meters did occur. More pronounced flooding happened only locally at the mouths of estuaries and resulted in the formation of small washover fans (BAN A and B, Fig. 1c).

4.4.1 Bantayan A (BAN A)

At BAN A, the NE-exposed beach section (Figs 11a, b) is separated from an estuary river mouth by outcrops of the Pleistocene coral reef limestone with 1–2 m high cliffs. Cross sections reveal a succession of shore-parallel beach ridges with elevations of 1.5-1.8 m above msl that are interrupted by ~1 m deep swales (Fig. 12a). While recent flooding levels were indicated by debris lines at 1.4 m above msl along the seaward and landward slopes of the second beach ridge, as well as on top of the 2.9 m high (above msl) reef platform to the NW, the maximum wave height during Haiyan was estimated to have reached 3.0–3.4 m above msl on the basis of eyewitness accounts (Tab. S1, online supplement). Furthermore, residents report flooding of approximately 50 m inland and strong beach erosion during Haiyan. However, for this section of the coast (E1–E5, Fig. 1c) similar effects were observed after tropical storm Basyang in February 2014 which had been less intense, but had struck at high tide (Fig. S3 and Tab. S1, online supplement).

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Gelöscht: a.s.l.

Storm erosion created a steep shoreface with an erosive scarp and uprooted palm trunks at the seaward slope of the first beach ridge. Residents report lateral erosion of more than 5 m due to the combined influence of Haiyan and Basyang along large sections of the beach (Tab. S1, online supplement). However, the formation of lobate washover fans in the back-barrier depression is already visible on satellite images from November 2013 (Fig. 11b). The washover fans are restricted to a 10 m wide section behind the beach, but form prominent landforms with two distinct stratigraphical units (Figs 11c, 12a).

The basal unit 1 is related to flat washover lobes characterized by planar lamination. It overlies a weakly developed soil with a sharp contact and extends slightly further inland compared to the subsequent unit 2, which is characterized by landwards inclined beds with a steep terminal front. The internal structure is illustrated by the sedimentology (Fig. 12b) and µCT scans (Fig. 7) of sediment core BAN 4. Below the pre-Haiyan soil, a thin sheet of medium sand (PE) was found along the erosive cliff in the ridge (Fig. 12a) as well as in BAN 4 (Figs. 7, 12b). The sand layer covers an older palaeosol, composed of brown, slightly loamy sand. The basal Haiyan deposit is composed of a laminated section of unimodal, moderately sorted (1.8) medium-coarse sand (mean of 600-770 µm), rich in strongly reworked foraminifer tests (35-60%) dominated by *Calcarina* sp. and *Amphistegina* sp. (unit 1). The uppermost 19 cm (unit 2) are composed of coarser (mean of 730-1300 µm) and slightly less sorted (2.0) unimodal sand with similar species composition but a higher percentage of fresh or only slightly reworked foraminifers (60-80%) between 19 and 10 cm below the surface (Fig. 12b). A reference sample collected at the present beach at 0.5 m above msl (BAN R_1) is slightly finer than unit 1 (mean of 400 µm) and better sorted (1.6).

4.4.2 Bantayan B (BAN B)

Site BAN B is located in direct vicinity of an estuary mouth in northern Bantayan, lined by a 500 m wide intertidal reef platform (Fig. 11d). While the coast south of the estuary is characterized by a 2.8 m high cliff (above msl) in the Pleistocene coral reef limestone, a c. 100 m wide sand spit backed by mangroves forms the section to the north (Fig. 11e). In a shore-perpendicular direction, a beach ridge at 2.4 m above msl is followed by a flat mud plain with mangroves and reef outcrops at 0.9–1.1 m above msl (Figs. 13a, S1). Eyewitnesses report significant flooding by Typhoon Haiyan, while Basyang – different from the southern part of Bantayan – caused no marked inundation (E6–10 in Tab. S1, online supplement). Flood marks in the form of floated debris on top of the cliff or trapped in bushes and mangroves document inundation of at least 200 m inland. Minimum water levels decrease landwards from 3.1 m above msl directly at the coastline, to 2.1–2.3 m above msl at 60 m from the shoreline and only 1.4 m above msl at 160 m (Fig. 11e).

Haiyan-induced onshore sand deposition is less than 1–2 cm in the back-barrier mangroves. Thicker deposits occur in the form of up to 30 cm thick and 50 m wide washover fans at two sections behind breaches in the barrier (Fig. 11e). Coast-perpendicular transects (T2 and T3, Fig. 11e) reveal landward thinning trends from 28 cm at 10 m behind the barrier to only 5 cm at a distance of 40 m (T2, Fig. 3), and from 15 cm at 10 m behind the ridge to 1 cm at a distance of 40 m respectively (T3 in Fig. S1a, online supplement). Similar to site BAN A, the pre-Haiyan soil had formed in a thin sand sheet, which has a composition similar to the modern storm deposit and covers a second palaeosol at the base of the trenches (PE in Fig. 13a). It might be the deposit of a former storm.

In both washover fans, two successive sedimentary units were distinguished and investigated in detail for cores BAN 1–3 (transect 2; Figs 13b, S2). Unit 1 is massive to slightly normally graded, composed of unimodal, moderately sorted (1.5–2.6)

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Gelöscht: a.s.l.
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Gelöscht: 9
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medium sand (mean = 250–320 µm) and shows a sharp boundary to the pre-Haiyan soil. It constitutes the entire typhoon layer in BAN 3, but is topped by a markedly thicker unit 2 in BAN 1 and 2. Unit 2 is composed of several planar to slightly inclined, normally or inversely graded beds of well-sorted (1.5–1.9) medium sand (mean = 300–480) with shell and coral fragments as well as pieces of litter. Both units contain >90% carbonates (aragonite and Mg-calcite). The Foraminifer assemblage is dominated by *Calcarina* sp. (32%), *Amphistegina* sp. (19%) and *Ammonia beccarii* (19%). Most of the tests are strongly reworked (<17% fresh), though test preservation is much poorer (<1% fresh) in the palaeosol which is mainly composed of *Amphistegina* sp. (22%), *Ammonia beccarii* (21%), *Elphidium craticulatum* (12%) and *Quinqueloculina* spp. (12%). While unit 1 thins landwards in T3, neither a clear thinning tendency nor a fining trend is detectable in T2. Unit 2 is restricted to the proximal part of the washover fans (BAN 1–2, Figs 13, S2 and A–B, Fig. S1a) and rapidly thins landwards. For comparison with modern environments, reference samples were collected at 0.6 m above msl (BAN R_2) and at msl (BAN R_3). Both samples show a similar granulometry of unimodal, moderately sorted (1.9-2.0) medium sand (mean of 280-550 µm).

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4.5 Inter-site comparison of sediment characteristics

4.5.1 Geochemistry, mineralogy and foraminifers

The comparison of XRD data from all four sites reveals two general types of mineralogical compositions. While sediments from the carbonate environments (MOL, HER, BAN) are dominated by calcite, Mg-calcite and aragonite (at least 80%) with minor percentages of feldspar or quartz, the samples from the siliciclastic coast (TOL) are mainly composed of feldspar and amphibole with a minor percentage of quartz (Fig. 8a).

A principal component analyses (PCA) on foraminifer data from the carbonate coasts indicates three PCs which explain 60% of the total variability. PC1 (31%) is characterized by positive loadings for the genera *Rosalina* sp., *Quinqueloculina* spp., *Peneroplis* sp., *Milionella* sp., *Globigerinoides* sp. and *Coscinospira* sp., while *Calcarina* and *Amphistegina* are negatively correlated. PC2 (18%) shows positive scores for *Amphistegina* sp. and strong reworking, and negative ones for *Heterostegina* sp. PC3 (11%) is positively correlated with *Challengerella* sp. and negatively with *Spirillina* sp. and *Schlumbergerella* sp. Plotting of PC1 against PC2 (Fig. S4, online supplement) reveals differences between sediment from the foreshore at Molocaboc (MOL R_{subt}) on the one hand, and beach reference samples and storm deposits from all locations on the other. Differences between beach and storm deposits from different sites are less pronounced.

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4.5.2 Granulometry

PCA combining granulometric data from all sites reveals three PCs that explain 82% of the total variability. Plotting of PC1 (positive loadings for mean, sorting, gravel and mode, negative ones for skewness and medium sand) versus PC2 (positive loadings for mean, skewness and mode, negative ones for sorting and mud) reveal both site-dependent properties as well as distinct clusters for samples from units 1, units 2 and the palaeosols (Fig. 8b1).

In addition, PCAs on grain-size parameters were performed for each site separately. For TOL, PC1 (62.8%) and PC2 (33.5%) explain 96% of the total variability. Plotting of PC1 (positive loadings for skewness, mode and medium sand, negative ones for sorting and mud) versus PC2 (positive scores for sorting, mode and medium sand, negative ones for skewness) reveals clusters for unit 1, unit 2 and the pre-Haiyan soil (Fig. 8b3). Samples from HER reveal three PCs explaining 84% of the total variability. Plotting of PC1 (positive loadings for sorting, mud and fine sand, negative ones for skewness and coarse sand) versus PC2 (positive scores for fine and medium sand, negative ones for mode and sorting) reveals clustering of unit 1 and the palaeosol, while unit 2 forms two separate sample groups (HER 10 and all other trenches) (Fig. 8b2). At BAN, three PCs explain 86% of the total variation. Plotting of PC1 (positive loadings for mean, skewness and medium sand, negative ones for sorting and mud) versus PC2 (positive scores for mean, sorting, mode and gravel, negative ones for medium sand) reveals clusters for unit 1, unit 2 and the palaeosol, whereas reference samples from the upper and lower beach plot into the cluster of unit 2 (Fig. 8b4), pointing to this area as the main sediment source.

Gelöscht: profiles

5. Discussion

5.1 Sedimentary footprint of Typhoon Haiyan on the Philippines

Based on eyewitness accounts and the interpretation of satellite images, most of the documented storm deposits can unambiguously be related to Typhoon Haiyan. Even at BAN A, where eyewitnesses report strong coastal erosion by tropical storm Basyang for the period between Haiyan and the field survey, satellite images from November 11th clearly document the formation of the washover fans by Typhoon Haiyan. Only at TOL, where both satellite images and eye witnesses cannot unambiguously relate all of the documented onshore deposits with Haiyan, the proximal parts of the washover sediments (unit 2 at TOL) cannot be excluded to be associated with post-Haiyan storm waves of Basyang. In addition to the fine-grained storm deposits reported in this study and summarized in figure 14, Haiyan moved block- and boulder-sized reef-rock clasts at the coast of Eastern Samar, which have been discussed elsewhere (May et al., 2015b).

5.1.1 Sandy onshore deposits

Based on sedimentary and morphological criteria, the here presented sandy onshore deposits of extreme wave events are classified into sand sheets and washover fans. The classification reflects different flooding regimes and, therefore, is assumed to represent hydrodynamic processes that lead to different sediment characteristics (Fig. 14).

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Gelöscht: (ii)

Sand sheets: separated from the underlying soil by a layer of bended grass, the base of the typhoon deposits at TOL, HER, BAN B and MOL (the local units 1) is formed by slightly normally graded to massive layers of sand (some of the layers were too thin to detect potential grading without laboratory analyses). All these sand sheets extend at least 100 m inland, are relatively thin (<10 cm), and exhibit clear landward thinning and slight fining trends (Fig. 3). Their appearance is similar to

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storm deposits formed under inundation regimes related to extensive flooding of back-barrier marshes described by Donnelly et al. (2006) or Wang and Horwitz (2007). Indeed, complete inundation of coastal barriers and back-barrier areas at HER, TOL, BAN B and MOL is documented by flood marks. While at MOL and BAN B flooding is facilitated by the absence of a pronounced beach ridge or by a nearby river mouth, flow depths of nearly 4 m above surface and the complete submergence of barriers with crests more than 3 m above msl at TOL and HER are either due to the high storm surge levels (TOL) or due to a combination of storm surge, high storm waves and related infra-gravity waves such as surf beat (HER) (Bricker et al., 2014; Roeber and Bricker, 2015; Kennedy et al., 2016). The associated overland flow generally followed shore-perpendicular directions, if not re-directed by shore-parallel wall structures (TOL, Fig. 5). As indicated by scour marks (µCT scan of TOL 8, Fig. 7) and a mostly normally graded structure of these sand sheets, sediment dynamics related to this inundation regime (i.e., inundation overwash; cf. Donnelly et al., 2006) are assumed to be characterized by turbulent flow conditions and deposition from suspension. Even if clear suspension grading as described by Jaffe et al. (2011) could not be detected, the deposits are very similar to suspension-settled sediments described by Williams (2009) for Hurricane Rita at the US coast. At least at TOL and HER the deposition of these sand sheets was influenced by few tsunami-like flooding pulses due to infra-gravity waves or seiches that amplified peak inundation (Mori et al., 2014; Roeber and Bricker, 2015). Comparison of granulometry as well as foraminifer taphonomy and species composition with reference samples point to the beach as the dominant sediment source (BAN R_{1-3}) rather than foreshore (MOL R_{subt}) or other environments (Figs 8b, S4). Nevertheless, obvious differences in the granulometry and faunal composition of the sand sheets and modern beach sand (Fig. 8b, S4) may indicate also minor contributions of sediments from other source areas (the foreshore, deeper water, or landward areas), as reported by Pilarczyk et al. (2016) for deposits of Typhoon Haiyan from Tanauan (Leyte) and Basey (Samar). Alternatively, at least the differences in foraminifer taphonomy may reflect alteration of the sediments due to wearing and fracturing of foraminifer tests during transport in high energy flows (Quintela et al., 2016).

Washover fans: Unit 2 at TOL, HER, and BAN B, as well as the entire storm deposits at BAN A (the local units 1 and 2) are formed by lobate landforms of several decimetres thickness directly behind the barrier. As they (a) are restricted to the proximal part of back-barrier depressions (within <50 m from the shoreline), (b) form lobes with a gently inclined upper surface (1–5°) and a steep landward front, (c) show multiple grading within horizontally to inclined laminated sections, and (d) reveal landward thinning and fining trends, these features resemble typical storm-induced washover fans, e.g. described by Sedgwick and Davis (2003), Phantuwongraj et al. (2013), or Williams (2015). They formed due to wave-induced sediment transport over the coastal barriers. This took place after the first flooding pulses inundated the coastal barriers, most likely during the peak of the storm surge when the largest storm waves occurred (Williams, 2009). Where coastal barriers were already inundated due to the wind induced storm surge (at TOL and BAN B), or due to the impact of infra-gravity waves (at HER, May et al., 2015b), deposition is assumed to be caused by waves breaking at the inundated barrier. At site BAN A on the other hand, where a basal sand sheet (unit 1 at TOL, BAN B and HER) is absent, flood marks indicate maximum water levels lower than the coastal barrier, and deposition was related to confined overwash (i.e., run-up overwash; cf. Donnelly et al., 2006). The internal

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stratification and washover morphology allow for a discrimination of a basal section with horizontal bedding associated with flat lobes (unit 1) and a section with steeply inclined layers with a steep avalanching front on top (unit 2). Horizontal lamination is interpreted as the result of initial barrier overtopping into dry back-barrier depressions associated with high flow velocities, whereas steep lobes with inclined bedding are associated with delta-front sedimentation into already flooded back-barrier depressions (Sedgwick and Davis, 2003; Switzer and Jones, 2008), e.g. due to high levels of the preceding storm surge or intensive rainfall.

Anyway, the washover fans either form isolated structures such as at TOL, HER and BAN B, or coalescing washover terraces (BAN A). Since breaching is associated with barrier erosion and radial spread of water and sediment into back-barrier depressions, granulometry, foraminifer assemblages and taphonomy indicate that storm sediments were mainly derived from the beach (Figs. 8b, S4). The swash of multiple individual waves generates successions of laminae which are probably caused by density separation in mixtures of heavy minerals, quartz and shell fragments during transport as traction load (Komar and Wang, 1984). Vertical changes of granulometry and faunal composition within individual washover deposits – such as the upward trend towards coarser and stronger reworked deposits at BAN A (Fig. 12) – could be related to slightly different sediment sources as a result of a successively changing beach profile. On the other hand, the coarsening trend could just be an artefact of the reduced settling velocity of platy shell fragments, which are particularly abundant in this section of BAN 4 (Fig. 7), compared to more spherical grains (Woodruff et al., 2008).

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Gelöscht: At site BAN A, where a basal sand sheet (unit 1 at TOL, BAN B and HER) is absent, flood marks indicate maximum water levels lower than the coastal barrier, and deposition is related to confined overwash. The internal stratification and washover morphology allow for a discrimination of a basal section with horizontal bedding associated with flat lobes (unit 1) and a section with steeply inclined layers with a steep avalanching front on top (unit 2). Horizontal lamination is interpreted as the result of initial barrier overtopping into dry back-barrier depressions associated with high flow velocities, whereas steep lobes with inclined bedding are associated with delta-front sedimentation into already flooded back-barrier depressions (Sedgwick and Davis, 2003; Switzer and Jones, 2008), e.g. due to high levels of the preceding storm surge or intensive rainfall.

5.1.2 Intertidal coral-rubble ridges

Considering the interviews with local fishermen and the fact that parts of the intertidal coral ridge at Carbin Reef in February 2014 covered reef organisms which must have been alive shortly before, formation or at least significant heightening can unambiguously be attributed to Typhoon Haiyan. Coral rubble ridges have repeatedly been reported to be a typical cyclone signature (Scheffers et al., 2012), e.g. on Funafuti Atoll, where Maragos et al. (1973) describe a cyclone-generated, intertidal coral ridge dominated by sand to boulder-sized rubble derived from the foreshore. Diving surveys before and after Haiyan revealed significant impact of the typhoon at the seaward reef slope while organisms on the intertidal platform were nearly untouched (Reyes et al., 2015), pointing to the entrainment of sediment from the foreshore and its deposition at the reef edge. Since ridge formation requires the repeated impact of breaking waves and wave swash is attenuated by the high porosity of rubble ridges (Spiske and Halley, 2014), ridge generation during Haiyan is mainly due to the impact of multiple storm waves breaking on top of the inundated reef platform.

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The two morpho-sedimentary ridge units at Carbin allow for two possible explanations: A first interpretation is that the entire ridge was formed by Typhoon Haiyan, whereas the distinct units would reflect changing wind and wave directions. In accordance with a rotation of wind directions reported for the passage of Haiyan, unit 2 is present only at the W-exposed section of the ridge and may be interpreted as the result of stronger wind waves connected with increased destruction of the

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living reef at Carbin's slope as indicated by the fresh, angular coral fragments incorporated in unit 2. On the other hand, the more pronounced algae cover on coral rubble of unit 1 and the eyewitness accounts of ridge occurrence after Haiyan might also be explained by the impact of several typhoons. In this case, formation of the initial ridge (unit 1) that was not pronounced enough to be recognized by local fishermen, could have taken place during former storms. Afterwards, Haiyan increased its height by adding fresh coral rubble on top (unit 2), which made the ridges widely recognizable.

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5.2 Spatial variability of fine-grained typhoon signatures

The spatial distribution and sedimentary structure of deposits formed by Typhoon Haiyan was critically influenced by both local setting and the hydrodynamic characteristics during inundation. Although onshore transport of sand is rather ubiquitous, widespread sand sheets with a significant inland extent >100 m in the study area are restricted to locations with exceptional surge and/or inundation levels. This includes the exposed coastlines of Eastern Samar (HER) and the funnel-shaped San Pedro Bay (TOL), where a remarkable amplification of surge levels to values >8 m above msl occurred during Haiyan (Mori et al., 2014). However, pressure and wind driven surge alone do not explain the high inundation levels for Eastern Samar, since numerical storm-surge models combined with phase-averaged wave models infer rather low water levels of ~2 m (Bricker et al., 2014). While surge levels in the San Pedro Bay were additionally heightened by wave reflection in the enclosed embayment (Mori et al., 2014), phase-resolved wave models imply that the surprisingly high flooding levels along Eastern Samar result from infra-gravity waves, caused by non-linear wave interactions with the fringing reef (Roeber and Bricker, 2015; May et al., 2015b; Kennedy et al., 2016).

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On the other hand, washover features were even formed in areas with limited flooding levels and restricted landward inundation such as Bantayan and Northern Negros. Since washover deposits require high waves capable to overtop coastal barriers, their local occurrence seems to be predetermined by bathymetry (river estuaries) and coastal morphology (pre-existing gaps or depressions in sandy barriers) as observed on Bantayan. Hence, they are limited to small sections of the coast even in heavily affected areas. For the localized occurrence of coral ridges on the reefs north of Negros, obligatory requirements seem to be the presence of intertidal reef platforms with coral rubble in the foreshore zone; exposure towards the main direction of the storm waves; and waves high enough to entrain the foreshore sediment and to lift it onto the reef platform.

Gelöscht: (a)
Gelöscht: (b)
Gelöscht: (c)

Local geology, geomorphology and sediment source are also the main factors determining the composition of the investigated typhoon deposits (Fig. 8). On the one hand, variations of total sediment composition (mineralogy and granulometry) between different sites are more significant than variations between different units at individual sites (Fig. 8a, b). The granulometry of storm-transported sediment varies with the sediment availability at the beach and the foreshore zone so that dominant grain size varies between HER, TOL and BAN (Fig. 8b). Geochemistry and mineralogy basically reflect differences between siliciclastic and carbonate coasts (Fig. 8a). Varying site-specific compositions have also been reported for foraminifer assemblages of Haiyan deposits by Pilarczyk et al. (2016). Likewise, clearly laminated washover deposits (alternation of dark and light laminae) are linked to the presence of heavy minerals at siliciclastic coastlines (TOL), while bedding structures are

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less prominent in carbonate environments (BAN and HER). On an intra-site level, on the other hand, mineralogy and geochemistry (due to insignificant differences) and microfauna (due to a limited dataset) only allow for a separation between storm deposits and underlying palaeosols, while sedimentary structures and grain-size data enable further discrimination of distinct subunits (Fig. 8b). Although the number of reference samples from recent environments is very limited in this study, the granulometric differences between internal sublayers of the same storm deposit seem to be related to varying sediment sources (beach vs. foreshore), or to different hydrodynamic transport conditions as it has been described by Switzer and Jones (2008). This is the case for the units 1 and 2 at sites TOL, HER and BAN (Fig. 8b), while the large scatter within the unit 2 deposits at HER might be explained by deposition of the HER 10 deposits by backwash, since the core was taken close to a fluvial channel.

5.3 Implications for palaeotempestology

Since the sedimentary characteristics of Typhoon Haiyan's deposits show significant site-specific variations, it is not possible to infer one particular storm signature type. Nevertheless, storm deposits can clearly be distinguished from most other depositional processes on the basis of granulometry, internal structures, mineralogy and faunal composition. Only tsunamis might be capable to produce similar features, due to comparable hydrodynamic characteristics that potentially allow for barrier overwash, landward transport of sand for hundreds of meters, and the generation of waves strong enough to entrain and lift subtidal coral rubble onto intertidal reef platforms (Shanmugam, 2012). Although numerous features have been established to discriminate between tsunami and storm deposits, including among others thickness, lateral extent, granulometry, source areas and sedimentary structures of the event deposits (e.g., Morton et al., 2007; Switzer and Jones, 2008), most of these sedimentary indicators seem to be of local value only and cannot serve as universal discrimination criteria (Shanmugam, 2012). Unfortunately, only very few tsunami signatures that might facilitate discrimination by providing typical site-specific features (e.g., Kortekaas and Dawson, 2007) have been described for the Philippines (Imamura et al., 1995), making it hard to evaluate which of the sedimentary characteristics documented for Typhoon Haiyan in this study are unique for the impact of local typhoons.

So far, coral ridges have been reported to be exclusively generated by cyclones (Scheffers et al., 2012), which seems straightforward. Ridge formation requires repeated breaking waves as observed during cyclones (Nott, 2006), while the small number of inundation pulses characteristic for tsunamis tends to produce randomly scattered boulder fields (Richmond et al., 2011; Weiss, 2012). However, preservation of coral ridges is often limited (Baines and McLean, 1976), and age determination remains challenging due to potential reworking of the components (Scheffers et al., 2014). On the other hand, suspension-settled, normally graded sand sheets with large inland extents as described at TOL or HER are typical signatures of tsunamis as well (e.g., Jankaew et al., 2008), and also washover fans with internal lamination as present at BAN or TOL have been reported for both storms (Switzer et al., 2012) and tsunamis (Atwater et al., 2013). Likewise, most features described for the sand sheets and washover fans in the study area have already been observed for tsunami deposits: The composition and

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Nevertheless, Haiyan and its sedimentary record offer some valuable considerations regarding the interpretation of palaeoevent deposits in geological records both in the Philippines (e.g. for the young palaeoevents documented on Bantayan) and in general. While t

granulometry of the storm-induced sand sheets and washover fans presented here are mainly controlled by local geology rather than transport processes typical for cyclones. With most sediment derived from the littoral zone, the main sediment origin of the Haiyan deposits is similar to that of typical tsunami deposits (e.g., Brill et al., 2014), and apart from that not analysed with sufficient detail to determine secondary source areas that might enable better differentiation from tsunami deposits. Finally, the documented landward thinning and fining trends in the Haiyan deposits are similar to those observed in many tsunami deposits (e.g., Goto et al., 2008).

Nevertheless, by adding local data to the knowledge on the manifold expressions of storm deposits, the sediments accumulated by Haiyan offer some valuable considerations regarding the interpretation of palaeoevent deposits in geological records during future studies both in the Philippines (e.g. for interpreting the young palaeoevents documented on Bantayan) and in general. On the one hand, with not more than ~250 m the inland extent of the Haiyan-laid sand sheets presented here seems to be limited compared to sandy deposits of many recent tsunamis with comparable inundation levels in settings with flat topography that extend landwards for several kilometres (e.g., Jankaew et al., 2008; Goto et al., 2011). This is true even at site TOL that experienced onshore flooding levels >5 m above msl, and where the flat topography did not hinder lateral inundation and sediment transport. Although the landward limit of coastal inundation may be indicated by mud deposits rather than by sand layers (e.g., Williams, 2010; Abe et al., 2012; Goto et al., 2014), and our comparison is not based on tsunami deposits from the same location (e.g., Kortekaas and Dawson, 2007), our findings seem to corroborate previous conclusions that the landward extent of tsunami sand sheets in low lying coasts tends to be larger in comparison with sandy storm deposits (cf. Morton et al., 2007). On the other hand, the combined occurrence of (i) a thin (i.e., a few cm), massive to slightly normally graded basal unit formed by suspension-settling due to surge-related extensive coastal flooding (unit 1 at TOL and HER), and (ii) a laminated, swash-induced, spatially limited washover unit on top (unit 2 at TOL, BAN B and HER, units 1 and 2 at BAN A) that in case of HER can both be unambiguously related to Haiyan and therefore a single storm event, might be rather indicative for cyclone-generated deposition. However, at TOL we cannot exclude that part of this succession (i.e. the washover unit on top) is the result of deposition by Basyang, since its time of formation could not be proven by eyewitnesses or satellite images. In this case, the association of the two units might also be explained by several storm events in a quick sequence, whereas the strong beach erosion during a major event such as Supertyphoon Haiyan would only increase the susceptibility of the sedimentary coastline towards storm overwash during follow-up events.

6. Conclusions

The deposits of Typhoon Haiyan is strongly influenced by local factors causing a wide variety of site-specific sedimentary and morphological characteristics. Nevertheless, in spite of their spatial variability, the deposits exhibit several storm-related depositional patterns – including washover fans, sand sheets and coral rubble ridges – that can be related to specific hydrodynamic processes and resemble typical storm features from all over the world (Fig. 14).

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Gelöscht: so
Gelöscht: that
Gelöscht: ; in this case
Gelöscht: seems to
Gelöscht: geological imprint
Gelöscht: Haiyan’s geological legacy
Gelöscht: s
Gelöscht: typical
Gelöscht: extensive
Gelöscht: depositional environments

Massive to normally graded onshore sand sheets extend 100–250 m inland, tend to fine and thin landwards, and are related to suspension settling during initial surge pulses that causes widespread inundation of coastal lowlands and complete submergence of the coastal barrier. They have formed in areas of significant amplification of the storm surge. In contrast, washover fans are composed of small (10–50 m inland) sand lobes with steep landward fronts and a distinct internal stratification that occur localized behind breaches or depressions in coastal barriers as the result of traction transport by overtopping waves and repeated overwash. Coral rubble ridges were formed on intertidal reef platforms by storm waves entraining coral fragments from the reef slope and breaking at the reef edge.

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Since Haiyan was one of the most powerful cyclones ever recorded, these and other findings from the Philippines particularly add to the general knowledge of extreme wave deposits and, ultimately, may contribute to discriminating sediments of strong cyclones and tsunamis. While coral rubble ridges so far seem to be a unique feature of strong storms, the sandy onshore deposits left by Haiyan – both sand sheets and washover fans – resemble those generated by tsunamis in terms of sedimentary structure, granulometry and sediment sources (Fig. 14). However, the inland extents of sand sheets documented in this study are significantly smaller compared to those of large tsunamis with comparable flooding levels in similar topographical settings. Although more extensive sand layers have been reported for other TC and moderate tsunamis generate sand sheets in the range of the Haiyan deposits, the inland extent of onshore sand sheets at least provides a valuable tendency for the discrimination of cyclones and strong tsunamis. In addition, the combined occurrence of basal sand sheets and overlying confined and well-stratified sand units may be indicative for cyclones, since they result from the succession of surge-related extensive coastal inundation and subsequent wave overwash during Haiyan at HER, which is not known to be typical for tsunamis. But the ambiguous origin of the respective units at TOL, where they might as well result from two successive storms, prevents a more definite conclusion.

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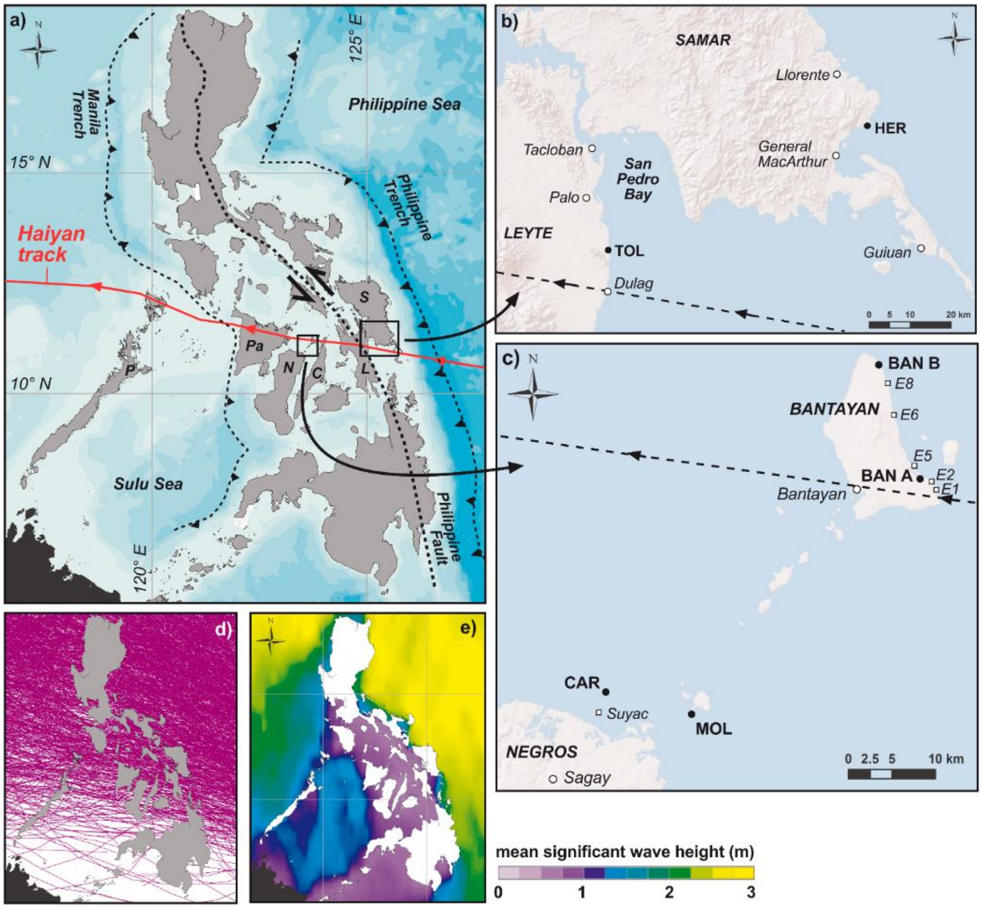

Fig. 1: Overview of the study area. a) Philippine archipelago with main tectonic structures (Rangin et al. 1989), track of Typhoon Haiyan (NDRRMC 2014), and position of research areas on Samar and Leyte (b), as well as northern Negros and Bantayan (c) (based on ESRI basemaps). S – Samar, L – Leyte, C – Cebu, N – Negros, Pa – Panay, P – Palawan. d) Historical cyclone tracks crossing the Philippines since the beginning of weather recording (NOAA Historical Hurricane Track Pool) illustrate a decreasing cyclone frequency from north to south. e) Mean significant wave heights (Navy METOC 2014) indicate highest wave energy during winter monsoon along the exposed east coasts and usually calm conditions in the interior parts of the archipelago.

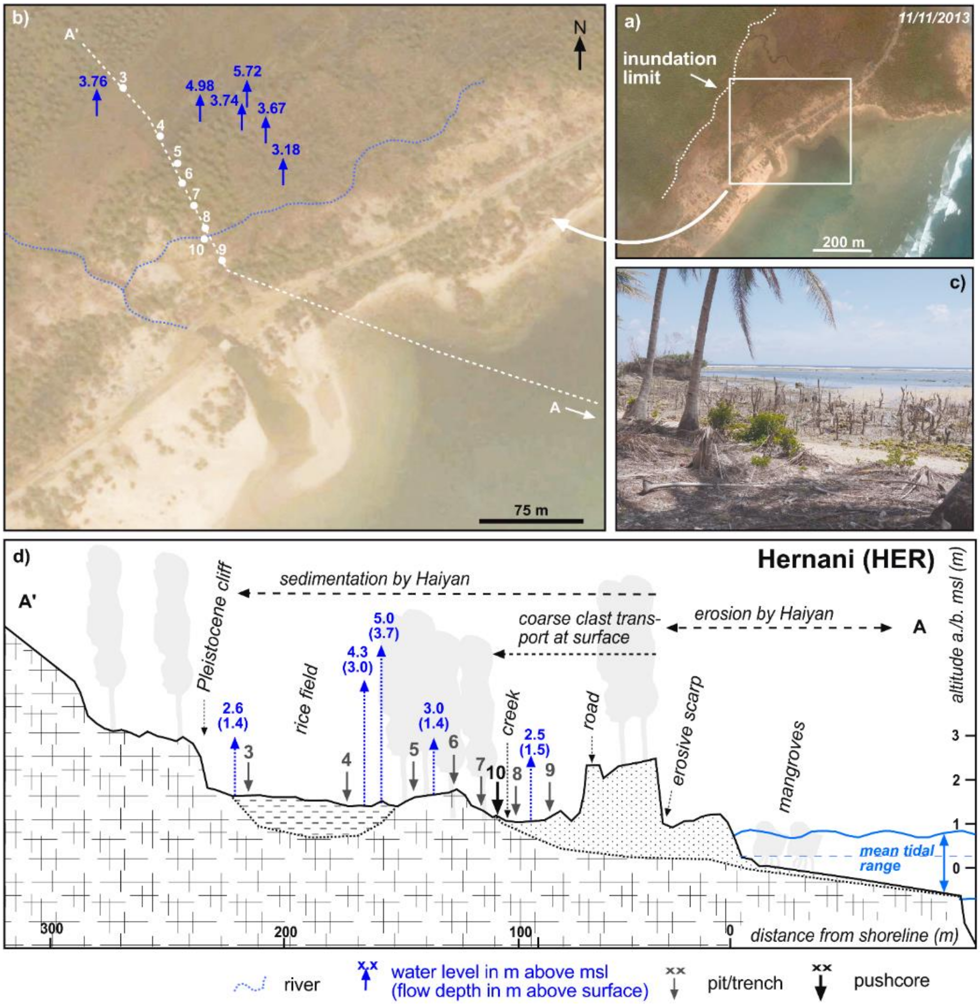

Fig. 2: Hernani (HER) study site with documented Haiyan flood marks and positions of sampled typhoon deposits. a) Local Typhoon Haiyan inundation limit (based on Google Earth/Digital Globe 11/11/2013). b) Onshore sediments were investigated along a coast-perpendicular transect (A–A') crossing the flooded area. c) Destroyed mangroves in front of the beach (view from the shore-parallel main road, photography: February 2014). d) Topographical cross section (A–A') with sampling sites. With water levels of at least 5 m above msl flooding during Haiyan overtopped the sandy coastal barrier, destroyed the road on its top, and transported sand nearly 300 m inland to the foot of the former cliff.

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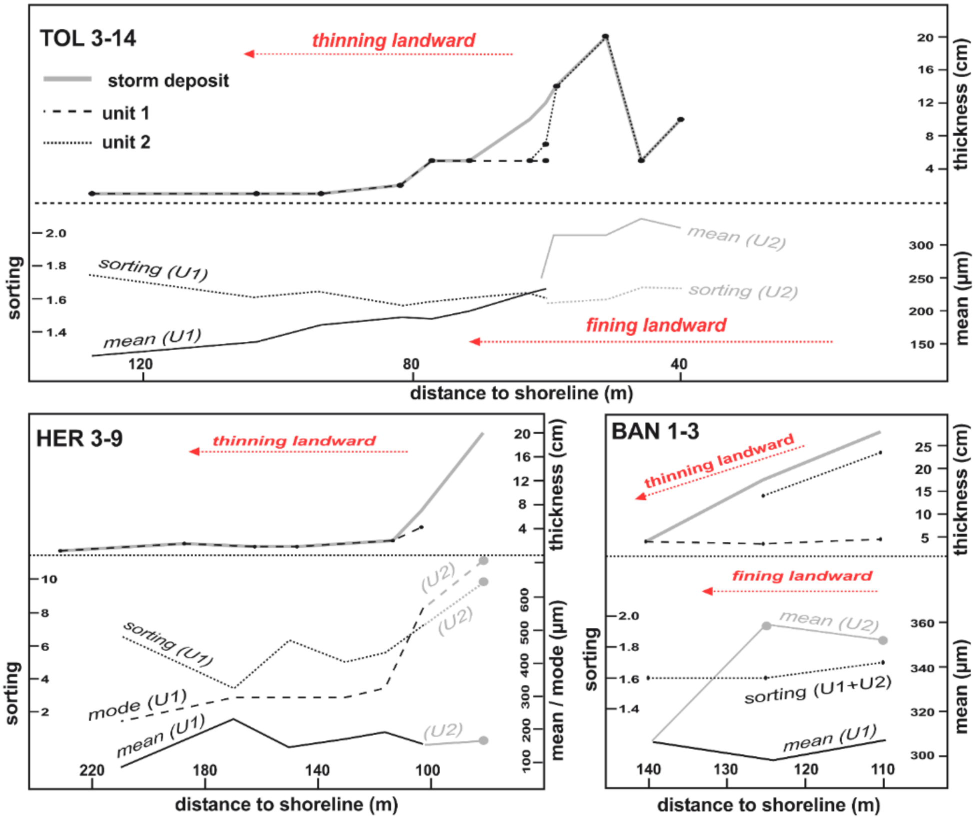

Fig. 3: Landward trends of grain size and thickness in typhoon deposits. Onshore deposits at sites TOL, HER and BAN B tend to thin landward. While the deposits at HER and BAN be are also characterized by fining trends of the mean grain size, a monotonic landward fining is not observed at TOL. Clear trend in sorting are not detected at all sites. Note the different scales.

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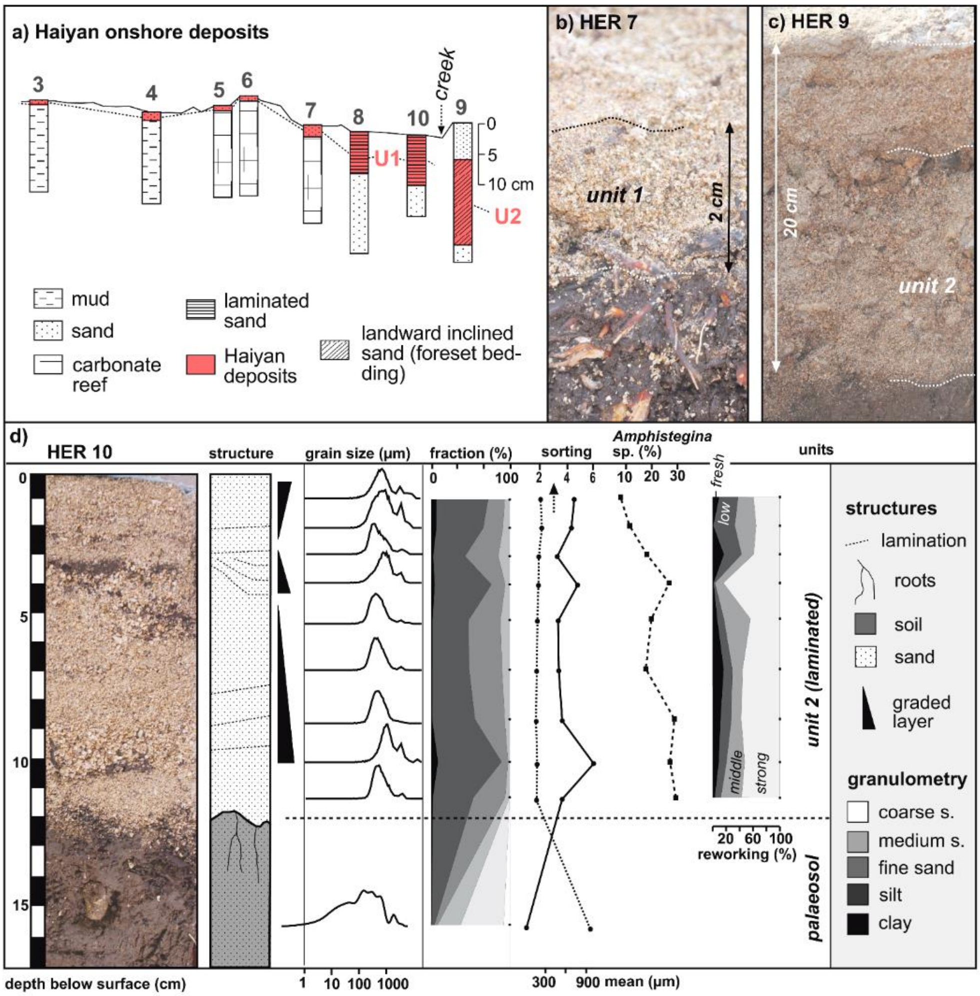
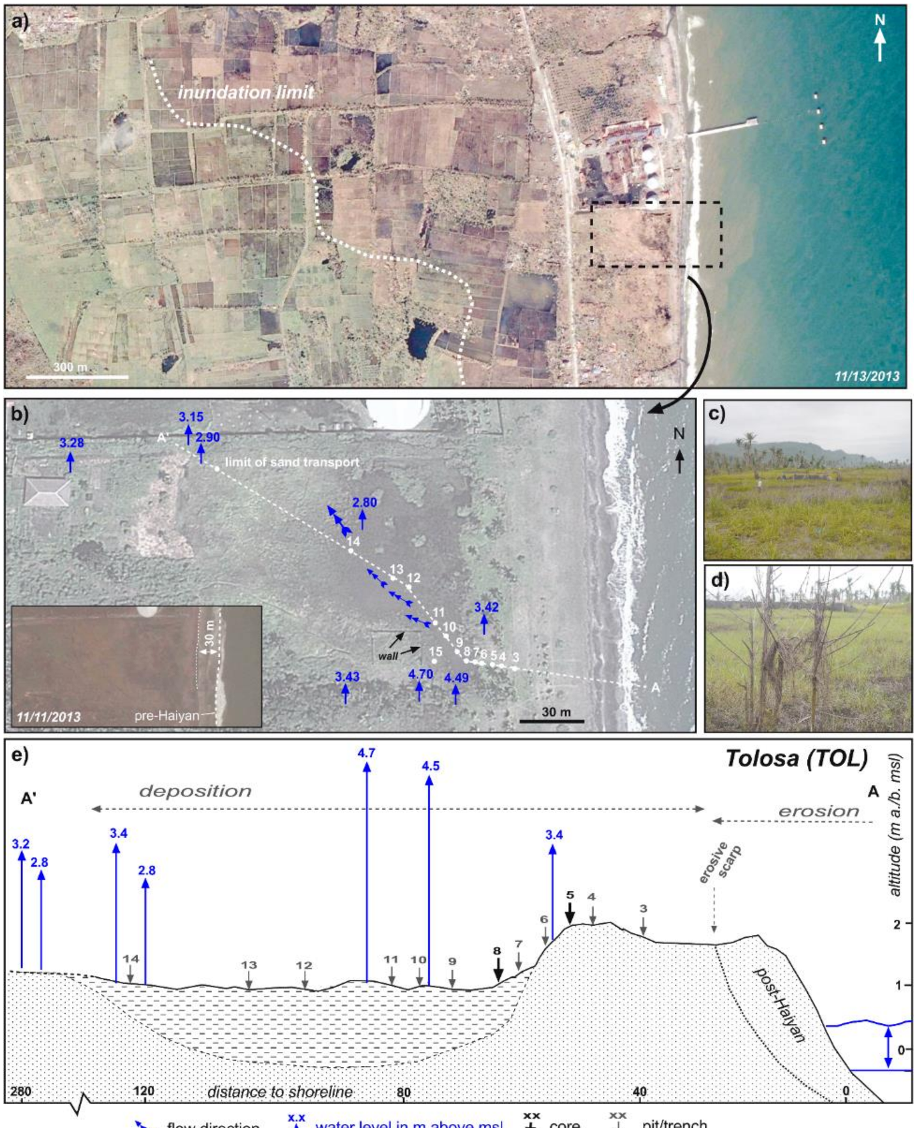


Fig. 4: Onshore deposits of Typhoon Haiyan at site HER. a) Coast-perpendicular transect illustrating the succession of typhoon deposits (see Fig. 2 for location). The basal unit 1 (U1) continuously thins landwards, while unit 2 (U2) is restricted to the proximal part of the coastal plain (HER 9). b) The 2 cm thick unit 1 at HER 7 (photography: February 2014). c) The 20 cm thick unit 2 at HER 9 (photography: February 2014). d) Sedimentary characteristics of HER 10. A 12 cm thick typhoon layer can clearly be separated from the palaeosol. The storm layer reveals repeated normally and inversely graded laminae, in which the amount of strongly reworked foraminifera is highest within the coarse basal sections.



a)
N
inundation limit
300 m
11/13/2013
b)
3.15
3.28
A'
2.90
limit of sand transport
N
2.80
14
13
12
11
3.42
10
9
wall
15
8 7 6 5 4 3
A
3.43
4.70
4.49
30 m
11/11/2013
pre-Haiyan
c)
d)
e)
Tolosa (TOL)
A'
A
deposition
erosion
4.7
4.5
3.2
2.8
3.4
2.8
3.4
erosive scarp
altitude (m a./b. msl)
post-Haiyan
distance to shoreline
flow direction
water level in m above msl
core
pit/trench

Fig. 5: Tolosa (TOL) study site with documented Haiyan flood marks and positions of sampled typhoon deposits. a) Local inundation limit reached several 100 metres inland (based on Google Earth/Digital Globe 11/11/2013, i.e. immediately after Haiyan). b) Onshore sediments were investigated along a coast-perpendicular transect (A–A') crossing the inundated area (based on Google Earth/Digital Globe 02/23/2012; insert: Google Earth 11/11/2013). c) Westward view from the beach ridge over the back-barrier marsh. d) Flood debris in bushes served as an indicator for flow depth. e) With flow levels of at least 4.5 m above msl, Haiyan flooded the beach ridge entirely and transported sand nearly 300 m inland.

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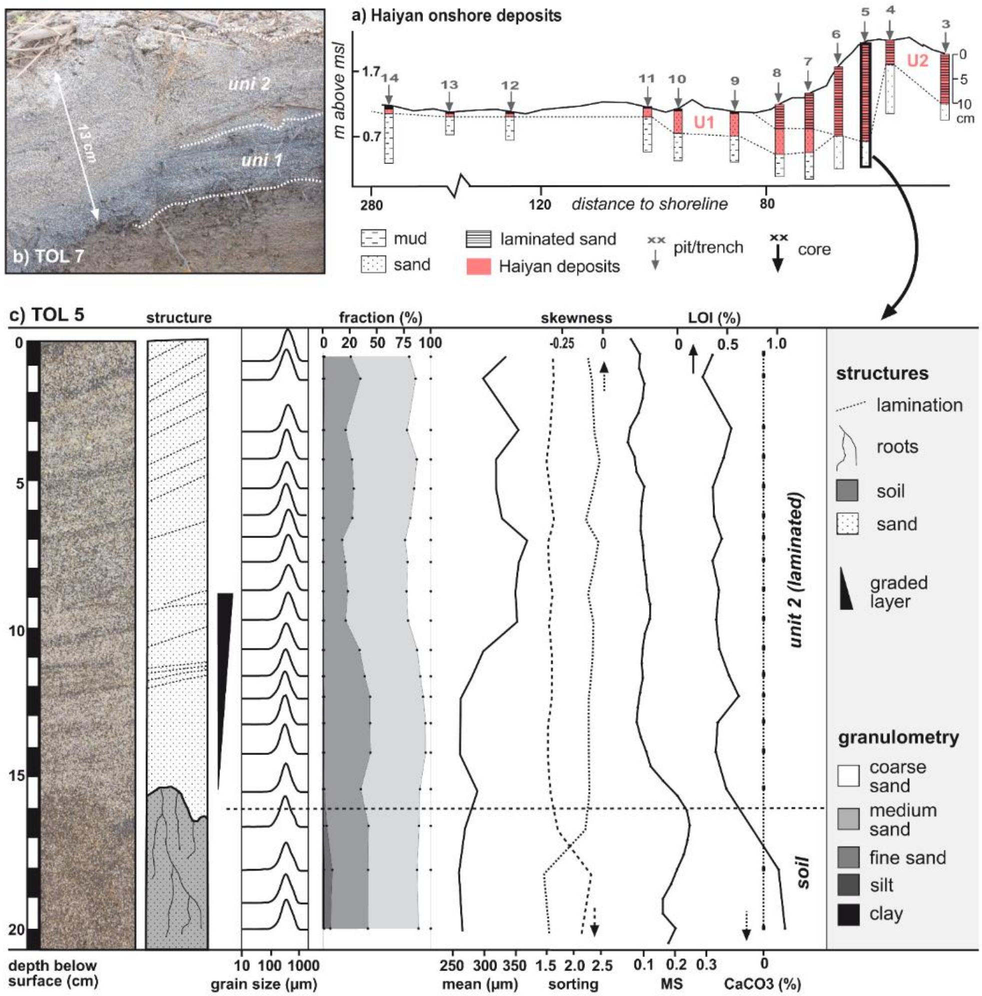

Fig. 6: Typhoon Haiyan onshore deposits at site TOL. a) Transect illustrating the succession of typhoon deposits in landward direction. A graded to massive basal unit (U1) is covered by a laminated unit (U2) in the proximal part of the coastal plain (TOL 3–8). b) The 10 cm thick deposit at TOL 7 consists of massive sand at the base (unit 1) and laminated sand on top (unit 2). c) Sedimentary characteristics of TOL 5. The 16 cm thick, laminated typhoon layer can clearly be separated from the palaeosol due to lower LOI and magnetic susceptibility (MS).

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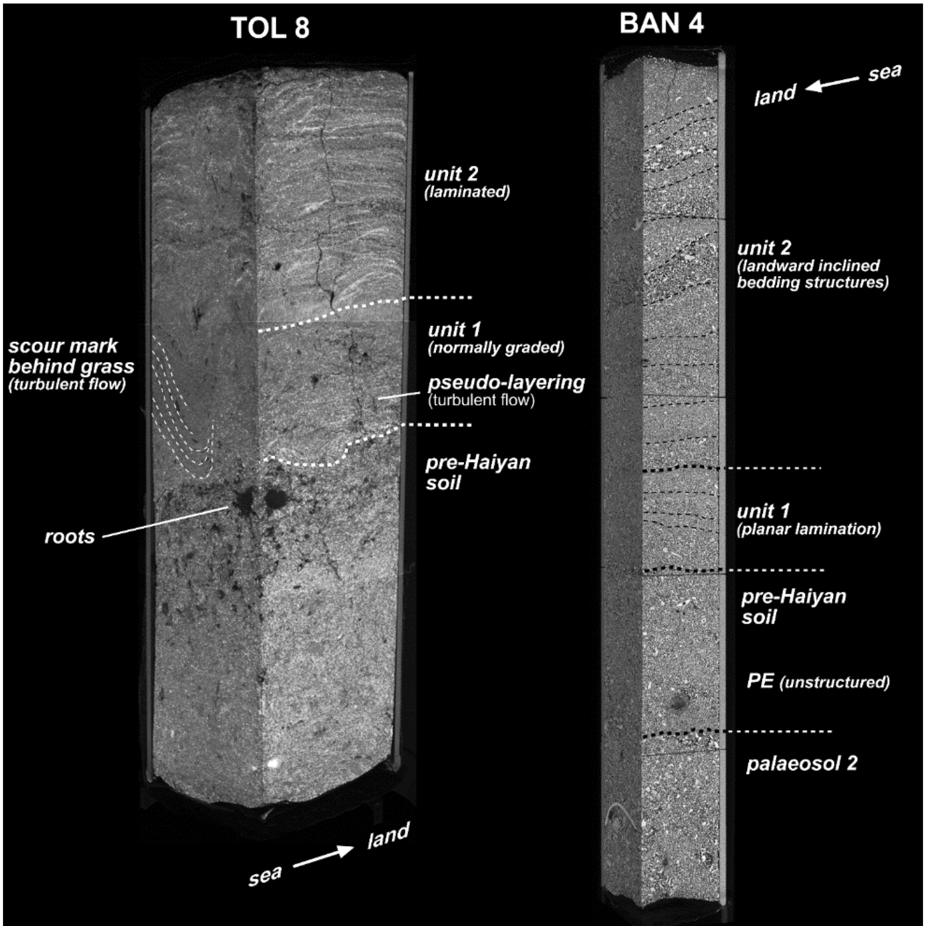


Fig. 7: µCT scans of sediment cores TOL 8 and BAN 4 (as for locations see figures 5d and 10f, respectively). The 3D data support the documentation and interpretation of sedimentological features and different units within the typhoon deposits. The basal unit of TOL 8 is slightly normally graded and characterized by scour structures behind bended grass stems (unit 1). The upper part is horizontally laminated (unit 2). In BAN 4 the deposit of Typhoon Haiyan clearly contrasts the unstructured pre-Haiyan sediments composed of two palaeosols separated by an older sand sheet. It is divided into a planar bedded unit 1 at the base, and steeply landward inclined laminae in unit 2.

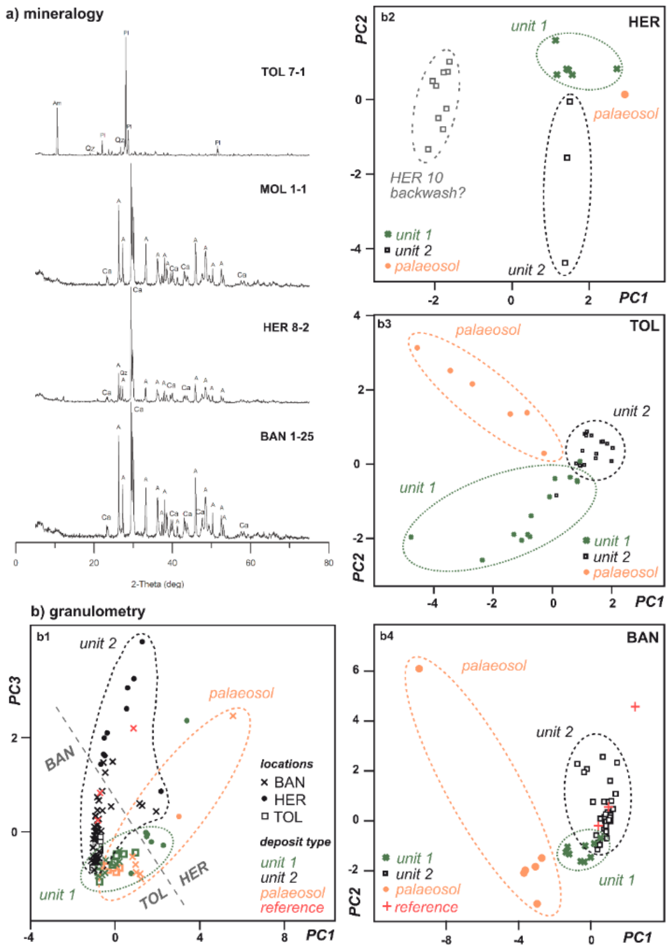
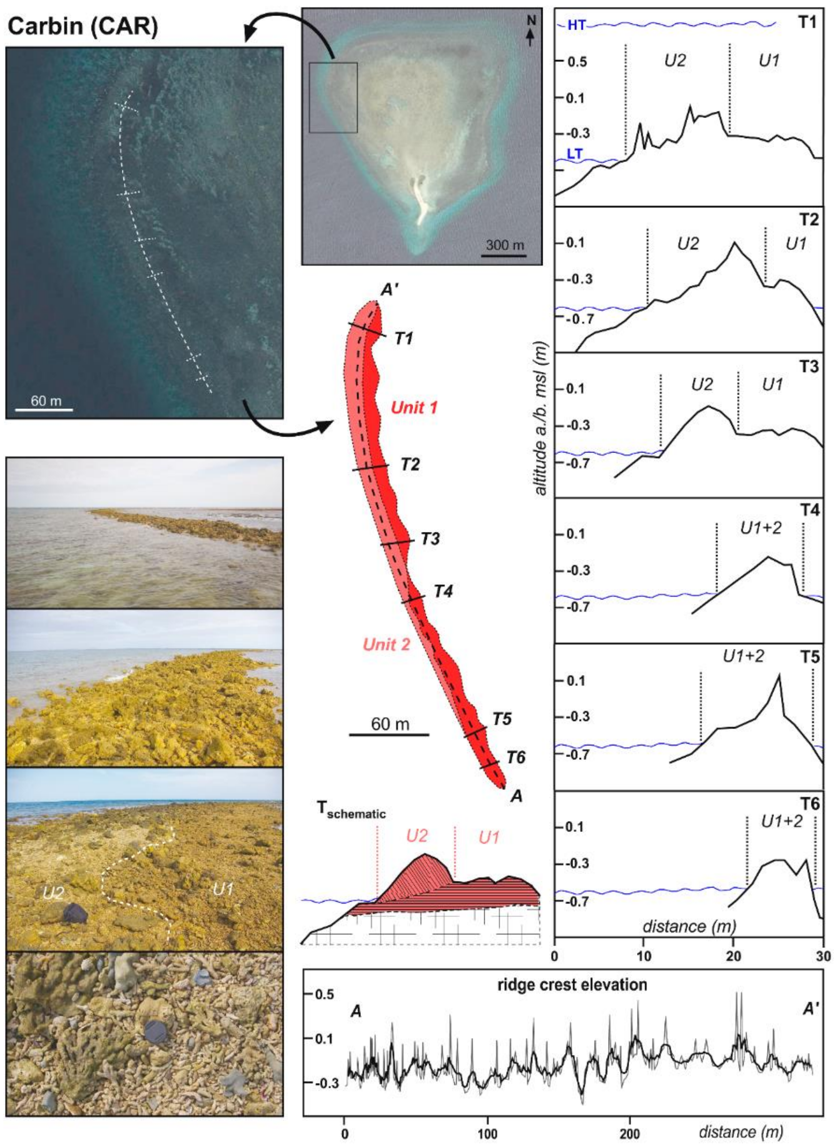


Fig. 8: PCA results for sandy deposits of Typhoon Haiyan. a) XRD studies allow for a separation of deposits from carbonate coasts (MOL, HER, BAN) and the siliclastic coast (TOL) on the basis of bulk-mineralogy. Ca = calcite, A = aragonite, Qz = quartz, Pl = plagioclase, Am = amphibole. b) Grain-size data reflect both site-specific characteristics (TOL, BAN, HER) and differences in formation (unit 1, unit 2, palaeosol) (b1). A discrimination of sediment formation (unit 1, unit 2, palaeosol) due to particular clusters is even more pronounced on the intra-site level (b2-4).



Carbin (CAR)
60 m
300 m
N
A'
T1
T2
T3
T4
T5
T6
A
Unit 1
Unit 2
60 m
T schematic
U2
U1
HT
LT
0.5
0.1
-0.3
-0.7
U1+2
altitude a./b. msl (m)
distance (m)
0
10
20
30
ridge crest elevation
100
200

Fig. 9: Carbin Reef (CAR) study site with typhoon-generated coral rubble ridge. The ridge at the western edge of the reef platform shows no clear trend of crest elevation, but significant differences in width and shape between six coast-perpendicular transects (T1–T6). In the northern part of the ridge, flat and up to 30 m wide lobes composed of algae-covered, greyish coral fragments form the basal unit of the ridge (U1). Unit 1 is topped by steeper lobes with a significant percentage of freshly broken coral fragments that occur along the whole ridge section but reach widths of only 10 m (U2). The presence of two morpho-stratigraphical units might be due to either changing wind directions during formation entirely by Haiyan, or due to the impact of successive storms where Haiyan only deposited the uppermost unit.

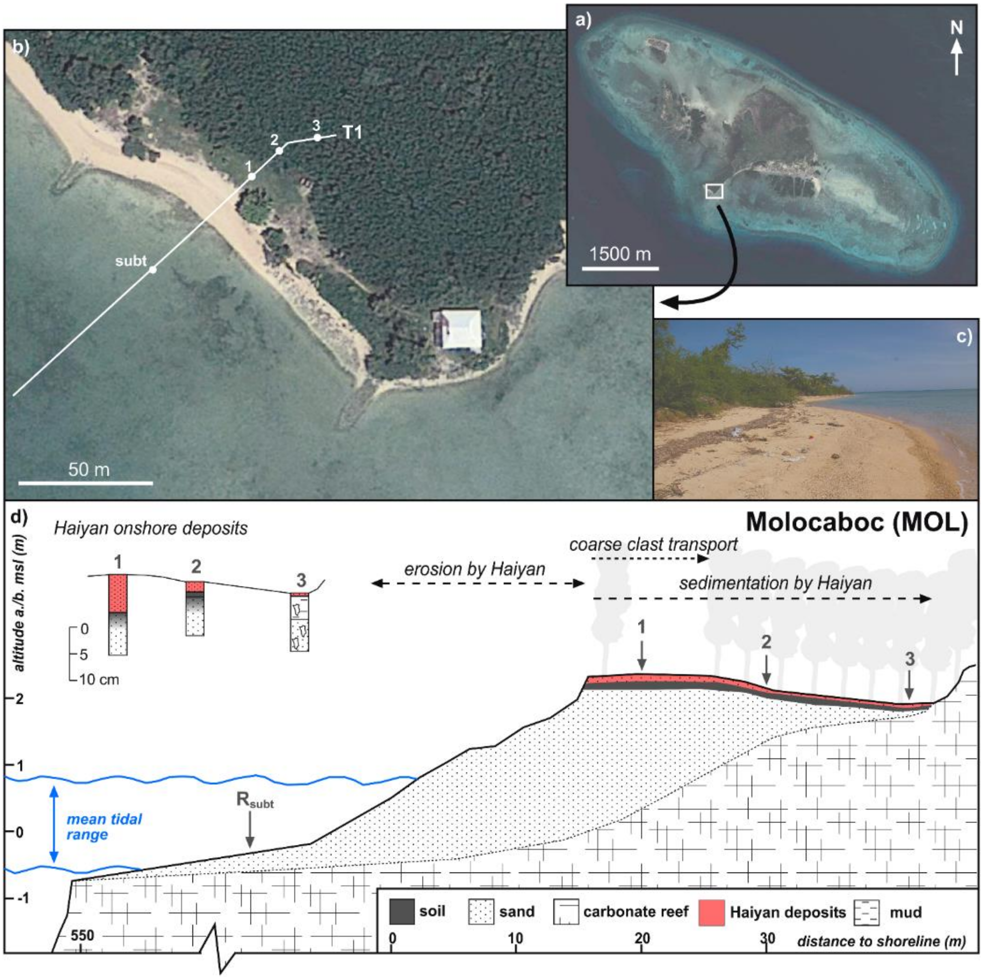


Fig. 10: Molocaboc study site (MOL) with depositional and geomorphological effects of Typhoon Haiyan. a) Location of studied beach section on Molocaboc. b) Onshore sediments of Haiyan were investigated in three trenches (MOL 1–3) along a landward transect (T1). c) Beach profile after the Haiyan impact (view towards SE; date: 20 Feb 2014). d) Topographical cross section: the pre-Haiyan beach was substantially eroded and Haiyan generated a landward thinning sand sheet reaching up to 40 m inland in the back-barrier depression.

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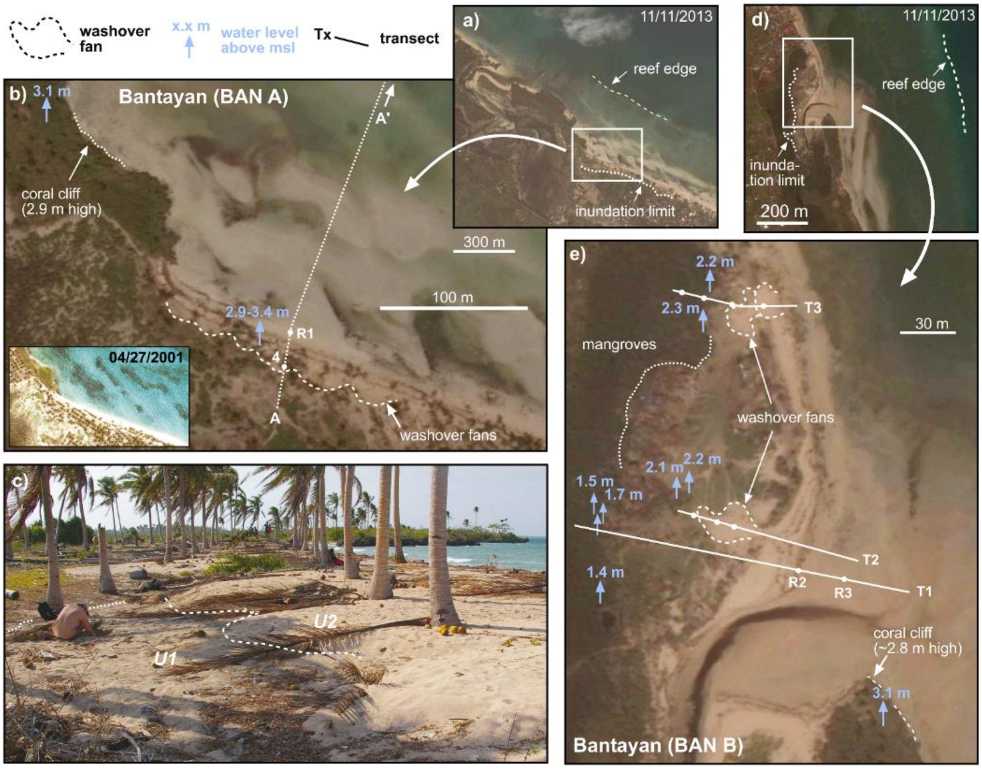

Fig. 11: Bantayan study sites (BAN A and BAN B) with documented flood marks and geomorphological impact of Typhoon Haiyan. a–b) At BAN A, Haiyan flooded the proximal part of the back-barrier plain and formed a series of overlapping, small washover fans directly behind the beach ridge (based on Google Earth/Digital Globe 11/11/2013 [inset in b: 04/27/2001]). c) The washover fans reveal flat lobes at the base (U1), and steep lobes on top (U2). d–e) At BAN B, flooding levels of more than 3 m above msl generated several distinct washover fans (based on Google Earth/Digital Globe 11/11/2013).

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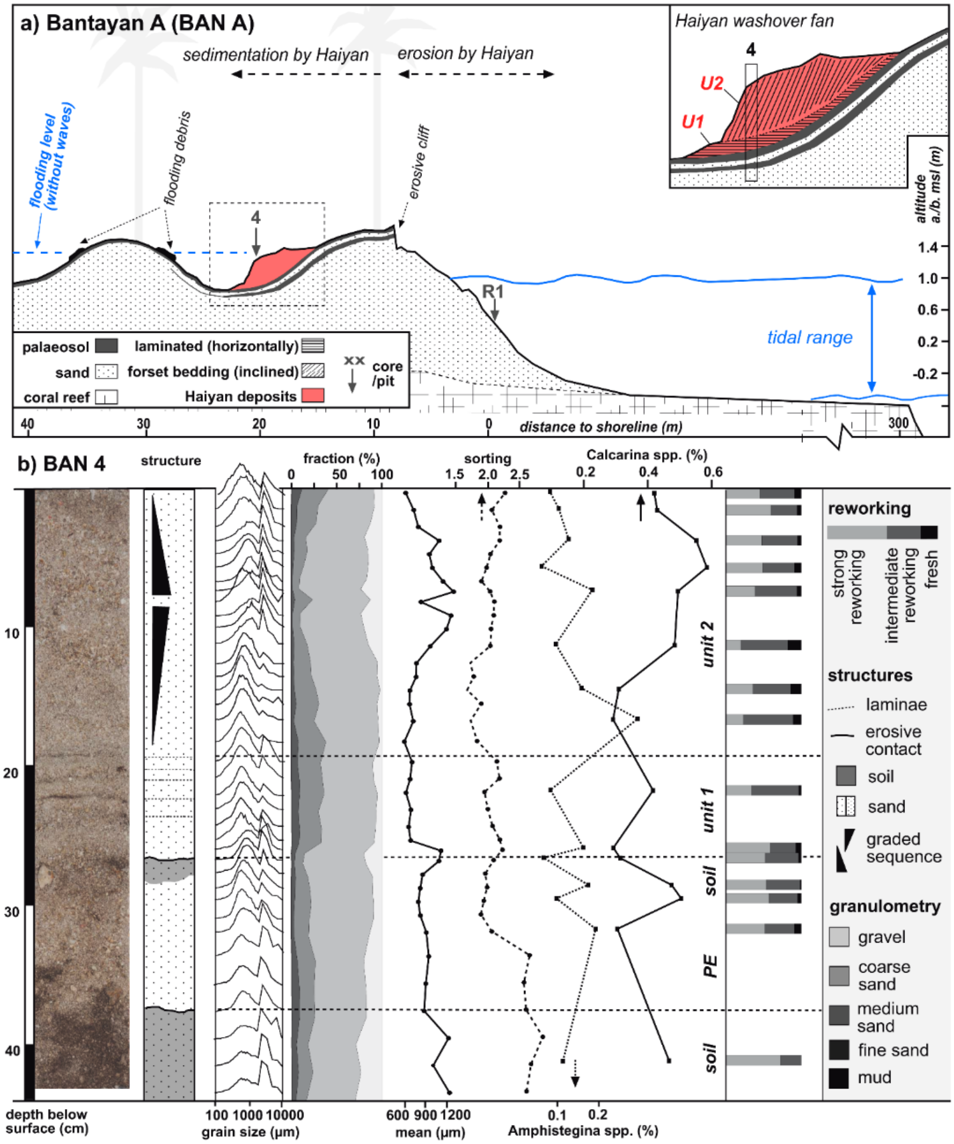

a) Bantayan A (BAN A)
sedimentation by Haiyan
erosion by Haiyan
Haiyan washover fan
U1
U2
4
flooding level (without waves)
flooding debris
erosive cliff
R1
tidal range
altitude a./b. msl (m)
distance to shoreline (m)
palaeosol
sand
coral reef
laminated (horizontally)
forset bedding (inclined)
Haiyan deposits
core /pit
b) BAN 4
structure
fraction (%)
sorting
Calcarina spp. (%)
depth below surface (cm)
grain size (μm)
mean (μm)
Amphistegina spp. (%)
unit 2
unit 1
soil
PE
reworking
strong reworking
intermediate reworking
fresh
structures
laminae
erosive contact
soil
sand
graded sequence
granulometry
gravel
coarse sand
medium sand
fine sand
mud

Fig. 12: Typhoon Haiyan onshore deposits at site BAN A. a) A shore-perpendicular cross section (see Fig. 11 for location) reveals two sedimentary units within the washover fans, a flat and planar laminated unit at the base (U1), and steep, landward inclined lobes on top (U2). Below the pre-Haiyan soil, a second palaeosol is covered by a thin sand layer (PE), possibly a former extreme wave event. b) Sedimentary characteristics of core BAN 4. The 26 cm thick Haiyan deposits are clearly separated from older sediments by an initial soil formation. While the basal unit 1 is laminated, unit 2 is characterised by gradual coarsening, changing foraminifer composition (more *Calcarina* spp., less *Amphistegina* spp.) and a decreasing percentage of fresh foraminifer tests towards the top.

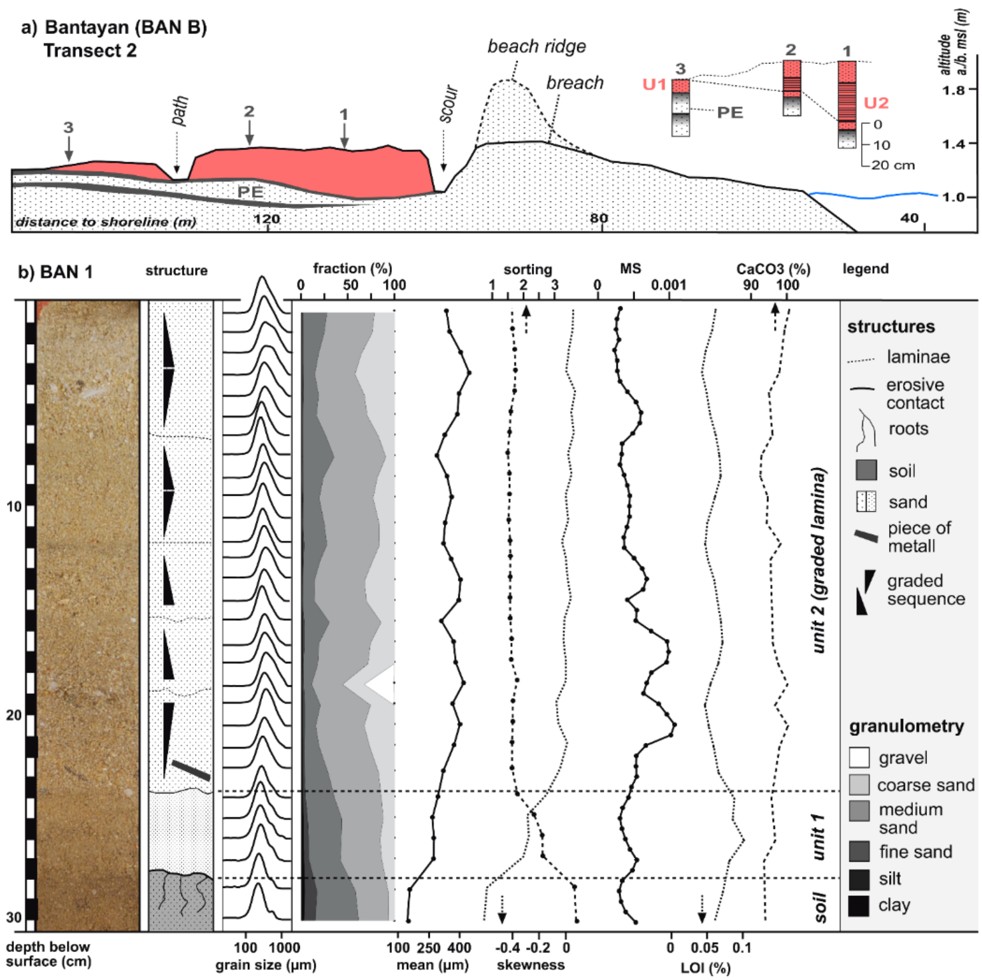

Fig. 13: Sedimentary characteristics of Typhoon Haiyan deposits at site BAN B. a) Transect 2 (see Fig. 11 for location) reveals a landward thinning structure directly behind a storm-induced breach in the coastal barrier. A massive sand sheet at the base (U1) is overlain by a laminated section (U2) in the proximal part of the washover fan. b) BAN 1 is composed of two distinct units, a massive unit at the base (unit 1) and a laminated unit on top (unit 2).

	Coral ridges	Sand sheets	Washover fans
sedimentary structure	Coral rubble ridge on intertidal reef platform, 0.5-1.0 m high with two different units (at least uppermost due to Haiyan)	Normally graded to massive sand layer; <10 cm thick; thinning and fining in landward direction	Wedge-shaped sand lobes behind coastal barrier; up to 30 cm thick with planar and/or landward in-clined lamination
Locations	CAR (unit 1 + unit 2)	HER (unit 1) TOL (unit 1) BAN B (unit 1) MOL (unit 1)	HER (unit 2) TOL (unit 2) BAN A (unit 1 + unit 2) BAN B (unit 2)
Lateral extent	10-20 m	100-250 m	<50 m
Processes of transport & deposition	Storm-wave transport as traction load	Flooding pulse during early stage of the surge; mainly suspension load	Storm-wave trans-port during peak of the storm surge; mainly traction load
Sediment source	Mainly subtidal reef slope (coral rubble) with minor contribution from reef plat-form (fresh corals)	Mainly littoral zone; other source areas minor (poorly constrained)	Mainly littoral zone
Reference storm	Maragos et al., 1973; Scheffers et al., 2012	Wang & Horwitz, 2007; Williams, 2010	Williams, 2009; Sedgwick & Davis, 2003; Nott, 2006
Reference tsunami		Jankaew et al., 2008; Goto et al., 2011; Hawkes et al., 2007	Atwater et al., 2013
schematic sketch			

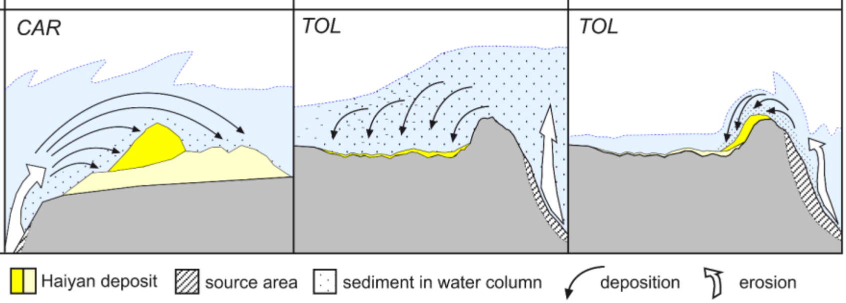

Fig. 14: Compilation of sedimentary characteristics and inferred formation processes for the three different types of Haiyan deposits: coral ridges, sand sheets, and washover fans. The cited references report on storm or tsunami signatures with similar characteristics.