nature portfolio

Peer Review File

Millions of seafloor pits, not pockmarks, induced by vertebrates in the North Sea

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

25th Apr 23

Dear Dr Schneider von Deimling,

Please allow us to apologise for the delay in sending a decision on your manuscript titled "Harbor porpoises cause millions of seafloor pits". It has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

* Present additional compelling evidence that the seafloor pits you observe were formed by harbor porpoise feeding practices or soften this conclusion to reflect the level of uncertainty involved with this hypothesis.

* Place your interpretations firmly in the context of existing data both for and against alternative explanations, such as the discharge flares observed in Krämer et al. (2017).

* Provide full details of the cruises and data generation procedures clearly referenced and explained within the text.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers’ comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter) and any completed checklist:

[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Andrew Green, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0001-9438-1315

Joe Aslin
Senior Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This paper presents evidence that, in a survey area in the German North Sea, seabed depressions identified on multi-beam echo sounder (MBES) are not pockmarks formed by escaping fluids, but pits formed by bottom-feeding Harbour Porpoises. To do this they report evidence of the absence of features that might be expected to be associated with pockmarks (shallow gas, methane-derived authigenic carbonate MDAC, seabed gas seeps, etc.) on a range of geophysical and other data. They explain that the area has a significant population of sandeels (that burrow into the seabed), and that harbour porpoises feed on them. To a non-specialist, the biological / ecological argument in favour of this hypothesis seems reasonable, although the estimated abundance of Harbour Porpoise in the German Bight (23,219 individuals) seems to me remarkably high.

The detailed examination of the morphology of the “pits” show that they are not characterised by a common shape, and that (unlike most pockmarks) mounds of displaced material are to be found around the pits. It would perhaps have been useful to compare the morphology of both the pits and the mounds to the dominant tidal current direction, as a correlation might be expected if the pits are extended or enlarged by current scour, as the authors claim.

The appearance of new pits between the May and November 2021 surveys is significant. The claim that the pts are destroyed during winter storms seems to be a reasonable speculation; why was it not supported by evidence from the MBES data collected during the February 2021 cruise?

The argument that these pits are formed by porpoises seems plausible (to a non-specialist like me), as the authors present evidence that the ecological conditions are conducive to such activity. But, as the authors admit, “the exact mechanism of initial pit formation in our case remains unobserved” (lines 273-4). The evidence to support this hypothesis is largely circumstantial. It would be helpful if the habits of both sandeels (and other prey) and harbour porpoises could be explained in more detail. At what time(s) of year are sandeels present in the surficial sediments, and when are the porpoises feeding in this area? Can the authors be certain that there are no other animals capable of producing these pits in the German Bight?

The suggestion that seabed depressions can be formed by mechanisms other than fluid escape is important; it is too easy for the unwary to interpret any seabed depressions as fluid-escape pockmarks on the basis of the morphology alone. In these days when Greenhouse gases are of particular concern, it is particularly important that potential Greenhouse gas sources are fully understood, and that relevant data are scrutinised carefully. This paper provides appropriate scrutiny for one potential natural methane source in one particular location. However, the suggestion that all seabed depressions are not caused by fluid escape is not new, indeed the authors acknowledge this by citing some (not all) of the publications reporting other (possible) formation mechanisms. One other publication (Iglesias et al., Pockforms: an evaluation of pockmark-like seabed features on the Landes Plateau, Bay of Biscay. Geo-Marine Letters, DOI 10.1007/s00367-009-0182-2 (2009)) suggested that the term “pockmark” should be reserved for seabed depressions formed by escaping fluids; morphologically-similar features with other formation mechanisms would, they suggest, be better referred to as “pockforms”.

In the final section of this paper the authors speculate on the geological significance of megafauna feeding pits. To do this consideration should be given to other bottom-feeding predators; porpoises are not the only animals capable of detecting prey buried within seabed sediments, whether by echolocation or electrolocation. The bare statement “The number of megafauna in the seas, feeing and breeding on or close to the seabed, is innumerable [incalculable?]” is insufficient to support the speculation that “geological implications. … would … be enormous”. Bioturbation is not a novel concept, although the influence of megafauna may have been under-represented in there literature.

I am unsure whether the authors aimed to refute the conclusion of Krämer et al. (2017 - reference 21) that fluid-escape pockmarks are present in the German Bight. They imply this, yet Krämer et al. provided evidence (a possible sub-seabed gas migration pathway, water column ‘flares’ and high methane concentrations in the water column) which support the conclusion that methane escape was involved in their formation. Is it not possible that both pockmarks and pits (pockforms) are present in this area?

Methods: A statement about the different cruises used to acquire the data upon which the paper depends (cruise identification/number, ship, dates etc.) is provided in Extended Data Tab. 1. However, although the Methods section, which is essential and generally good, the individual sub-sections do not refer to the individual cruises in a consistent manner. Also, Extended Data Tab. 1 would be more useful if it was accompanied by a map showing the extent of each of the surveys mentioned and, for comparison, the survey area of Krämer et al. (2017) - how much do they overlap?

References cited: The selection of papers cited to indicate the widespread distribution of pockmarks (Refs 3 - 8) could be replaced by more recent representative examples of the >700 pockmark-related papers identified by ResearchGate. Furthermore, Ref. 4 is incorrectly cited; the report referred to is McQuillin, R., Fannin, N. G. T. & Judd, A. G., 1979. I.G.S. pockmark investigations 1974-1978. Report 98 of the Institute of Geological Sciences. This report is old, somewhat obscure, and probably unavailable; it has also been superseded by numerous other publications and reports. It would be better omitted.

In summary, this paper is an example of the necessity of examining all possible formation mechanisms of pockmark-shaped seabed features (pockforms). As the study area is in shallow water, the (apparently mistaken) assumption that these features are formed only by the escape of methane from the seabed would imply the emission of large volumes of this important 'Greenhouse' gas to the atmosphere. For this reason, if for no other, the conclusion of this study is significant. However, as the authors acknowledge, others have previously suggested that 'pockforms' are not necessarily 'pockmarks', and pockforms can be made by feeding cetaceans (albeit not necessarily harbour porpoises); bioturbation is not a new concept. Thus, this is an original and noteworthy conclusion when applied to the German Bight and to porpoises. It is also a timely reminder that bioturbation by megafauna may be a significant geological process.

Reviewer #2 (Remarks to the Author):

Thank you for the opportunity to review. It is an interesting hypothesis. I feel it would benefit from some further discussion of the evidence that links the pits to cetaceans; and the reasons why they cannot be purely abiotic in origin. Please see my attachment.

Reviewer #3 (Remarks to the Author):

An improved understanding of the genesis and controls of seafloor depressions or pockmarks has value for a broad range of questions related to geohazards, energy resources, the global carbon cycle, and marine environmental protection. In this manuscript, the authors have proposed an alternative interpretation for the formation of seafloor pockmarks in the German Bight, Baltic Sea, and suggest that harbor porpoises excavate significant amounts of sediments during benthic foraging within a large sandeel habitat by poking the seabed, thereby initiating pit formation. The resulting pits are small (< 10 m in diameter) and have been detected by high-resolution multibeam bathymetry and sidescan sonar.

Given the distribution of pits, feeding harbor porpoises, sandeel (prey), and a find-sand substrate bearing the sandeel in this portion of the Baltic Sea, they offer one of the best possible interpretations and argumentation to address the origin of the seafloor pockmarks. As such, I find this manuscript quite exciting and essential to advancing the science of seafloor pockmarks. While focused on the Baltic Sea, the results are likely to be applicable to other continental margins around the world, where such non-fluid pockmarks are common.

Below I listed some moderate comments and the authors are recommended to follow them.

1) I think the sedimentological aspects should be improved in the current manuscript. The authors collected 45 sediment samples using box coring and conducted a grain-size analysis to verify the acoustic backscatter response of the seafloor. I have not seen any figures showing this correlation or discussions concerning sedimentology or grain size analysis. Are there any box cores inside or outside of the seafloor pits? If so, do sedimentary structures and grain sizes differ? Geologically, as the harbor porpoises profoundly disturb the substrate, box cores of the transgressive sand sheet should not show any evidence of primary sedimentary structures probably because of intense feeding activity. Nevertheless, some of the core photographs, including the sedimentary structures should be shown and described.

2) The currents and their strengths as well as their seasonal variability should be introduced earlier in the section called “Geologic and oceanographic setting in the German Bight”. In the results and discussion, the enlargement by current scouring should be expanded. For instance, are the enlarged pits oriented parallel to the predominant current direction? I suggest the authors go one more step and classify the pits as fresh (formed during the most recent feeding season) or modified (remnants of the past feeding seasons) based on their width and length using histograms. It would also be a good addition to compare their dimensions with known examples such as those found on the Bering Shelf, Alaska (Nelson et al., 1987).

3) The authors presented a seismic profile to show the Holocene sediment thickness below the seafloor pits and to prove the lack of acoustic evidence related to shallow gas. However, given the data resolution in Ext. Fig. 3, it is hard to see such acoustic anomalies related to shallow gas and thus judge the interpretation. Hence I suggest the authors provide two or three close-up seismic sections immediately below the seafloor pits. Also, provide a few more seismic profiles crossing the different parts of the study area to better appreciate the seismic interpretation as well as the seismic stratigraphy. I suggest the authors provide a few more sub-bottom chirp profiles traversing the different parts of the study area. Apparently, there is only one seismic profile presented in the manuscript. The authors are also recommended to show the locations of the sub-bottom chirp profiles as well as the box cores.

4) I think the seismic stratigraphy is a bit underrepresented in the current manuscript. I suggest the authors explain more about seismic stratigraphy (seismic facies, unconformities, unit thickness variations, etc.) beneath the seafloor pits. For instance, it would be a great addition to construct a Holocene thickness map (if feasible) in the study area to better appreciate the relationship between thickness distribution, pit formation, and current activity.

Other comments
Line 49: Please include more recent references.
Line 65: “shallow incision depth…” Please provide some numbers.

Line 70 and ff: Demark all the tectonic and bathymetric features in Figure 1.
Line 86: Change "(< 10 diameter)" to (< 10 m diameter).
Lines 105-107: Please expand this section and give some numbers for the current strengths etc. This is important for the discussion.
Lines 160-162: It is hard to see such acoustic anomalies related to shallow gas given the data resolution in Ext. Fig. 3. I suggest the authors provide two or three close-up seismic sections immediately below the seafloor pits. It would be a piece of good evidence to support the data interpretation and argumentation.

Line 147: Change "8.7%" into "9%".
Lines 181-182: It seems to me the other way around. The depressions in "November 2021" data seem to become more irregularly shaped than those acquired in "May 2021" data. Just for clarification, I suggest the authors give the seafloor pits representative numbers on both images so that one can compare them easily.

Line 229: These tidal currents should be introduced earlier.
Line 237: Could there be other benthic animals for Harbor porpoise?
Line 291: Fig. 6 appears to be cited before Fig. 5. Please correct this in the text.

Figures
Fig. 1: Include the distance scale. Add coordinates (lat. and long.) to the inset on the upper left.
Fig. 2: a) I am not sure if it is Okay to use black and white color for displaying the bathymetric map. Why not use the same color font as shown in Fig. 2b? In this way, it would be more consistent. Please increase the font of the coordinates in Figure 2a and move the lat. coordinates to the left. I suggest using the same font for all labels, i.e., for coordinates, scale, etc. For instance, figure labels (a), (b), and (c) have all different font sizes. In Figure 2b, the coordinates have a bigger size which I think is not necessary. Instead, I would suggest the increase the font size of "mounds" and "furrows" in Figure 2b which is the focus of the figure.
Fig. 4: a) Include the north arrow. C, d, e) Include coordinates (lat. and long.) and bathymetric color bar. Change the label " Mai 2021" to "May 2021".
Fig. 6: Add the distance scale.
Extended Data Fig. 1: Add the distance scale.
Extended Data Fig. 3: Add the vertical exaggeration in the seismic profile.
I hope my review is helpful.
Best regards,
Deniz Cukur

Review of “Harbor porpoises cause millions of seafloor pits”

The paper proposes that the activity of harbor porpoises digging in the seabed for sand eels generates small seafloor pits that eventually grow into wide but shallow pits covering a significant proportion of the seafloor within the German Bight of the North Sea.

That is certainly a novel hypothesis which has not been proposed before, and is an interesting and thought-provoking one.

Based on the data presented, however, I don’t find it an entirely convincing one. In part this may be because the paper does not provide a coherent or logical story (I realise that is also driven by the publication, as information is separated into three documents – main paper, a separate Methods and then Extended Data, but I think the various components nevertheless could be tied together a bit better). Better understanding might be supported by a brief, chronological description of:

- The research cruises and data generated, and figures more clearly labelled with identifying information;
- The authors own investigation and understanding of the phenomenon (e.g., they saw something unusual, they reviewed historical data, gathered new data, they considered and discounted other hypotheses for stated reasons, etc);
- The geological process by which a small pit in the seabed becomes a 10 m (and up to 60 m) wide depression.

The latter is my primary question. We see some unusual pits with associated positive relief mounds and rims in Figure 2 that were previously described by Krämer et al (2017). The suggestion that detail previously missed has been revealed by closer inspection of the data is perhaps a bit strong, since that morphology (of rims and mounds) is also clearly visible in the figures of Krämer et al (2017), and described in the text. But OK: we start with some unusual, perhaps unexplained, morphologies.

Firstly, I would like to see a hypothesis as to what sedimentological process will erode a small disturbance of the seabed by a harbor porpoise grubbing for a sand eel in loose sand – which I envisage as being perhaps 10-30 cm long and a few centimeters deep(?) – into an elliptical depression 10-20 m long. In Krämer et al (2017) we see scour pits that, over the course of two years, have *not* transformed into larger pits, so why would smaller pits do so? Also in Figure 4b of the manuscript we see rippled, mobile sand in which we would expect any minor disturbance to be quickly lost. We commonly see that effect with trawl scars, for example, which are erased from the seafloor within days or weeks in areas where the seafloor comprises loose, mobile sand (but remain for months and years in low energy environments and cohesive sediments).

Secondly, I did not see any evidence provided to support a connection between the pits illustrated in Figure 2 and those in Figure 4 and Extended Data Figure 2. From a brief glance, they seem to have different morphologies, and they are spatially disconnected. The latter figure in particular shows more of a continuous texture than a series of pits, and I would say requires some extraordinary evidence to tie it back to harbor porpoises. (I sent an example of a similar texture from the western Atlantic to the lead author; I don’t have a good explanation for its origin, but also no reason to associate it with cetaceans.)

Finally, the manuscript Summary states that, “Time-lapse data reveals the initially small feeding pits serve as nuclei for scouring…”, but Figure 4 shows smaller pits appearing on the second pass. We don’t see those small pits subsequently evolving into the larger, shallow pits. I don’t know if I read it correctly, but the Extended Data suggests that the Norbit data was not processed for outliers, so the reader may question whether the small pits indicated in Figure 4 are noise. The comment about the spatial alignment of pits (“linear,… radial”) reminds me of Spina (2018)[1], in which multibeam noise was clearly misinterpreted as pockmarks.

The discussion begins by questioning the general lack of evidence for shallow gas, which is fair enough, and then notes that cetaceans create assorted pits and furrows in the seabed (also true). Harbor porpoises occur in the area, as do sand eels, and sand eels form part of the porpoise’s diet (OK). But there is no real evidence provided for a connection between porpoises and the pits. As the authors state, “it is difficult to imagine that a single erosive grub into the sediment is capable of producing the up to 50 m diameter pits”. Yes, indeed. So there needs to be some more convincing argument to overcome that difficulty.

Also noted by the authors, the pockmark field of Krämer et al (2017) was found to wax and wane over the course of weeks and months. It is a bit difficult to understand how all these pits can form in such numbers and to such a size (from a biotic origin), and then disappear again. Why does the same process that enlarges pits also erase them? (Yes, tidal versus storm wave oscillatory currents, but if tidal as the enlarging force, there should be some consistent alignment to the pits/mounds.) Also, porpoise activity is a constant, so it is unexpected that no pits were found by Krämer et al (2017) in 09/2014 (their Supplementary Figure S3), or indeed by many researchers over the years (even on lower resolution multibeam – the pits are large enough).

I think some more compelling evidence is needed to advance this hypothesis. As a fellow author of a “topic discussed controversially” (fish excavation; albeit not really controversial - it is proven from the Gulf of Mexico), I believe I was able to present such evidence in the form of conical mounds for which there is no abiotic formation mechanism. I don’t know if something similar can be found in this case from the available data, either to link the pits indisputably to cetaceans, or conclusively delink them from purely geologic and oceanographic processes.

Personally, I am of the opinion that seabed bedforms without alignment are the product of surface wave oscillatory currents. We have some evidence in the form of Rippled Scour Depressions (or “sorted bedforms”; e.g., Diesing et al, 2006[2]), the boundaries of which have no particular orientation. Surface waves can somehow also erode small, circular depressions (e.g., Speller, 2000[3]; or the “shell accumulation” images that I sent the lead author previously). Below is another example of an unusual texture, in 40 m of water, that is surely purely geological. I guess a 90° change in ocean current direction (+ surface waves?) has overprinted the old bedforms with newer ones; however outside the main “new” field are small (5-7 m), isolated depressions. Since they appear on the bedform crests, they are not scours

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[1] *The pockmark stars: radial structures in the seabed surrounding the Hawaii Islands*
[2] *Decadal scale stability of sorted bedforms, German Bight, southeastern North Sea*
[3] *"Pock Marks" in Nearshore Sands: Observations During Sandyduck97*

around objects (cetacean feeding pits, you will say, but I don’t think that works for the continuous texture to the east). Could similar pits also appear in smooth seabed under rare conditions?

Personally – without evidence – I would ascribe the pits in Extended Data Figure 2 to surface wave action, without the need to invoke a biological agent. For those in Figure 2 (and Krämer et al, 2017), I don’t really have an opinion, although considering the above images, it is not entirely inconceivable that there is some poorly understood oceanographic process in play.

Apart from that, maybe the hypothesis could be stated somewhat less strongly. For example, “we… reveal the formation mechanism of the seafloor depressions” is a bit too definite.

Thank you for the opportunity to review.

We appreciate the thorough and constructive reviews from three reviewers. All reviewers addressed substantial points that helped us to improve the paper significantly. Overall, we soften the hypothesis and expanded the discussion by referring to additional processes that may act as erosive agents and therefore contribute to the formation of the pits. We further incorporated information from the papers below as recommended by the reviewers.

Harris, P. & Baker, E. *Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of seafloor geomorphic features and benthic habitats*. (Elsevier, 2011).

Iglesias, J., Ercilla, G., García-Gil, S. & Judd, A. G. Pockforms: an evaluation of pockmark-like seabed features on the Landes Plateau, Bay of Biscay. *Geo-Mar. Lett.* **30**, 207–219 (2010).

Greene, H. G., Baker, M. & Aschoff, J. A dynamic bedforms habitat for the forage fish Pacific sand lance, San Juan Islands, WA, United States. in *Seafloor geomorphology as benthic habitat* 267–279 (Elsevier, 2020).

Ferrini, V. L. & Flood, R. D. A comparison of rippled scour depressions identified with multibeam sonar: evidence of sediment transport in inner shelf environments. *Cont. Shelf Res.* **25**, 1979–1995 (2005).

Davis, A. C. *et al.* Distribution and abundance of rippled scour depressions along the California coast. *Cont. Shelf Res.* **69**, 88–100 (2013).

Micallef, A., Averes, T., Hoffmann, J., Crutchley, G., Mountjoy, J. J., Person, M., Cohen, D., Woelz, S., Bury, S. J., Ahaneku, C. V., Spatola, D., Luebben, N., Miserocchi, S., Krastel, S., Torelli, M., & Omosanya, K. O. L. (2022). Multiple drivers and controls of pockmark formation across the Canterbury Margin, New Zealand. Basin Research, March, 1–26. https://doi.org/10.1111/bre.12663

Paull, C., Ussler, W., Maher, N. M., Greene, H. G., Rehder, G., Lorenson, T. D., & Lee, H. (2002). Pockmarks off Big Sur, California. Marine Geology, 181(4), 323–335. https://doi.org/10.1016/S0025-3227(01)00247-X

Bartholomä, A., Capperucci, R. M., Becker, L., Coers, S. I. I., & Battershill, C. N. (2020). Hydrodynamics and hydroacoustic mapping of a benthic seafloor in a coarse grain habitat of the German Bight. Geo-Marine Letters, 40(2), 183–195. https://doi.org/10.1007/s00367-019-00599-7

Dick, S. (1987). Gezeitenströmungen um Sylt Numerische Untersuchungen zur halbtägigen Hauptmondtide (M2). Deutsche Hydrografische Zeitschrift, 40, pages 25–44.

Hillman, J. I. T., Klaucke, I., Pecher, I. A., Gorman, A. R., Schneider von Deimling, J., & Bialas, J. (2018). The influence of submarine currents associated with the Subtropical Front upon seafloor depression morphologies on the eastern passive margin of South Island, New Zealand. New Zealand Journal of Geology and Geophysics, 61(1), 112–125. https://doi.org/10.1080/00288306.2018.1434801

Lohrberg, A. et al. Discovery and quantification of a widespread methane ebullition event in a coastal inlet (Baltic Sea) using a novel sonar strategy. Sci. Rep. 10, 1–13 (2020).

Diesing et al. Decadal scale stability of sorted bedforms, German Bight, southeastern North Sea. Cont. Shelf Res. 26, 902–916 (2006).

Gilles, A., Andreasen, H., Müller, S. & Siebert, U. Nahrungsökologie von marinen Säugetieren und Seevögeln für das Management von NATURA 2000 Gebieten. Teil Mar. Säugetiere Final Rep. Submitt. Ger. Fed. Agency Nat. Conserv. BfN F E FKZ 805, 018 (2008)

Reviewer #1 (Remarks to the Author):

This paper presents evidence that, in a survey area in the German North Sea, seabed depressions identified on multi-beam echo sounder (MBES) are not pockmarks formed by escaping fluids, but pits formed by bottom-feeding Harbour Porpoises. To do this they report evidence of the absence of features that might be expected to be associated with pockmarks (shallow gas, methane-derived authigenic carbonate MDAC, seabed gas seeps, etc.) on a range of geophysical and other data. They explain that the area has a significant population of sandeels (that burrow into the seabed), and that harbour porpoises feed on them. To a non-specialist, the biological / ecological argument in favour of this hypothesis seems reasonable, although the estimated abundance of Harbour Porpoise in the German Bight (23,219 individuals) seems to me remarkably high.

We are thankful for the thorough review and agree with most points addressed by the reviewer. Similar points were risen by the editorial team which we answered with Comments 1-3 (confidentially in the CoverLetter). We now start with answering reviewer #1 comments:

Comment 4 The detailed examination of the morphology of the “pits” show that they are not characterized by a common shape, and that (unlike most pockmarks) mounds of displaced material are to be found around the pits. It would perhaps have been useful to compare the morphology of both the pits and the mounds to the dominant tidal current direction, as a correlation might be expected if the pits are extended or enlarged by current scour, as the authors claim.

A4 We address this point with adding information of the current regime in the German Bight with

L348 : Since the tides in the German bight introduce a rotating rather than bi-directional current regime[63] we would assume that initial depressions are not elongated in one direction but rather unidirectional.

Comment 5 The appearance of new pits between the May and November 2021 surveys is significant. The claim that the pits are destroyed during winter storms seems to be a reasonable speculation; why was it not supported by evidence from the MBES data collected during the February 2021 cruise?

A5 We realize that our wording in the previous version of the manuscript did not explain well the vanishing of the pits. Storms in the North Sea are more likely during winter, therefore, the likelihood of a flat seafloor during winter is higher than during summer. This doesn’t mean that pits can’t be observed during winter periods. It’s just less likely.

In February 2021 we surveyed only a very small area, where we documented pristinely looking pits. Based on this data, we can, however, not judge whether seafloor pits where present in the larger area that we later explored in May 2021 and November 2021. Buoy data of the past ten years close by our survey area are disclosing 8 to 10 m waves in almost every winter and spring (Fig. R4, 5). Both could be considered leveling out events, we simply do not know.

Fig. R4 North Sea Buoy Data position kindly provided by BSH.

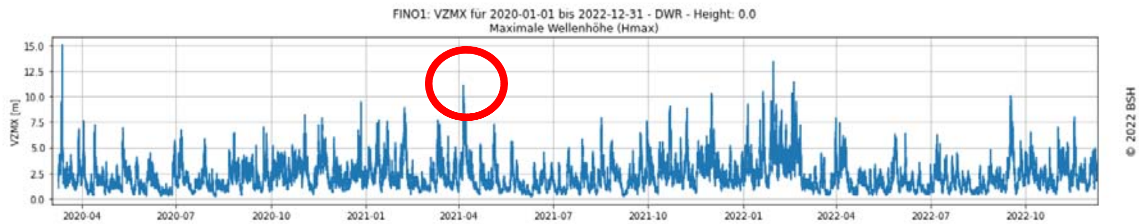


Fig. R5: (a) time series of maximum wave height measured close to the AOI. Note that the highest waves in 2021 occurred after the MSM98 cruise.

To account for this, we changed the caption of Fig. 5 to:

Episodic but severe storms predominantly in winter

Comment 6 The argument that these pits are formed by porpoises seems plausible (to a non-specialist like me), as the authors present evidence that the ecological conditions are conducive to such activity. But, as the authors admit, "the exact mechanism of initial pit formation in our case remains unobserved" (lines 259). The evidence to support this hypothesis is largely circumstantial. It would be helpful if the habits of both sandeels (and other prey) and harbour porpoises could be explained in more detail. At what time(s) of year are sandeels present in the surficial sediments, and when are the porpoises feeding in this area?

A6 For the sandeels we actually give some information regarding their habitat:

L299: Along the tidal mixing front, sandeels (Ammodytes marinus) are known to occur in large quantities in the North Sea[58] (Fig. 6). Sandeels feed on zooplankton during summer daytimes, but most of the time they hide and even hibernate up to 0.4 m deep buried in fine to medium sandy seafloor for shelter and energy savings reasons[59]. Thereby sandeels challenge predators to grub into the sediment. Sandeels are one of the preferred prey for North Sea harbor porpoises and account for 18-20% of their diet[42,44].

Additionally, we now incorporate grain size data to better describe the sandeel habitat,

Therefore, please check the new Fig. 4 and caption, where we better describe the sandeel habitat including grain size data.

Comment 7 **Can the authors be certain that there are no other animals capable of producing these pits in the German Bight?**

A7 This is a very valuable point, therefore we changed the title addressing 'vertebrates' and we now mention e.g. seals and other vertebrates as potential erosive agents:

L322: For the North Sea, other large vertebrates such as seals are known to dive to the seabed feeding on benthic fish, and should therefore be considered in future research on macrofauna benthic bioturbation.

We also now include more information on seafloor erosion by animals elsewhere, e.g. salmon feeding on Pacific sand lance

L317: By grubbing the seabed, porpoises may flush out nearby sandeels from the sediment. As sandeels are schooling fish, the expulsion of individuals may result in the entire school attempting to escape predation in an erosive manner. Similar fish like the Pacific sand lance (Ammodytes personatus), are known to be an important component of the diet of seabirds, harbour seals and other fish such as salmon[60]. The latter have been observed to carry scars on their heads, indicating that they have scraped the seabed (pers. comm. Garry Greene).

We also found evidence for the macro-bioturbation and now state in the manuscript:

L261: In several cases remains of sand were found in the stomachs of stranded animals[45]

Comment 8 The suggestion that seabed depressions can be formed by mechanisms other than fluid escape is important; it is too easy for the unwary to interpret any seabed depressions as fluid-escape pockmarks on the basis of the morphology alone. In these days when Greenhouse gases are of particular concern, it is particularly important that potential Greenhouse gas sources are fully understood, and that relevant data are scrutinised carefully. This paper provides appropriate scrutiny for one potential natural methane source in one particular location. However, the suggestion that all seabed depressions are not caused by fluid escape is not new, indeed the authors acknowledge this by citing some (not all) of the publications reporting other (possible) formation mechanisms. One other publication (Iglesias et al., Pockforms: an evaluation of pockmark-like seabed features on the Landes Plateau, Bay of Biscay. Geo-Marine Letters, DOI 10.1007/s00367-009-0182-2 (2009)) suggested that the term "pockmark" should be reserved for seabed depressions formed by escaping fluids; morphologically-similar features with other formation mechanisms would, they suggest, be better referred to as "pockforms".

A8 This is a good recommendation, we include the *Iglesias et al.* paper. We now also mention the term "pockform", but refrain from using this terminology for the observed depressions in the North Sea. This is mainly due to their unusual scale, truncated cone-pattern, and very unconventional median depth that separates them from the reported pockforms.

Comment 9 In the final section of this paper the authors speculate on the geological significance of megafauna feeding pits. To do this consideration should be given to other bottom-feeding predators; porpoises are not the only animals capable of detecting prey buried within seabed sediments, whether by echolocation or electrolocation. The bare statement "The number of megafauna in the seas, feeding and breeding on or close to the seabed, is innumerable [incalculable?]" is insufficient to support the speculation that "geological implications. … would … be enormous". Bioturbation is not a novel concept, although the influence of megafauna may have been under-represented in the literature.

A9 Please see #A7, where we address other vertebrates as possible agents. We realize that the statement on the "enormous" consequences was too generic. We therefore deleted this statement.

Comment 10 I am unsure whether the authors aimed to refute the conclusion of Krämer et al. (2017) that fluid-escape pockmarks are present in the German Bight. They imply this, yet Krämer et al. provided evidence (a possible sub-seabed gas migration pathway, water column 'flares' and high methane concentrations in the water column) which support the conclusion that methane escape was involved in their formation. Is it not possible that both pockmarks and pits (pockforms) are present in this area?

A10 We realize that our reference to (and critical discussion of) the methane discharge hypothesis presented by Krämer et al. (2017) was not sufficiently incorporated in the manuscript. In the section "*Challenging the idea of fluid escape as the origin of seafloor pits*" we now clearly state that we doubt the acoustic interpretation of Krämer et al. (2017). We now write:

L219: The previously reported 'gas flare'25 is the only one despite the tens of thousands of depressions, it is only 1.8 m high, and its sonar pattern is ambiguous. It does not meet flare imaging criteria for unambiguous gas bubble detections10,36. Given the high abundance of fish in the area, we propose a fish school as the more likely explanation for the observed echo anomaly.

This interpretation is supported by the facts that:

1. Krämer et al. (2017) interpreted only a single gas flare despite the presence of tens of thousands of pockmarks that vax and vanish over weeks to months.
2. The data shown were collected with a narrow beam (4°) sub-bottom profiler, which is neither suitable to discriminate between fish shoals and gas flares by diagnostic line pattern (Lohrberg et al. 2020), nor can it be calibrated for backscattering strength.
3. The gas flare shown by Krämer does not meet the necessary criteria to discriminate between flares and fish (Schneider et al. 2011).
4. The vertical extent of the interpreted gas flare is only 1.8 m.
5. We carefully analyzed 4,965 km subbottom data. Most of the data is of very high quality. In all the data we did not find a single indication for the presence of shallow gas such as acoustic turbidity or acoustic blanking. See. Fig. R6
6. previous geochemical equilibrator CH_4 survey (Schneider von Deimling 2015) did not show any indications for elevated methane in the study area.

Together, these observations clearly argue against gas seepage as genetic origin for the seafloor depressions.

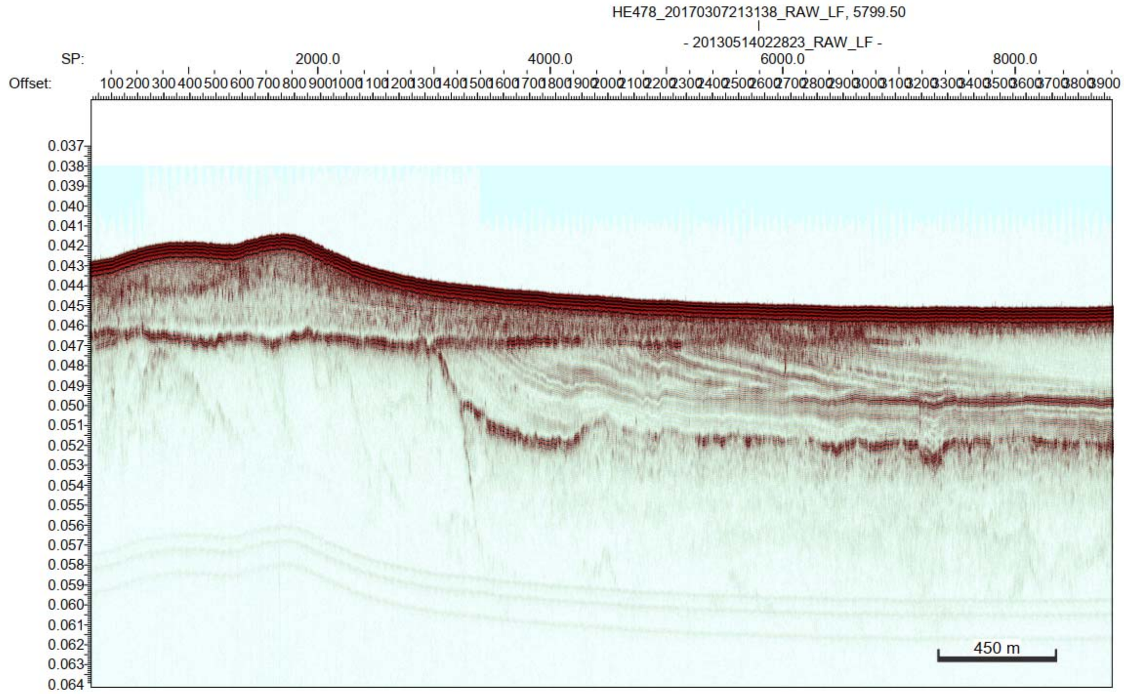


Fig. R6: Subbottom profiler data showing a featureless sand cover on top of the Paleocene acoustic basement. No signs for gas-related acoustic blanking or acoustic turbidity were found.

Comment 11 Methods: A statement about the different cruises used to acquire the data upon which the paper depends (cruise identification/number, ship, dates etc.) is provided in Extended Data Tab. 1. However, although the Methods section, which is essential and generally good, the individual sub-sections do not refer to the individual cruises in a consistent manner. Also, Extended Data Tab. 1 would be more useful if it was accompanied by a map showing the extent of each of the surveys mentioned and, for comparison, the survey area of Krämer et al. (2017) - how much do they overlap?

A11 The overlap in space between our study area and the area studied by Krämer et al. (2017) is outlined as red and yellow polygons in Fig. 1. It is further explained in the figure legend.

We think that the readability of the manuscript would suffer from mentioning each cruise in the main text. Instead we decided to integrate a chronological order of the cruises in the beginning of the methods, and complement with an additional figure (Ext. Data Fig. 1) outlining the cruises and coverages, and overlaps.

Comment 12 References cited: The selection of papers cited to indicate the widespread distribution of pockmarks (Refs 3 - 8) could be replaced by more recent representative examples of the >700 pockmark-related papers identified by ResearchGate. Furthermore, Ref. 4 is incorrectly cited; the report referred to is McQuillin, R., Fannin, N. G. T. & Judd, A. G., 1979. I.G.S. pockmark investigations 1974-1978. Report 98 of the Institute of Geological Sciences. This report is old, somewhat obscure, and probably unavailable; it has also been superseded by numerous other publications and reports. It would be better omitted.

A12 We agree with these suggestions and removed the reference to the old report. Instead we now mention renowned pioneering work and a more recent publication. (e.g. Micallef et al, Harris, et al….)

Comment 13 In summary, this paper is an example of the necessity of examining all possible formation mechanisms of pockmark-shaped seabed features (pockforms). As the study area is in shallow water, the (apparently mistaken) assumption that these features are formed only by the escape of methane from the seabed would imply the emission of large volumes of this important 'Greenhouse' gas to the atmosphere. For this reason, if for no other, the conclusion of this study is significant. However, as the authors acknowledge, others have previously suggested that 'pockforms' are not necessarily 'pockmarks', and pockforms can be made by feeding cetaceans (albeit not necessarily harbour porpoises); bioturbation is not a new concept. Thus, this is an original and noteworthy conclusion when applied to the German Bight and to porpoises. It is also a timely reminder that bioturbation by megafauna may be a significant geological process.

A13 We highly acknowledge and thanks reviewer #1 for his work and constructive criticism that helped us to improve this manuscript.

Reviewer #2

(Remarks to the Author):

Comment 14: Thank you for the opportunity to review. It is an interesting hypothesis. I feel it would benefit from some further discussion of the evidence that links the pits to cetaceans; and the reasons why they cannot be purely abiotic in origin. Please see my attachment.

A14 We appreciate the very comprehensive review and adapted the manuscript accordingly. We now refer to rippled scour depressions in our discussion and also softened the conclusion with respect to harbor porpoise representing the exclusive explanation for the observed pits. With respect to the proposed literature, we decided to include the Diesing et al. (2006) paper for referring to sorted bedforms. However, we decided to not include the other two publications (references both here), as they are not peer-reviewed.

Comment 15 The paper proposes that the activity of harbor porpoises digging in the seabed for sand eels generates small seafloor pits that eventually grow into wide but shallow pits covering a significant proportion of the seafloor within the German Bight of the North Sea. That is certainly a novel hypothesis which has not been proposed before, and is an interesting and thought provoking one. Based on the data presented, however, I don't find it an entirely convincing one.

A15 We agree with this comment and put some more evidence into the manuscript. We also changed the title of the manuscript. From the available data, we cannot infer whether bottom grubbing by harbor porpoises represents the exclusive mechanism that controls the formation of the pits. Our biologist Anita Gilles, however, reported on sand and cobbles in the guts of stranded harbor porpoise. Assuming that the sand was not transported into their guts post mortem, this is a direct evidence for their erosive trait.

We added text and a new reference in the manuscript with:

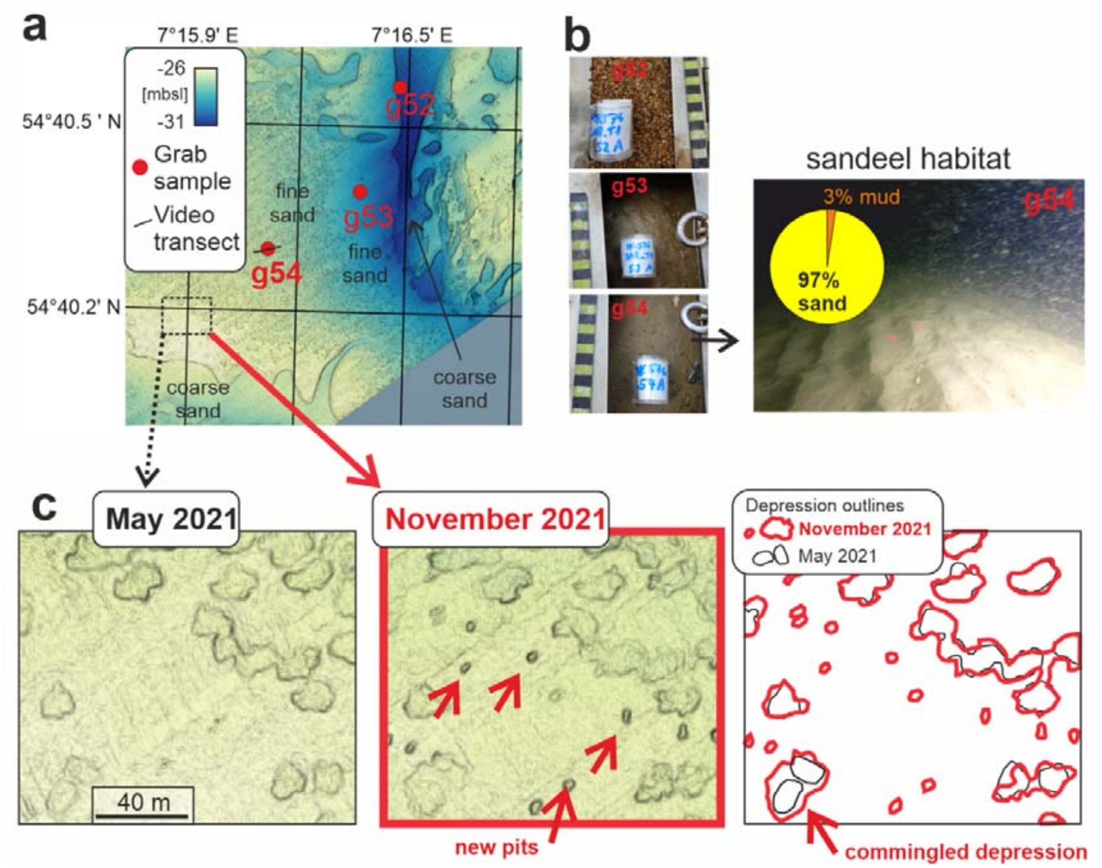
L261: In several cases remains of sand were found in the stomachs of stranded animals[45]

We now also discuss alternative mechanisms for pit formation that could play a role. We now mention that other upper trophic level vertebrates such as seals or fish may also erode the seafloor during benthic feeding.

To account for the uncertainties, we changed the title of the manuscript to

Millions of seafloor pits, not pockmarks, induced by vertebrates in the North Sea

In response to reviewer #2, rippled scour depressions are introduced as an additional possible explanation for the genesis of the depressions. Rippled scour depressions are characterized by different sediment types that allow for sorting mechanisms. Our pits and their surroundings, however, consist of the same material and grain size. This information is now included in an adapted *Fig. 4b*, by means of grab sample analyses. G53 and g54 emphasize that the pits occur in an area where the same sediment is present. This is also reflected in the fact that the pits do hardly appear in the sidescan data (Extended Data Fig. 3, Fig. R11).



New Fig. 4: grab sample analyses are provided now demonstrating the main sedimentological domains with gravel, partly forming sorted bedforms, and fine-to medium presenting a sandeel habitat, in which pits can occur.

We also modified the text and extended the discussion of scouring.

L346: Pockmarks can occur as self-scouring features and can be modified by bottom currents after their initial formation[62]. The depression in the seafloor introduces a turbulence of the bottom current which in turn further removes the sediments. Since the tides in the German bight introduce a rotating rather than bi-directional current regime[63] we would assume that initial depressions are not elongated in one direction but rather unidirectional.

Comment 16 In part this may be because the paper does not provide a coherent or logical story (I realise that is also driven by the publication, as information is separated into three documents – main paper, a separate Methods and then Extended Data, but I think the various components nevertheless could be tied together a bit better).

A16 We tried to implement the suggested changes for a more comprehensive structure that, however, also has to meet the demands from the Journal's style and scope. Please see our replies below for details.

Comment 17 Better understanding might be supported by a brief, chronological description of:

The research cruises and data generated, and figures more clearly labelled with identifying information;

A17 We agree and now provide additional information about the cruises and also added a figure that shows all cruise tracks.

New text: see Methods, New figure: Ext. Data Fig. 1

Comment 18 The authors own investigation and understanding of the phenomenon (e.g., they saw something unusual, they reviewed historical data, gathered new data, they considered and discounted other hypotheses for stated reasons, etc);

A18 We disagree that the paper is not following a logical path.

Comment 19 The geological process by which a small pit in the seabed becomes a 10 m (and up to 60 m) wide depression.

A19 This is a very important remark, and we realize that more discussion is needed with respect to this point. The most likely process to enlarge the pits seems to be scouring. A final proof of this, however, would go beyond the scope of this manuscript.

We modified the text, incorporated references to self-scouring processes and adapted the text:

L346: "Pockmarks can occur as self-scouring features and can be modified by bottom currents after their initial formation[62]*. The depression in the seafloor introduces a turbulence of the bottom current which in turn further removes the sediments. Since the tides in the German bight introduce a rotating rather than bi-directional current regime*[63] *we would assume that initial depressions are not elongated in one direction but rather unidirectional"*

Our co-author Jasper Hoffmann from AWI/University Malta tried to investigate submarine geomorphology in the German Bight with respect to bottom scouring by using an in-situ lander (Fig. R7) with a sector scanning sonar. However, due to nasty sea conditions and possible interference with fisheries activities, it got lost, and was only recently rediscovered and fished it out of the sea.

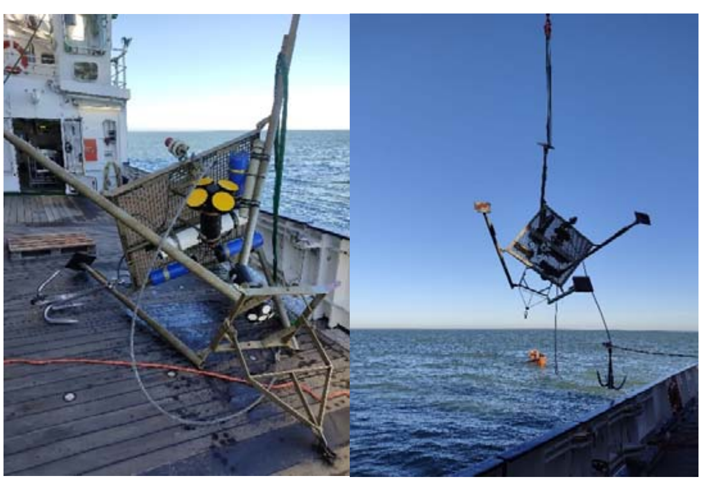


Fig. R7

Comment 20 The latter is my primary question. We see some unusual pits with associated positive relief mounds and rims in Figure 2 that were previously described by Krämer et al (2017). The suggestion that detail previously missed has been revealed by closer inspection of the data is perhaps a bit strong, since that morphology (of rims and mounds) is also clearly visible in the figures of Krämer et al (2017), and described in the text.

A20 We are still convinced that the high resolution of our data allows us to resolve details in the morphology of the pits that have escaped attention and possibly also resolution before. Fig. R8 below is from the supplement of Krämer et al. (2017). Even on the regional scale shown below, there are enormous errors in the multibeam data that mask underlying small-scale structures and morphologies. We therefore decided to keep the conclusion that our data allows us to see details that have been previously missed.

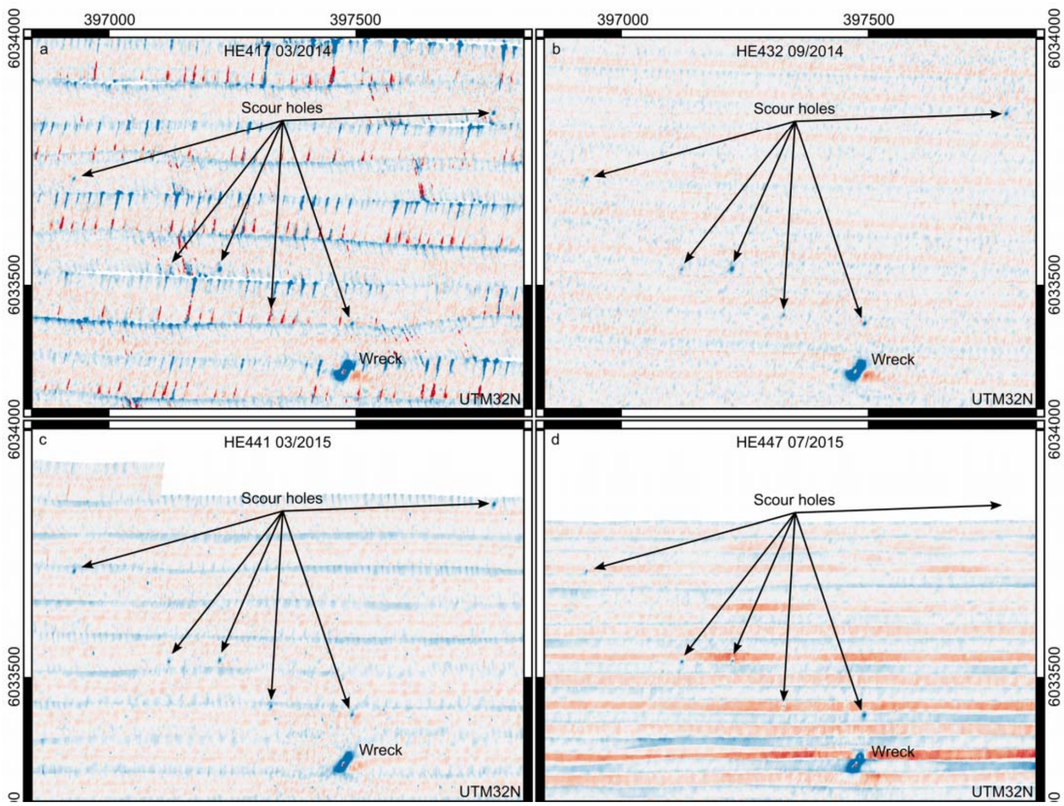


Fig. R8: Multibeam data from the previous Krämer et al. study

Comment 21 But OK: we start with some unusual, perhaps unexplained, morphologies. Firstly, I would like to see a hypothesis as to what sedimentological process will erode a small disturbance of the seabed by a harbor porpoise grubbing for a sand eel in loose sand – which I envisage as being perhaps 10-30 cm long and a few centimeters deep(?) – into an elliptical depression 10-20 m long.

A21 Following on **A19**, scouring might be the most likely process. But a direct proof is beyond the scope of this manuscript and also difficult to obtain (see above). To account for this, we now also discuss other process that may cause such an initial disturbance as well as widening of it.

E.g. we added sandeel chase erosion in

L317: By grubbing the seabed, porpoises may flush out nearby sandeels from the sediment. As sandeels are schooling fish, the expulsion of individuals may result in the entire school attempting to escape predation in an erosive manner

and refer to **A15**

Please also have a look at the paper we reference showing the erosive potential of dolphins (Fig. R9), being the larger sibling of harbor porpoises.

Fig. R9: from Rossbach & Herzing 1997

Comment 22 Krämer et al (2017) we see scour pits that, over the course of two years, have not transformed into larger pits, so why would smaller pits do so?

A22 This might be a misunderstanding. We think that the reviewer is referring to the scour holes (not pits) in Krämer et al. (2017). But those are due to obstacle scouring (Fig. R8: boulders, wreck) which are more or less time invariant.

Comment 23 Also in Figure 4b of the manuscript we see rippled, mobile sand in which we would expect any minor disturbance to be quickly lost. We commonly see that effect with trawl scars, for example, which are erased from the seafloor within days or weeks in areas where the seafloor comprises loose, mobile sand (but remain for months and years in low energy environments and cohesive sediments).

A23 We refer to our **A15**

Comment 24 Secondly, I did not see any evidence provided to support a connection between the pits illustrated in Figure 2 and those in Figure 4 and Extended Data Figure 2.

A24 The figures serve different purposes, and a direct connection is not relevant nor warranted. Fig. 2 highlights morphological peculiarities of the pits, Fig. 4 discloses their time-lapse evolution and the Ex. Data Figure 2 demonstrates that sidescan data merely resolves the pits, indicating little variations in grain sizes.

Comment 25 From a brief glance, they seem to have different morphologies, and they are spatially disconnected. The latter figure in particular shows more of a continuous texture than a series of pits, and I would say requires some extraordinary evidence to tie it back to harbor porpoises. (I sent an example of a similar texture from the western Atlantic to the lead author; I don't have a good explanation for its origin, but also no reason to associate it with cetaceans.)

A25 We fully agree that we have to consider rippled scour depressions. Please see our **A15** and our new sections in the manuscript describing RSD including new references and grain size data

L353: Sorted bedforms and specifically rippled scour depressions (RSD) are common features in many tidal effected nearshore environments. They are associated with the co-existence of different sediment grain sizes64,65, where the depressions are composed of coarser grained material. RSDs are widely distributed on the SOR and also observed in our datasets in regions where gravelly coarse sands are present in the bathymetrically deeper parts (Fig. 4). However, pits occur exclusively within fine to medium sandy seafloor, and not in the gravelly coarse sands (Fig. 4, grab sample g53 and g54)

Comment 26 Finally, the manuscript Summary states that, "Time-lapse data reveals the initially small feeding pits serve as nuclei for scouring…", but Figure 4 shows smaller pits appearing on the second pass. We don't see those small pits subsequently evolving into the larger, shallow pits. I don't know if I read it correctly, but the Extended Data suggests that the Norbit data was not processed for outliers, so the reader may question whether the small pits indicated in Figure 4 are noise. The comment about the spatial alignment of pits ("linear,… radial") reminds me of Spina (2018)1, in which multibeam noise was clearly misinterpreted as pockmarks.

A 26 We realize that our wording was misleading and changed it.

L416: Especially with the NORBIT 400 kHz data we sailed slow survey lines during good weather leading to very clean point cloud data without the need of manual flagging or filtering

On another note, I actually wrote a comment on the Spina results in order to explain their "pockmark star" being purely MBES artefacts. The respective Journal has to be ranked "predatory", I often use this example to illustrate misinterpretation of MBES data in our multibeam classes at Kiel University.

Comment 27 The discussion begins by questioning the general lack of evidence for shallow gas, which is fair enough, and then notes that cetaceans create assorted pits and furrows in the seabed (also true). Harbor porpoises occur in the area, as do sand eels, and sand eels form part of the porpoise's diet (OK). But there is no real evidence provided for a connection between porpoises and the pits. As the authors state, "it is difficult to imagine that a single erosive grub into the sediment is capable of producing the up to 50 m diameter pits".

Yes, indeed. So there needs to be some more convincing argument to overcome that difficulty.

A 27 We agree that we have to phrase our conclusions more carefully. This was also mentioned by reviewer 1 and the editorial comments, and we accordingly changed the manuscript in many parts.

Though, we also provide more evidence with

L261: In several cases remains of sand were found in the stomachs of stranded animals[45]

See also **A7**

A final proof is indeed challenging and definitely beyond the scope of our manuscript. It may have to involve GPS tracking, environmental DNA analyses, and possibly porpoise attached video observations. But catching wild harbor porpoise is generally challenging. This will require a huge effort with respect to funding applications, ethic clearances, cruise planning and realization, time-lapse multibeam mapping and other aspects. However, we will be working on realizing this over the years to come.

Nevertheless, we consider our line of argumentation (despite its now more carefully formulation) sound and pertinent and we feel that this was also acknowledged by the reviewers and the editors.

Comment 28 Also noted by the authors, the pockmark field of Krämer et al (2017) was found to wax and wane over the course of weeks and months. It is a bit difficult to understand how all these pits can form in such numbers and to such a size (from a biotic origin), and then disappear again. Why does the same process that enlarges pits also erase them?

A 28 This is a very valid comment and we realize that this explanation was lacking in the previous version of the manuscript. There are two different processes at work, the interplay of which can explain this observation.

First, there are infrequent severe storms. Please also see the wave height plot (Fig. R5) in our answer **A5**. Wave heights in the area can reach up to 18 m, while the seafloor is only about 25 m deep. Those high-energetic events are likely super-erosive and consequently may level out most bottom topography. Secondly, the German Bight is characterized by strong tidal flow, and tidal scouring is likely an ongoing process, changing the morphology of the pits over time.

To better explain this, we modified the text as follows:

L254: Episodic but severe storms predominantly in winter completely level out the structures over time

Comment 29 (Yes, tidal versus storm wave oscillatory currents, but if tidal as the enlarging force, there should be some consistent alignment to the pits/mounds.)

A 29 Yes, this is something we tested as pockmarks generally align in the direction of the main current direction but did not find conclusive trends. We now argue:

L348: Since the tides in the German bight introduce a rotating rather than bi-directional current regime[63] *we would assume that initial depressions are not elongated in one direction but rather unidirectional*

Please also note that the shapes evolving from scouring can look peculiar in this region (Figure R10 below is an example from offshore Sylt).

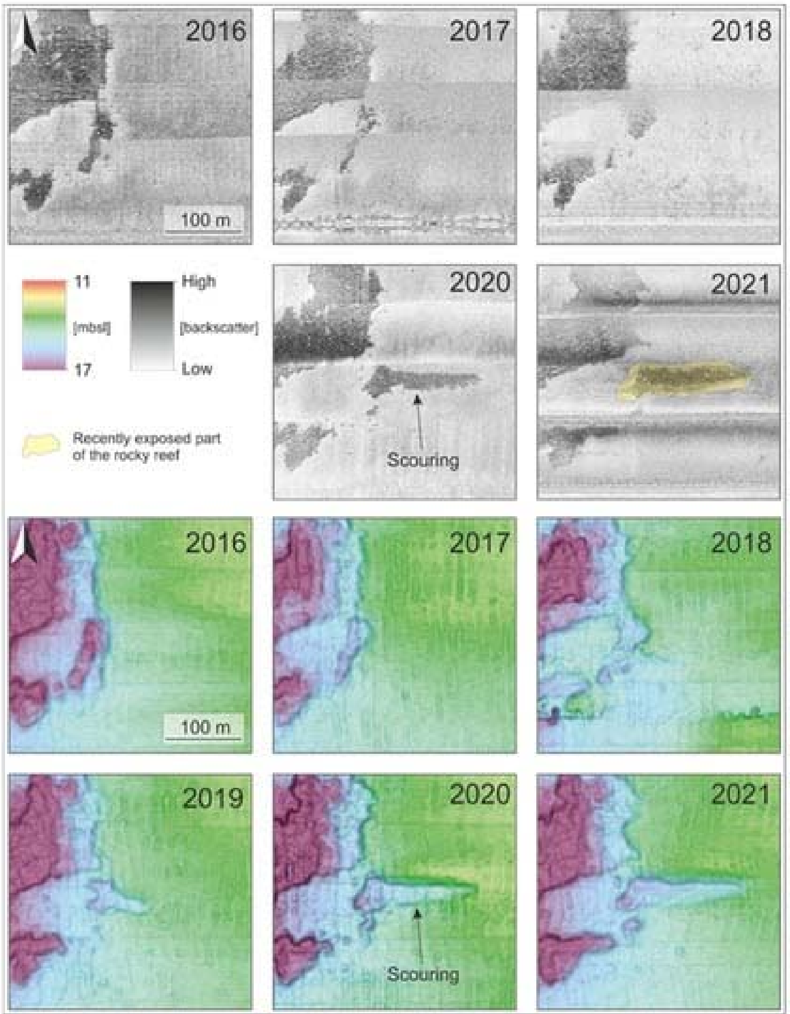


Fig. R10: Evolution of the seafloor around a rocky reef with scouring observed over a longer time period. Taken from Hoffmann, J. J., Michaelis, R., Mielck, F., Bartholomä, A., & Sander, L. (2022). Multiannual Seafloor Dynamics around a Subtidal Rocky Reef Habitat in the North Sea. *Remote Sensing*, *14*(9), 2069.)

Comment 30 Also, porpoise activity is a constant, so it is unexpected that no pits were found by Krämer et al (2017) in 09/2014 (their Supplementary Figure S3), or indeed by many researchers over the years (even on lower resolution multibeam – the pits are large enough).

A 30 We mainly disagree with this comment due to the reasons listed below:

1: One reason why the pits have barely been detected before is because habitat mapping in the study area has almost exclusively been conducted with sidescan sonar. Given the homogeneous (sandy) grain size in the larger area, the pits are hardly visible in sidescan sonar records.

2. Although their dimeter is large (couple of meters), the depth of the pits is only small, with an average value of 11 cm (with respect to the surrounding seafloor). Not all multibeam studies, especially not those conducted back in time, did capture such small morphologies.

3. Harbor porpoise are known to be opportunistic regarding prey and move in between hunting grounds over the seasons.

4. The North Sea is currently under heavy environmental stress with windmill installations. The pile ramming is so noisy that the harbor porpoise populations migrate away occasionally.

Comment 31 I think some more compelling evidence is needed to advance this hypothesis. As a fellow author of a "topic discussed controversially" (fish excavation; albeit not really controversial - it is proven from the Gulf of Mexico), I believe I was able to present such evidence in the form of conical mounds for which there is no abiotic formation mechanism. I don't know if something similar can be found in this case from the available data, either to link the pits indisputably to cetaceans, or conclusively delink them from purely geologic and oceanographic processes.

Personally, I am of the opinion that seabed bedforms without alignment are the product of surface wave oscillatory currents. We have some evidence in the form of Rippled Scour Depressions (or "sorted bedforms"; e.g., Diesing et al, 20062), the boundaries of which have no particular orientation. Surface waves can somehow also erode small, circular depressions (e.g., Speller, 20003; or the "shell accumulation" images that I sent the lead author previously). Below is another example of an unusual texture, in 40 m of water, that is surely purely geological. I guess a 90° change in ocean current direction (+ surface waves?) has overprinted the old bedforms with newer ones; however outside the main "new" field are small (5-7 m), isolated depressions. Since they appear on the bedform crests, they are not scours to the east). Could similar pits also appear in smooth seabed under rare conditions?

A 31 We agree that more evidence is needed for a final proof. However, we consider our line of argumentation thoroughly. We now also thoroughly discuss Rippled Scour Depressions and integrated grain size analyses in the paper. We updated the text and adapted Fig. 4:

L353: Sorted bedforms and specifically rippled scour depressions (RSD), are common features in many tidal effected nearshore environments. They are associated with the co-existence of different sediment grain sizes[64,65], where the depressions are composed of coarser grained material. RSDs are widely distributed on the SOR and also observed in our datasets in regions where gravelly coarse sands are present in the bathymetrically deeper parts (Fig. 4). However, pits occur exclusively within fine to medium sandy seafloor, and not in the gravelly coarse sands (Fig. 4, grab sample g53 and g54).

Comment 32 Personally – without evidence – I would ascribe the pits in Extended Data Figure 2 to surface wave action, without the need to invoke a biological agent. For those in Figure 2 (and Krämer et al, 2017), I don't really have an opinion, although considering the above images, it is not entirely inconceivable that there is some poorly understood oceanographic process in play.

Apart from that, maybe the hypothesis could be stated somewhat less strongly. For example, "we… reveal the formation mechanism of the seafloor depressions" is a bit too definite.

A 32 We agree, changed the title, and soften the wording throughout the manuscript.

Reviewer #3 (Remarks to the Author):

An improved understanding of the genesis and controls of seafloor depressions or pockmarks has value for a broad range of questions related to geohazards, energy resources, the global carbon cycle, and marine environmental protection. In this manuscript, the authors have proposed an alternative interpretation for the formation of seafloor pockmarks in the German Bight, Baltic Sea, and suggest that harbor porpoises excavate significant amounts of sediments during benthic foraging within a large sandeel habitat by poking the seabed, thereby initiating pit formation. The resulting pits are small (< 10 m in diameter) and have been detected by high-resolution multibeam bathymetry and sidescan sonar.
Given the distribution of pits, feeding harbor porpoises, sandeel (prey), and a find-sand substrate bearing the sandeel in this portion of the Baltic Sea, they offer one of the best possible interpretations and argumentation to address the origin of the seafloor pockmarks. As such, I find this manuscript quite exciting and essential to advancing the science of seafloor pockmarks. While focused on the Baltic Sea, the results are likely to be applicable to other continental margins around the world, where such non-fluid pockmarks are common.

Below I listed some moderate comments and the authors are recommended to follow them.

We thank the reviewer for his careful review and the valuable comments which we all implemented into the manuscript.

Comment 33 1) I think the sedimentological aspects should be improved in the current manuscript. The authors collected 45 sediment samples using box coring and conducted a grain-size analysis to verify the acoustic backscatter response of the seafloor. I have not seen any figures showing this correlation or discussions concerning sedimentology or grain size analysis. Are there any box cores inside or outside of the seafloor pits? If so, do sedimentary structures and grain sizes differ? Geologically, as the harbor porpoises profoundly disturb the substrate, box cores of the transgressive sand sheet should not show any evidence of primary sedimentary structures probably because of intense feeding activity. Nevertheless, some of the core photographs, including the sedimentary structures should be shown and described.

A 33 We agree that more information on these sedimentological aspects would benefit the manuscript. We included the grain size information into Fig. 4 and also now emphasize on the fine to medium sand hosting both, the sandeel habitat and the pits. The pits do hardly appear in sidescan data (Fig. R11). But we also want to note, that a “deeper looking sedimentological” analyses is beyond the scope of the study.

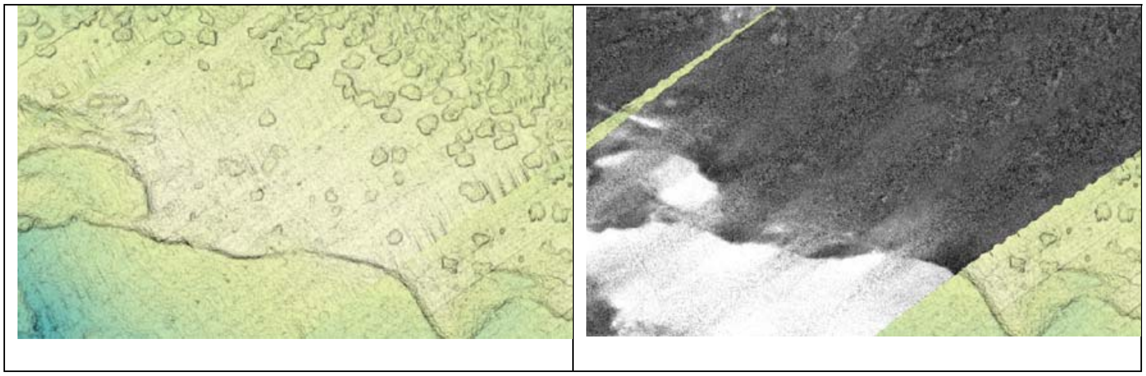


Fig. R11: (left) MBES bathymetry (right) MBES snippet sidescan imagery. It shows that the sidescan does not clearly disclose the pits thus supporting the uniform grain size distribution within pit areas.

Comment 34 2) The currents and their strengths as well as their seasonal variability should be introduced earlier in the section called “Geologic and oceanographic setting in the German Bight”. In the results and discussion, the enlargement by current scouring should be expanded. For instance, are the enlarged pits oriented parallel to the predominant current direction?

A34 This is a valuable point and familiar questions were risen by the other reviewers. We accounted for this by providing more information, e.g.:

L109: tidal currents of almost 1 m/s[31]

L348: Since the tides in the German Bight introduce a rotating rather than bi-directional current regime[63] *we would assume that initial depressions are not elongated in one direction but rather unidirectional*

L346: Pockmarks can occur as self-scouring features and can be modified by bottom currents after their initial formation[62]*. The depression in the seafloor introduces a turbulence of the bottom current which in turn further removes the sediments.*

Comment 35 I suggest the authors go one more step and classify the pits as fresh (formed during the most recent feeding season) or modified (remnants of the past feeding seasons) based on their width and length using histograms. It would also be a good addition to compare their dimensions with known examples such as those found on the Bering Shelf, Alaska (Nelson et al., 1987).

A 35 At the current stage of research, it is unclear when the “feeding season” actually happens, or if this process takes place throughout the year. Therefore, we want to stick to our classification with “pits (<10 m) and pit-scours (>10 m).

Comment 36 3) The authors presented a seismic profile to show the Holocene sediment thickness below the seafloor pits and to prove the lack of acoustic evidence related to shallow gas. However, given the data resolution in Ext. Fig. 3, it is hard to see such acoustic anomalies related to shallow gas and thus judge the interpretation. Hence I suggest the authors provide two or three close-up seismic sections immediately below the seafloor pits. Also, provide a few more seismic profiles crossing the different parts of the study area to better appreciate the seismic interpretation as well as the seismic stratigraphy. I suggest the authors provide a few more sub-bottom chirp profiles traversing the different parts of the study area. Apparently, there is only one seismic profile presented in the manuscript. The authors are also recommended to show the locations of the sub-bottom chirp profiles as well as the box cores.

A36 We see the point of the reviewer. The sedimentological setting in the study area is controlled by very mobile sands. These ultimately prohibit the deposition of “coherent” reflectors making the plots looking blurry. We accounted for this by adaption Ext. Data Fig. 4 caption with

In general, the mobile sand units on top of the Paleocene do not hold coherent reflectors resulting in a transparent imagery.

Since the top sand layer is often only very thin (<1 m) the acoustic penetration is generally limited in many regions. In the dataset we were also not only focusing our efforts on gas detection within the sediment but also in the water column. One profile in the north of the study area is shown in R6 where penetration is higher due to an increased sediment cover on top of the Paleocene surface.

As the scope of the paper is on the near surface habitats rather than geology we refrain from showing more seismic profiles

Comment 37 4) I think the seismic stratigraphy is a bit underrepresented in the current manuscript. I suggest the authors explain more about seismic stratigraphy (seismic facies, unconformities, unit thickness variations, etc.) beneath the seafloor pits. For instance, it would be a great addition to construct a Holocene thickness map (if feasible) in the study area to better appreciate the relationship between thickness distribution, pit formation, and current activity.

A37 We agree that the seismic stratigraphy is underrepresented in the manuscript. Since high resolution airgun seismic data is not available and sub-bottom profiler data has only limited penetration, a geological interpretation with seismic facies analysis and description of unconformities is not possible and would be beyond the scope of this manuscript. From the sub-bottom profiler data we derived the thickness of the Holocene sediments, which appears unrelated to the occurrence of the pits:

L163: The thickness of Holocene sediments on top of the Pleistocene varies roughly between 0 and 10 m (Ext. Data Fig. 4). We found no correlation between the occurrence of pits and Holocene sand sediment thickness, nor any acoustic blanking, bright spots, or flares being reliable acoustic proxies for shallow gas or gas ebullition.

L164 We found no correlation is based on analyses of the large subbottom profiler dataset (Fig. R12)

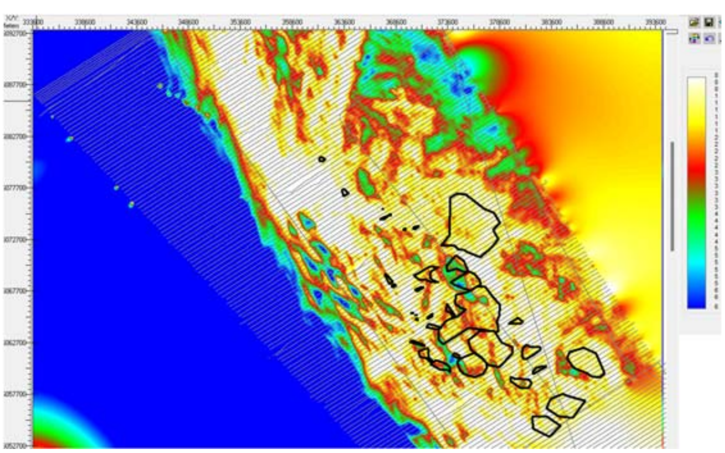


Fig. R11: Holocene sediment thickness map derived from subbottom profling data. The pits (black polygon) areas occur in any setting with top layer thicknesses ranging between 1 and 6 m.

We do not feel that an extra figure is needed to transport this information. Arguments against fluid escape as possible drivers are thoroughly handled in our answer **A10**.

Other comments

We implemented almost all the minor comments below

Line 49: Please include more recent references.

Done

Line 65: "shallow incision depth…" Please provide some numbers.

Done, changed to *with 0.11 m mean depth*

Line 70 and ff: Demark all the tectonic and bathymetric features in Figure 1.

There are no tectonic features, we want to keep the depressions as features here

Line 86: Change "(< 10 diameter)" to (< 10 m diameter).

Done

Lines 105-107: Please expand this section and give some numbers for the current strengths etc. This is important for the discussion.

Done

L111: currents of almost 1 m/s[31]

Lines 160-162: It is hard to see such acoustic anomalies related to shallow gas given the data resolution in Ext. Fig. 3. I suggest the authors provide two or three close-up seismic sections immediately below the seafloor pits. It would be a piece of good evidence to support the data interpretation and argumentation.

see **A36**

Line 147: Change "8.7%" into "9%".

OK

Lines 181-182: It seems to me the other way around. The depressions in "November 2021" data seem to become more irregularly shaped than those acquired in "May 2021" data. Just for clarification, I suggest the authors give the seafloor pits representative numbers on both images so that one can compare them easily.

We relabeled Fig. 4 with *new pits and commingled depressions*

Line 229: These tidal currents should be introduced earlier.

Done

Line 237: Could there be other benthic animals for Harbor porpoise?

This is a very good remark, which has been mentioned by all reviewers. We now e.g. introduce seals, and self sandeel self-erosion, see our answer **A7**

Line 291: Fig. 6 appears to be cited before Fig. 5. Please correct this in the text.

No, Fig. 5 is references in l243 already

Figures

Fig. 1: Include the distance scale. Add coordinates (lat. and long.) to the inset on the upper left.

OK, we include now scale bar and coordinates in the inlet

Fig. 2: a) I am not sure if it is Okay to use black and white color for displaying the bathymetric map. Why not use the same color font as shown in Fig. 2b? In this way, it would be more consistent. Please increase the font of the coordinates in Figure 2a and move the lat. coordinates to the left. I suggest using the same font for all labels, i.e., for coordinates, scale, etc. For instance, figure labels (a), (b), and (c) have all different font sizes. In Figure 2b, the coordinates have a bigger size which I think is not necessary. Instead, I would suggest the increase the font size of "mounds" and "furrows" in Figure 2b which is the focus of the figure.

We appreciate the thorough remarks and changed the font sizes and labels in Fig. 2. We want to guide the reader with the colors and highlight the most important Figures. Therefore, we want to leave Fig. 2a in b/w.

Fig. 4: a) Include the north arrow. C, d, e) Include coordinates (lat. and long.) and bathymetric color bar. Change the label " Mai 2021" to "May 2021".

We changed the typo and corrected to "*May 2021*". Considering we are providing long/lat and a bounding box is enough and we left out a North arrow

Fig. 6: Add the distance scale.

We now provide a distance scale bar in Fig. 1 , which is showing the same area.

Extended Data Fig. 1: Add the distance scale.

As we now provide a distance scale bar in Fig. 1, we assume degrees ° to be known for translation into distance.

Extended Data Fig. 3: Add the vertical exaggeration in the seismic profile.

Done

2nd Oct 23

Dear Dr Schneider von Deimling,

Your manuscript titled "Millions of seafloor pits, not pockmarks, induced by vertebrates in the North Sea" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

Please note that it may still be possible for your paper to be published before the end of 2023, but in order to do this we will need you to address these points as quickly as possible so that we can move forward with your paper.

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thank you for considering my previous comments so carefully. I have no further comments to make, other than to say that, whilst I am not wholly convinced that these features are initially formed by cetaceans, I think it is important that the idea is presented and discussed. Future work may be able to confirm or refute it.

Reviewer #2 (Remarks to the Author):

Thank you again for the opportunity to review. I see that you put a lot of effort into addressing the

comments on the original version. Based on memory, the revised version is significantly reduced in length and as you say, much softened in its presentation of the hypothesis.
I was intrigued to see the picture of dolphins with their noses in the sediment in the Rebuttal document. But I don't think it is the same thing – sand eels occupy the upper few centimetres of loose sand and porpoises have no reason to penetrate so deeply. Related to that, on line 258, they are "capture" suction feeders, I believe, not "caption". (Also, "unidirectional" [one direction] would be better termed "non-directional" [no direction]?)
In truth, I am still not convinced of the hypothesis. A rapid escape of sand eels from danger, en masse, would at best lift a few handfuls of clean sand 10 cm into the water column, which will almost immediately settle back in the same place?
My comment 24 about the figures was that there appear to be three types of morphology shown: small, irregular pits at one end (Fig 2) and flat-bottomed "pits" that are so broad that they make up more than 50% of the seabed at the other end (Extended Data Fig 3). The former could be biogenic in origin, but I would struggle to ascribe such an origin, even in the distant past, to the latter. If (unexplained) abiotic processes can enlarge small pits to such large features, would the processes even need biogenic nucleation or could it just be spontaneous (like the formation of ripples)?
But I will try to overcome my preconceptions and prejudices - we all suffer from assorted cognitive biases. The editor has chosen to accept the manuscript and you did your best to address the reviewers concerns. Good luck, and you may well be ultimately proven correct.

Reviewer #3 (Remarks to the Author):

I was very excited about this manuscript and appreciated the detailed response of the authors and the improvements made from the initial version. I do not have further comments and recommend that the manuscript be accepted.
Best regards,
Deniz Cukur

Rebuttal Letter #2

Millions of seafloor pits, not pockmarks, induced by vertebrates in the North Sea

Reviewer #1 and #3 have no further suggestions.

We now respond to the points raised by reviewer #2:

Thank you again for the opportunity to review. I see that you put a lot of effort into addressing the comments on the original version. Based on memory, the revised version is significantly reduced in length and as you say, much softened in its presentation of the hypothesis.
I was intrigued to see the picture of dolphins with their noses in the sediment in the Rebuttal document. But I don't think it is the same thing – sand eels occupy the upper few centimetres of loose sand and porpoises have no reason to penetrate so deeply.

We only partly agree. The mean depth of the pits is only 0.11 m (Fig. 3), so the digging does not go deeply. The bottle nose dolphin picture was just used to illustrate the bottom grubbing in general, we do not show it in the manuscript.

Related to that, on line 258, they are "capture" suction feeders, I believe, not "caption".

We agree and now re-phrase to

L260: *capture suction feeders*

(Also, "unidirectional" [one direction] would be better termed "non-directional" [no direction]?)

We agree and now re-phrase to

L352: *non-directional*

In truth, I am still not convinced of the hypothesis. A rapid escape of sand eels from danger, en masse, would at best lift a few handfuls of clean sand 10 cm into the water column, which will almost immediately settle back in the same place?

As reviewer #1 and #2 point out this needs to be justified in future research. The area is characterized by strong currents, so a sediment plume would be transported away quickly.

*My comment 24 about the figures was that there appear to be three types of morphology shown: small, irregular pits at one end (Fig 2) and flat-bottomed "pits" that are so broad that they make up more than 50% of the seabed at the other end (Extended Data Fig 3). The former could be biogenic in origin, but I would struggle to ascribe such an origin, even in the distant past, to the latter. If (unexplained) abiotic processes can enlarge small pits to such *large features, would the processes even need biogenic nucleation or could it just be spontaneous (like the formation of ripples)?*

We do not know the answer to this question. However, our extensive mapping and GIS analyses of 40,000 pits discloses a distinct correlation between pockmark occurrence and harbor porpoise observations and sandeel habitats. In L315 we write pits were exclusively found "*within a radius of 10 nm (18.5 km) of areas inhabiting sandeels*": This argues against spontaneous formation on ripples, which are geomorphological features spread all over the place.

But I will try to overcome my preconceptions and prejudices - we all suffer from assorted cognitive biases. The editor has chosen to accept the manuscript and you did your best to address the reviewers concerns. Good luck, and you may well be ultimately proven correct.

Finally, we thank all reviewers and the editorial team for the great reviewing!