

Anti-repeating earthquakes and how to explain them



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23rd Oct 23

Dear Dr Cesca,

Your manuscript titled "Anti-repeating earthquakes and how to explain them" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

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

- * Present a fair and balanced assessment of existing work on anti-repeating earthquakes, including examples from beyond the work carried out by the authors of the present manuscript, and ensure that the distinction between new work and discussion of previous work is clear throughout the manuscript.
- * Re-consider and/or justify the definitions you use throughout the manuscript for anti-repeating earthquakes, including the distinction between earthquakes which occur on the same fault plane and those which do not.

We are committed to providing a fair and constructive peer-review process. Please don't 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 referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the 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.

Please do not hesitate to contact us 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,

Joe Aslin

Senior Editor,
Communications Earth & Environment
<https://www.nature.com/commsenv/>
Twitter: @CommsEarth

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provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at <http://www.nature.com/authors/policies/availability.html>.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript entitled « Anti-repeating earthquakes and how to explain them » by Simone Cesca and collaborators, is dealing with particular cases of seismic waveform similarity between earthquakes. Repeaters, whose very close waveforms are interpreted as events rupturing the same fault area with the same focal mechanism, have already been relatively extensively studied, whereas only few studies are focusing regarding anti-repeaters. Anti-repeaters are earthquakes with anti-correlated waveforms, interpreted as generated in the same area or very close from each other (referred as true anti-repeaters and quasi anti-repeaters) but with opposite mechanisms. The manuscript provides a convincing review of the contexts in which anti-repeaters events have been observed and a review of the conceptual models that may explain their occurrence. The aim is to try to explain how reversal focal mechanisms at the same location or neighbouring location can occur alternatively, at different time. Numerous relevant references permit to present the diversity of the contexts in which anti-repeaters have been reported (from volcanic context, including dike intrusion, trapdoor faulting or ring faulting, to intermediate depth seismicity or induced seismicity by injection), illustrated with some examples with a large range of magnitude, time delay, frequency content and context. A review of the conceptual models proposed to explain the occurrence of anti-repeaters allows the reader to understand the phenomenological implications in the case of anti-repeaters detections in different contexts. The authors also discuss the strategy and the methods of detection of anti-correlated waveforms for a large range of magnitudes and instrumental configurations.

Moreover, the manuscript is clear, well-written, easy to read, the arguments are balanced, relevant and well-documented.

I recommend this manuscript for publication as a nice and original review paper regarding an interesting type of observations, still little studied, despite the interest they represent for tracking perturbations of stress in space or time, that can also be considered in some contexts as indicators for potential fluid transfers.

Nevertheless, I'd like to suggest few minor corrections.

They are described in an attached file.

Reviewer #2 (Remarks to the Author):

Review of Anti-repeating earthquakes and how to explain them, by S. Cesca, P. Niemi, T. Dahm, and S. Ide.

This paper describes the phenomenon of “anti-repeating” earthquakes—signals that are highly

negatively correlated and thus have reversed focal mechanisms and inverted waveforms. The authors summarize observations of such events seen in a variety of environments and discuss possible mechanisms for their formation. The paper is largely well written and clear, and the topic is important: this is a phenomenon of which the seismological community may be unaware, and this paper will do much to inform them. That said, I have some concerns with the structure of the paper, as described below.

A primary question relates to whether the scope of the paper is sufficient or appropriate. The study describes in detail four examples of anti-repeaters, all of which were described in other studies, which is to be expected in a review paper. However, of the four primary examples, three were first described in papers written by the authors of this manuscript (Mid-Atlantic ridge: Cesca et al., 2023; Mayotte: Cesca et al., 2019; Apso Hard Rock Laboratory, Niemz et al., 2020). This leaves only the Bucaramanga nest as work that was not led by one of this study's authors. The description of a review paper on the Communications Earth and Environment page states "The scope of a Review should be broad enough that it is not dominated by the work of a single research group, and particularly not by the authors' own work." Given that there are not a ton of publications on this topic this may be difficult, but the manuscript can clearly be broadened to include other examples. In particular, the authors could expand on the results from the references below, many of which are briefly mentioned in the article:

- Rubin, A. M., Gillard, D., & Got, J. L. (1998). A reinterpretation of seismicity associated with the January 1983 dike intrusion at Kilauea Volcano, Hawaii. *Journal of Geophysical Research: Solid Earth*, 103(B5), 10003-10015.
- White, R. S., Drew, J., Martens, H. R., Key, J., Soosalu, H., & Jakobsdóttir, S. S. (2011). Dynamics of dyke intrusion in the mid-crust of Iceland. *Earth and Planetary Science Letters*, 304(3-4), 300-312.
- Shelly, D. R., & Hill, D. P. (2011). Migrating swarms of brittle-failure earthquakes in the lower crust beneath Mammoth Mountain, California. *Geophysical Research Letters*, 38(20).
- Hotovec-Ellis, A. J., Shelly, D. R., Hill, D. P., Pitt, A. M., Dawson, P. B., & Chouet, B. A. (2018). Deep fluid pathways beneath Mammoth Mountain, California, illuminated by migrating earthquake swarms. *Science advances*, 4(8), eaat5258.
- Cassidy, J. F., Balfour, N., Hickson, C., Kao, H., White, R., Caplan-Auerbach, J., ... & McCormack, D. (2011). The 2007 Nazko, British Columbia, earthquake sequence: injection of magma deep in the crust beneath the Anahim Volcanic Belt. *Bulletin of the Seismological Society of America*, 101(4), 1732-1741.

Because so much of what is presented here was originally done by this study's authors, the manuscript sometimes blurs the lines between what was done in the original studies, and what is being presented for the first time here. For example, the authors state that for the Mid-Atlantic ridge data, "we identified anti-correlated waveforms on...station G.IVI.00". Was that work performed for this study or was in part of Cesca et al., 2023? Further, although it is not clear that any of these authors worked on the Bucaramanga nest, the paper states "here we perform a similar search for anti-correlated waveforms". This makes it sound as if new analysis was done for the present manuscript, but no methods are described (how was the search performed? What parameters were used to identify anti-repeaters?). The only place we have information about

methods is hinted in the code availability section which reads “The codes used to generate individual results are available through the contact information from the original publications”, which implies that all analysis was performed in the original studies. In short, I am confused by what is new here, and what summarizes existing work.

In each of the four cases presented in this manuscript, the authors present a single example of a reversed pair, even though some of the works describe clusters of anti-repeaters. If the paper is summarizing previously presented work, then it seems that all of the results should be discussed, not just a selected quake/reversed quake pair. If new analysis is to be included, it would be interesting to use the number of anti-repeaters, as well as their temporal patterns to discriminate between the different models proposed within the paper.

The authors distinguish between anti-repeaters (true repeaters whose slip direction has reverses), and quasi-anti-repeaters (events occurring proximal to one another with different senses of motion). This is a good and important distinction, as it has implications for the cause of these events. However, there is little discussion of how easily this can be resolved. The paper is clear about the quarter-wavelength rule and why it is useful (where possible) to evaluate similarity at high frequencies, but there isn’t much discussion about how often locations are known with high enough certainty to distinguish proximal faults.

I strongly agree with the authors that there is a need to advertise the presence of these events to the seismological community—if researchers are already looking for multiplets it’s relatively easy to search for anti-repeaters as well. I suspect this is a situation in which such events are simply out there waiting to be discovered and observed, and we’re just using the wrong tools to find them.

Comments specific to individual lines follow:

Line 34: Are there examples of studies that refer to events on different faults as multiplets? And as noted above, is their occurrence on different faults confirmed, or is it a question of location certainty?

39-40: describes anti-repeaters as “earthquakes occurring at the same, or similar, location but with an opposite mechanism, manifested in highly anti-correlated seismic waveforms” This should be clarified—must they have inverted waveforms, or is a reversed mechanism sufficient? This also speaks to the location issue above: if the events are true repeaters (reverse slip on the same fault) we would expect inverted waveforms. But events can reverse mechanism with variability in waveform.

Lines 58 and onward: this is one of the places where the authors use “we” in the context filtering and correlating waveforms, but no methods are shown or described here. If this reflects work done in a previous paper, this should be stated, and the use of “we” should be replaced by a citation to that original source.

Line 66-68: good to define the concept of quasi-anti-repeaters, but it’s hard to know how easy that is to identify without really robust and high resolution locations.

Line 73: says that reversed focal mechanisms “imply anticorrelated waveforms”. This may not be the

case if the size of the seismogenic volume is large (or the events are not on the same fault).

Lines 102-103: Another use of “we identified”. Is that this study or the previous?

Line 111: while the term “nest” appears to be widely used for intermediate depth earthquake clusters, it is a term with which I was totally unfamiliar. Given that the audience for this paper is likely to be broad, it might be good to add a clause defining this term.

Line 115: change “compact extension” to “compact extent” or “compact size” (“extension” may be confused with the stress field).

Line 116 states that the Bucaramanga site is a likely place to host anti-repeaters. This suggests that it is likely to cause anti-reversing behavior, which isn’t obvious. I think it’s more appropriate to say that it is a good place to look for such events (given the small size and variability in mechanism).

Line 118 and 119 again state that the authors did a search for anti-repeaters, and they show a single example. Prieto et al., however, show clusters of such events. Is there a reason the authors of this work chose to show a single example? Is there benefit to looking at a larger cluster?

Line 133: not sure why the S-P time matters here?

Line 145: Again, it is unclear whether the authors of this study performed the cross-correlation analysis, or if this was done in the original study.

Line 150: please define “highly correlated”

Line 173-174: I’m not sure how this line fits into the discussion here (the use of “for instance” suggests it relates to the previous line, and I don’t see a connection).

Line 175: the phrasing “further differences in seismicity migration” is awkward and unclear.

Line 179: I’m not sure what is meant by the “back tip” of a dike. Does this mean that the dike is propagating in one direction only? And does “eventually” refer to a time when the dike depressurizes and so is under compression? This isn’t clear to me.

Line 200 calls these events anti-repeaters, but it sounds like they should be quasi-anti-repeaters?

Line 221: Change “time interevent” to “interevent time”

Line 227-8: I’m not sure why tsunamis are mentioned here unless it’s to justify the need to search for anti-repeaters?

Line 231 and onward: there’s a long discussion here about CLVDs and their mechanisms. I find the connection between this and anti-repeaters to be hard to follow. I get that this is a situation in which researchers could look for anti-repeaters via reversed CLVD mechanisms, but this seems to be only briefly touched on here. I think the paragraph from lines 249-259 could probably be cut with no significant loss of information to the paper.

Line 262 mentions “focal mechanism reversal”. As noted earlier, this is important, but it’s not the same thing as full waveform inversion. In general I think the paper would benefit from more clarity between these two perspectives (the focal mechanism can be reversed for some event pairs that are not anti-repeaters).

Line 282 and 290: Abbreviations SH, Sh, Sv, Smin, and Smax are used here but not defined and not used elsewhere in the paper. I think this can be deleted.

Lines 305-6: These lines discuss triggering of anti-correlated quakes by larger events, and the paper cited describes different mechanisms near the Loma Prieta fault. My reading of that paper is that this results from very low friction and high pore pressure, not from “overshoot” (the topic of the paragraph).

Line 337 again discusses the question of whether anti-repeaters occur on the same fault or not. I think it would be worthwhile to comment on the likelihood that this can be resolved in a given dataset. Some discussion of average location uncertainty would be helpful for readers interested in looking for anti-repeaters in their own datasets.

Line 380 and onward: I struggled to understand what was done in this section. I appreciate that correlation coefficients vary significantly with different frequencies, durations, etc., and I’m glad the authors brought this up. But I am struggling to follow the description of the synthetic waveform tests. I think this section needs to be made more clear: what does it tell us if the difference between Cmax and Cmin is small or large? Note that this could be important for monochromatic signals, where cycle-skipping (or half-cycle skipping) would yield both a high Cmin and Cmax.

Line 388: What does DC mean here?

Line 425: need a space between “presence” and “of”

Line 457 describes that the code is available via the contact info from the original studies?

In summary, I think this is an important topic and I'm glad the authors have written this manuscript, but I have concerns about the structure and completeness of the material presented.

You are welcome to include my name with this review:

Jackie Caplan-Auerbach
Western Washington University

Reviewer #3 (Remarks to the Author):

The paper discusses the evidence of repeating events but with reverse polarity, what they call anti-repeating earthquakes. The topic is interesting and I agree a review paper on these events is warranted, but I think the paper is not there yet, it requires significant work.

Major concerns

1) The definition of an anti-repeater.

There have been a number of recent papers on repeating earthquakes. In particular, a lot of attention has been put into a strict definition of what a repeater really means. I think the definition is these are ruptures on the same fault patch. But how do we define that two events occur on the same patch? Well, earthquake location is one (even relative locations), the size of the fault patch, and the waveform similarity.

The new papers have argued that waveform similarity alone is not an appropriate criteria. The introduction on this contribution is vague in the discussion of the definition of a repeating event. It obviously applies to anti-repeating events. In various places in the text the waveform similarity is used as a criteria, and in other places the patch size and rupture location is discussed. The authors should be very clear about this.

Later in the examples, a more relaxed definition is used, based mostly on waveform similarity. The authors do not discuss earthquake location much, at least not in all examples. And finally, because the determination of similarity is based on a certain frequency range, empirically determined, no discussion about the choice of frequency band is given. For example, given a certain frequency range, and a preliminary velocity model, the wavelength could be discussed and relate it to the eventual patch size or earthquake location uncertainties. None of this is done.

Finally, later in the text, the authors use two definitions, a true anti-repeater and a quasi-anti-repeater. I tend to agree that such terms are fine and needed because of the limited data available, but this needs to be clearly stated in the text.

From my point of view, I think the paper should use the term reverse polarity events, and one special case of those would be a anti-repeater when location, patch size, etc pass a certain criteria. I know the literature has not done this (including myself) but since this paper could be the first to review such types of events, I think being thorough would be nice.

2) The examples

These are nice examples. But I think the examples are solely showing waveform similarity.

Because the case for a repeating earthquake requires not only waveform similarity but being over the same patch, in Figure 1e) , where the authors have the frequency band, can you also add what that frequency band represents in terms of the corresponding size of the patch or wavelength that we are using to correlate the waveforms? In the intro, the authors say they filter below the corner frequency, which makes sense, but how far below.

In fact, if i were to look at the Bucaramanga nest events, with source radii is of the order of 1 km or less for a M5.0, the wavelengths are of that same order? Please show or discuss this.

3) The models to explain anti-repeaters. Most of the models presented, explain reverse polarity events on distinct fault planes. Some models explain true anti-repeaters, the explanation is needed here.

I think the models presented are the best part of this contribution. They are not new, but are

cleverly presented as examples where you would expect reverse polarity events in very close fault planes. I really like that.

But I also think that the models show cases where we are dealing with anti-repeating events, that can be expected to occur in the same fault plane, while in other cases the polarity of the events is reversed but occur in different or distinct fault planes. I understand in real life it is very difficult to determine if two events with high CC are occurring in the same fault plane or not, but the models do not have that problem. The authors can directly say whether these are examples of true repeats or quasi-repeats.

The examples of dikes or fluids with volume increase or decrease, and overshooting are examples of true anti-repeaters. This is great. But they should correlate with the volume increase, or complete stress drop. But other cases, the model suggests that different fault planes are involved and thus are not anti-repeats. This is fine, the model is useful, but I think the authors can do a better work at helping the reader or future work to interpret the waveform polarity reversals with the available tectonic setting information.

Good points to highlight

4) Positive and negative CCs

I think the authors have tried to add to the discussion two things that I would like to see improve but should in any case not be forgotten if a revised version is requested.

By looking only at positive CC or the absolute value, significant information may have been missed in past work. I agree and I think this is a highlight to keep in mind.

The second is that real data might have both high positive CCs as well as large negative CCs. How to decide? Is a simple threshold enough? Probably not.

The results suggest that using multiple components is better. Great.

Second, that sometimes you can have large positive CC and large negative CCs. But here I think the authors should be more thorough discussing how to decide what is a significant anti-repeat. This is a problem people have discussed a lot, called cycle-skipping. Even looking only at positive CCs. So, this is also true, and even more complex when looking at polarity.

It would be good to add some note on the statistics of CC. The CC robustness, or difference between two CC values depends on the length of the time series used. There is a very robust theory of the Z-transform of the cross-correlation and the statistically significant difference between two estimates of CC. Most of the seismology literature has neglected statistics in CCs.

5) Conclusions

Not sure you proved that "we proved the widespread existence of anti-repeating earthquakes". You documented a number of anti-repeating events in various tectonic settings. This is relevant, but you have not proved this.

Line 434 - You make conclusions on true and quasi anti-repeaters, but the definitions are not clear.

The manuscript entitled « Anti-repeating earthquakes and how to explain them » by Simone Cesca and collaborators, is dealing with particular cases of seismic waveform similarity between earthquakes. Repeaters, whose very close waveforms are interpreted as events rupturing the same fault area with the same focal mechanism, have already been relatively extensively studied, whereas only few studies are focusing regarding anti-repeaters. Anti-repeaters are earthquakes with anti-correlated waveforms, interpreted as generated in the same area or very close from each other (referred as true anti-repeaters and quasi anti-repeaters) but with opposite mechanisms.

The manuscript provides a convincing review of the contexts in which anti-repeaters events have been observed and a review of the conceptual models that may explain their occurrence. The aim is to try to explain how reversal focal mechanisms at the same location or neighbouring location can occur alternatively, at different time. Numerous relevant references permit to present the diversity of the contexts in which anti-repeaters have been reported (from volcanic context, including dike intrusion, trapdoor faulting or ring faulting, to intermediate depth seismicity or induced seismicity by injection), illustrated with some examples with a large range of magnitude, time delay, frequency content and context. A review of the conceptual models proposed to explain the occurrence of anti-repeaters allows the reader to understand the phenomenological implications in the case of anti-repeaters detections in different contexts. The authors also discuss the strategy and the methods of detection of anti-correlated waveforms for a large range of magnitudes and instrumental configurations.

Moreover, the manuscript is clear, well-written, easy to read, the arguments are balanced, relevant and well-documented.

I recommend this manuscript for publication as a nice and original review paper regarding an interesting type of observations, still little studied, despite the interest they represent for tracking perturbations of stress in space or time, that can also be considered in some contexts as indicators for potential fluid transfers.

Nevertheless, I'd like to suggest few minor corrections. They are described below :

- Line 29 : References to some repeaters observed in a larger range of contexts than only California or Marmara could illustrate better the variability of the tectonic contexts where they have been studied (e.g. Greece...).
- L. 30 : add a reference.
- Chapter « Observations » : could you provide, for each case, some elements of quantification, if not statistics, regarding the number of anti-repeaters events that were found (considering that it is dependant on the way the waveform similarity is quantified) ? For example, did you find numerous anti-repeaters in each case (e.g. how many anti-repeaters have been found among how many checked events or did they appear to be unusual or sporadic events ?).
- L. 95 : « deep » should be replaced by « intermediate depth ».
- L. 99 : even if it is not essential for the purpose of the manuscript, I would appreciate if a map would have been proposed for the 4 examples (resuming the location/station configuration), as a supplementary material (as soon as a supplementary figure is possible).
- L. 104 : verify the reference to the corresponding network. It would be nice to at least add the name of the network in the text (even though references of the origin of the data sets are present in the dedicated chapter).

- L. 104 : I would appreciate to know where the station is located. Regarding the range of distance (« ~1000 to 2000 »), does it illustrate the distance between the 2022 swarm and the closest available stations, or the stations used in this study ?
- L. 113 : « less than 20 km in depth ». Could you be more precise, or could you give a range of depths ?
- L. 128 : precise « multiple earthquake pairs ». Did you detect similarity among the detected pairs (i.e. can some of them be considered as a family rather than just as pairs) ?
- L. 135 : in addition to quantifying the number of events, it would be interesting to know over what period of time the research was conducted ? Did anti-repeaters occurred in limited periods ?
- L. 201 : the occurrence of strike-slip events and associated anti-repeaters is not introduced as precisely as normal/thrust faulting events was (L. 198-200)). For the sake of uniformity, at least a reference should be added.
- L. 290 : the case of a horizontally-laying hydraulic fracture should be added in Fig. 2
- Chapter « Discussion » : Even if the discussion is well argued and rich, I would have appreciated some details on the portion of anti repeaters in the population of the studied earthquakes.
 - L. 368 : The case of intermediate-depth anti-repeaters is shorter on detail... Moreover, does some anti repeaters were found in other areas (e.g. Vrancea nest ?).
- L. 380 : Some details (e.g. tool ?) on the way the synthetic three-component waveforms were calculated could be added (as a supplementary material for example ?).
- L.385 to 397 : this part would benefit from further clarification for non-specialists.
- L. 415 : « deep » should be replaced by « intermediate depth »
- L. 425 : a space should be erased
- L. 447 : the name of CM and G networks should be detailed
- L. 450 : it should be written : « Résif – Réseau sismologique et géodésique français »
- L. 504 to be deleted
- Tab. 1 : For each case, I would have appreciated to see the number of anti-repeated events detected in the area with those parameters ? Where they unique ?
- Tab. 2 : For each case, I would have appreciated to see the distance events-station
- Tab. 2 : Does a more precise depth is available for the Mayotte events ? Or could you provide an uncertainty value ?
- Figure 1 : few elements about the events could be added after the name of the areas (eg. Magnitudes and distance source-stations).
- Figure 2 : the case of a horizontally-laying hydraulic fracture could be added.
- Suppl. Fig. 1 : They may be a mistake in the name of the station (IVI or FUTU ?).

1 **Anti-repeating earthquakes and how to explain them**

2 Simone Cesca¹, Peter Niemz^{1,2}, Torsten Dahm^{1,3}, Satoshi Ide⁴

3

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9 **Abstract**

10 Repeating earthquakes, or repeaters, are earthquakes with highly similar waveforms
11 resulting from similar locations and focal mechanisms, repeatedly observed at subductions
12 and plate boundaries, with important implications to track fault slip rates, aseismic
13 deformation, slow earthquakes and earthquake nucleation processes. Here, we discuss
14 earthquakes with highly anti-correlated waveforms, denoting a reversed seismogenic
15 process at the same or similar location, referred to as anti-repeating earthquakes, or anti-
16 repeaters. We first report observations of anti-repeating earthquakes in different
17 environments, including volcano seismicity, intermediate depth seismicity and injection
18 induced microseismicity. Then, we review conceptual models proposed to explain their
19 occurrence. **Anti-repeaters** can be robustly identified via a three-component single station
20 or distributed network data. They are key indicators for stress perturbation transients or
21 local stress heterogeneities. Since many observed anti-repeating earthquakes were
22 explained as the response to fluid migration processes, they may also help to identify and
23 track fluid movements in the subsurface.

24 Introduction

25 Earthquakes producing highly similar seismic signals¹ occurring repeatedly at different
26 times are known as repeating earthquakes, or repeaters. Because of their high waveform
27 similarity, repeaters are interpreted as earthquakes rupturing the same fault patch, with the
28 same location and with the same focal mechanism²⁻⁴. Repeaters have been observed in
29 different tectonic environments^{1,3-6} and most notably at different subduction zones, where
30 they are attributed to the repeated activation of asperities along the slab interface. Their
31 analysis and modelling have turned out to be very important to reveal, map and quantify
32 fault slip⁷⁻⁸ and as possible earthquake precursors⁹. Similar seismic events, still showing
33 similar waveforms, but occurring on neighbouring faults or fault segments, are sometimes
34 also referred to as multiplets. Indeed, while ideal repeaters are assumed to affect the
35 same fault area with a similar slip, an exact definition for repeaters and waveform similarity
36 criteria to identify them are still debated¹⁰.

37

38 Consistent with the standard definition of repeaters, we define anti-repeaters as
39 earthquakes occurring at the same, or similar, location but with an opposite mechanism,
40 manifested in highly anti-correlated seismic waveforms. The literature on such phenomena
41 is still limited. The term 'anti-repeaters' has been first used, to our knowledge, for
42 describing such observations at the Bucaramanga nest, Colombia¹¹⁻¹², where their
43 presence was confirmed by similar waveforms with reversed polarities at multiple
44 stations¹². More recently, anti-correlated waveforms have been reported¹³ during the
45 seismic swarm accompanying a magmatic intrusion offshore Mayotte, Comoro Islands¹³⁻¹⁵.

46 However, the reliable direct detection of anti-repeaters is not trivial. Relatively sparse
47 accounts for anti-repeaters might be caused by the fact that most studies applying
48 waveform cross-correlation only use the maximum cross-correlation or reject the polarity¹⁶.
49 When using cross-correlation to improve relative timing information for subsequent relative
50 earthquake location, the rejection can make sense. However, it leads to a loss of relative
51 information regarding the faulting mechanism. Only a few studies¹⁷⁻¹⁸ take into account the
52 minimum correlation that can reveal anti-correlated events.
53
54 Earthquake repeaters should be identified based on certain cross-correlation coefficients
55 and the processing of high frequency signals¹⁰. This ensures that the repeating
56 earthquakes affected overlapping patches. At the same time, it typically constrains this
57 type of observation to relatively small earthquakes. While the same argument would also
58 apply to anti-repeaters, in this work we chose to relax the conditions on the frequency
59 content of the seismic records, adapting them to each considered observational setup. We
60 choose the bandpass filters with the primary aim of preserving a good signal-to-noise ratio,
61 and ensuring that the high frequency corner is below the earthquake corner frequencies.
62 Adopting these smoother conditions implies that not all discussed cases may be strictly
63 considered anti-repeaters. We should thus distinguish among true anti-repeaters, which
64 can be robustly attributed to the reverse slip of the same patch or fault segment, with a
65 difference in location much smaller than the source size, and opposite focal mechanisms,
66 and quasi anti-repeaters, which represent a failure with a reversed focal mechanisms

67 occurring within a small seismogenic volume, but affecting neighbouring faults or fault
68 portions.

69

70 Besides the direct observation of earthquakes with anti-correlated waveforms, there are
71 several reports on earthquakes with reversed or rotated focal mechanism within the same
72 seismogenic volume, mainly concerning volcano seismicity¹⁹⁻²⁴. Following the above
73 definition of anti-repeaters, such reversed mechanisms imply anticorrelated waveforms.
74 Reversed mechanisms are not limited to double-couple focal mechanisms, but have also
75 been observed for moment tensor representations. Reversed moment tensors resolved for
76 different onsets during the 2022 Hunga Tonga eruption²⁴ could correspond to explosions
77 and caldera collapse episodes. Reversed vertical symmetric CLVD sources at
78 Bardarbunga volcano, Iceland, have been interpreted as the reversed motion of a ring
79 fault, accompanying e.g. inflation and deflation phases of the volcanic system²⁵⁻²⁶. In the
80 frame of tectonic processes, focal mechanism reversals have been reported more
81 sporadically and generally attributed to stress changes induced by large earthquakes and
82 overshooting²⁷⁻²⁹. Studies on hydraulic fracturing³⁰⁻³¹ and enhanced geothermal systems³²⁻
83 ³³ commonly observe multiplets or repeating events, but anti-correlated events are only
84 considered in a few studies³⁴⁻³⁶. Finally, it is worth noting that events with polarity reversal
85 within the same cluster were reported for deep moonquakes³⁷.

Starting from a collection of anti-repeater observations in different seismogenic contexts, spanning a wide variety of frequencies, magnitudes and observational setups, we review different models proposed to explain the observation of earthquakes with reversed slip motion. We discuss how to safely identify anti-repeaters (as well as repeaters) by assessing the waveform anti-correlation at multiple stations and/or components. Finally, we discuss the important implications of anti-repeaters.

Observations

The following cases concern volcanic, tectonic, deep and induced seismicity cases (Tabs. 1, 2).

North Mid-Atlantic Ridge

The 2022 swarm at the north Mid-Atlantic Ridge has been described as the result of a shallow magmatic intrusion³⁸, with the consequent activation of normal faulting earthquakes above a vertical dike and a few thrust earthquakes triggered by stress perturbation at the side of the growing dike, with a lateral offset of ~10-20 km. We identified anti-correlated waveforms on three-component recordings of the broadband seismic station G.IVI.00. Given the large distance to the seismic stations (~1,000-2,000 km) and the signal-to-noise ratio, good quality waveform recordings are available only at low frequencies, in the frequency range 0.02-0.1 Hz. The normalised velocity data are compared for two earthquakes of moment magnitude M_w 5.7 and 6.0³⁸ (Fig. 1a and Suppl. Fig. 1).

109

110 **Bucaramanga, Colombia**

111 The Bucaramanga nest is the most dense seismic nest on Earth³⁹. There, an average of 8
112 events per year (with body wave magnitudes larger than mb 4.7)⁴⁰ within a compact
113 volume extending only 5 x 5 km laterally and less than 20 km in depth^{12,39}. Focal
114 mechanisms at the Bucaramanga nest are reported to be heterogeneous¹². Thanks to its
115 compact extension, which grants similar hypocentral locations, and the variability of focal
116 mechanisms, the Bucaramanga nest is well suited to host anti-repeaters. The presence of
117 both repeaters and anti-repeaters at the Bucaramanga nest was indeed confirmed in
118 previous studies¹². Here, we perform a similar search for anti-correlated waveforms and
119 illustrate one case of anti-repeaters (Fig. 1b, Suppl. Fig. 2). The two earthquakes
120 generating these waveforms had moderate magnitudes (mb 4.0 and 4.4) and intermediate
121 depths (~155-158 km). Waveforms are shown after applying a bandpass filter between
122 0.375 and 1.0 Hz.

123

124 **Mayotte, Comoro Islands**

125 The recent volcano-tectonic unrest offshore the island of Mayotte¹³⁻¹⁴, Comoros Islands, is
126 most notably known for the global observation of long-duration long period signals¹³⁻¹⁴ and
127 for the formation and discovery of a newborn submarine volcano¹⁵. However, there was
128 evidence for multiple earthquake pairs with anti-correlated waveforms among the different
129 seismic signals recorded during the unrest¹³. Anti-repeaters at Mayotte (Tab. 1) show

volcano-tectonic signatures, with clear P and S onsets (Fig. 1c, Suppl. Fig. 3); they were recorded at the YTMZ strong motion sensor, on Mayotte island, with a waveform duration of ~8-10 s and a good signal-to-noise ratio in the range 0.4-4.0 Hz. For the reported anti-repeater, we estimated a differential S-P time at the closest station (YTMZ) of ~3.7 s. Due to the small magnitudes of ~3.2 and ~3.0, focal mechanisms have not been estimated⁴¹. A peculiarity of Mayotte anti-repeaters is that they occurred with short inter-event time in the order of one to few minutes.

Äspö Hard Rock Laboratory, Sweden

Observations of anti-repeating earthquakes are not limited to local or regional seismicity. We also identified such event pairs within massive acoustic emission activity (tiny earthquakes, here below M_w -3.5) induced during small-scale hydraulic fracturing experiments conducted in crystalline rock⁴². There, more than 19,600 induced events mapped the opening hydraulic fractures with extents of several metres⁴³⁻⁴⁴. While an inversion for focal mechanisms is difficult due to uncertainties in sensor characteristics⁴⁵, waveform similarity analysis revealed the presence of anti-correlated events/anti-repeaters within spatially and temporally constrained event clusters. The two example events (Fig. 1d) were induced within 6 seconds during an injection phase, in which the hydraulic fracture grew upwards and eventually passed the location of the two events. The absolute event locations indicate a separation of 0.45m, which is well within the location uncertainty of the catalogue⁴³. The anti-repeaters have highly anti-correlated waveforms within a

151 frequency band of 3 to 7 kHz across three sensors at a distance of ~10 m. Example
152 waveforms are presented in Fig. 1d and Suppl. Fig.4.

153

154 **Models**

155 Several physical processes have been considered to explain strong local stress anomalies
156 and the occurrence of earthquakes with reversed or rotated focal mechanisms. Stress
157 anomalies can be temporal or spatial, but temporal ones are necessary for true anti-
158 repeaters. Most of these models concern volcanic and induced seismicity, driven by
159 geophysical processes involving deformation, magma migration and/or fluid transfer.
160 Some, however, involve the effects produced by large earthquakes, and may become
161 relevant in other tectonic settings. For each of the aforementioned processes, the
162 occurrence of anti-repeaters depends on the local stress conditions and in some cases the
163 presence of preexisting sets of faults, fractures or otherwise weak zones with a
164 particular orientation. In the following, we review those underlying physical processes and
165 the most prominent models (Fig. 2) proposed in the literature. In some models, anti-
166 repeaters are controlled by stress rotation due to dike emplacement and growth (Fig.
167 2a,b). In other cases anti-repeaters correspond to reverse motion along pre-existing zones
168 of weakness (Fig. 2c,g).

169

170 **Dike intrusion and growth**

171 Magmatic intrusions can produce strong local stress perturbations and induce seismicity,
172 which vary with time, as the intrusion propagates, thickens, deforms, bends and/or
173 freezes⁴⁶⁻⁵⁰. For instance, emplacements (opening) of magmatic dikes may vary between
174 a few centimetres and more than 5 metres⁵¹. The stress induced by such intrusions (dikes
175 or sills) is spatially heterogeneous. Further differences in seismicity migration and focal
176 mechanisms are suggested if the dike migrates or thickens²¹. For example, a vertical dike
177 promotes extensional stresses above and below it, favouring normal faulting earthquakes.
178 A lateral migrating vertical dike favours strike-slip earthquakes ahead of its tip, and
179 eventually reversed mechanism behind its back tip⁵⁰. A thickening dike can alter
180 compressional stresses on its sides⁵⁰: small dike inflation in the order of 1 m may be
181 sufficient to produce a $\sim 90^\circ$ stress rotation and thus rotated focal mechanisms, as
182 observed at several volcanoes^{19,23,52-55}; such stress perturbation is further promoted in the
183 presence of highly viscous magmas²⁰. The close location of rotated and unrotated focal
184 mechanisms suggests a locally heterogeneous stress field, possibly involving a crack
185 network, rather than a single conduit or crack¹⁹. Something similar happens in the case of
186 fluid injection operations, e.g. accompanying hydraulic fracturing or geothermal
187 stimulation, which is discussed later. In both volcanic and injection induced seismicity
188 cases the stress field is both controlled by background tectonic stresses and the stress
189 perturbations introduced by the emplacement and migration of the dike or pressurised
190 fluid. However, in the case of magma dikes, with average thickness in the order of tens of
191 centimetres or more, locally reaching kilometres of lateral extension⁵¹, the stress

perturbation may overcome the tectonic stresses³⁸; while for fluid injection operations the stress perturbation is limited to a small volume around the injection point.

Fig. 2a,b provides a sketch of a dike intrusion and migration, highlighting the regions of stress perturbation and the focal mechanisms of induced seismicity promoted around the dike. Shallow normal faulting earthquakes often accompany dike migration and are generally observed above vertical dikes⁵⁰. On the sides of the dike the stress perturbation inhibits normal faulting earthquakes, and can sporadically favour thrust faulting³⁸, providing a first model for anti-repeaters, here occurring on different, parallel faults. Anti-repeaters can also concern strike-slip earthquakes, in consequence of spatio-temporal stress perturbations, upon the migration of a magma batch: in these cases, anti-repeaters may occur on the same fault or zone of weakness in the vicinity of the intrusion at different points in time (Fig. 2b).

Trapdoor faults

Trapdoor faults (Fig. 2c) have been proposed for volcanic environments, requiring a combination of vertical deformation, e.g. uplift or subsidence due to the expansion or depletion of a magma body, and shallow faulting⁵⁶. The trapdoor faulting process (Fig. 2c) has been modelled for intruding sills, with a lateral extension equal or larger than their depths. In such cases, the magmatic intrusion can bend and propagate upward, favouring faulting on outward-dipping or sub-vertical normal faults due to the intrusion interaction

213 with the free surface⁵⁷. A focal mechanism reversal on a trapdoor fault could occur, e.g. in
214 response to a later depletion of the magma body. A well described case of trapdoor faulting
215 is found at Sierra Negra volcano, Galápagos, affecting intra-caldera fault in response to a
216 rapid caldera uplift⁵⁸. However, there was no evidence of a reversed motion of the fault,
217 which was so far accompanied by uplift only and behaved predominantly aseismically⁵⁶.
218 Alternating slip along a trapdoor fault, accompanying the progressive failure of the
219 overburden above a large and relatively deep depleting magma reservoir, has been
220 hypothesised to explain the anti-correlated seismic signals at Mayotte¹³ (Fig. 1c). There,
221 the short time interevent among earthquakes producing reversed signals would rather
222 point to an intermittent pressurisation of the reservoir, with upward movement
223 accompanying pressurisation and downward movement following pressure drop, e.g. due
224 to gas release. The focal mechanism of a trapdoor faulting earthquake is close to a vertical
225 dip slip mechanism (Fig. 2c), which can turn into a steep normal or thrust faulting,
226 depending on the fault geometry and whether the deformation involves an uplift or
227 subsidence. Finally, it is worth noting that trapdoor faults can efficiently trigger tsunamis
228 because of their steep fault planes, when they are activated shallow under the seafloor⁵⁹⁻
229 ⁶⁰.

230

231 **Ring faults**

232 A trapdoor fault extending along a curved fault segment or even a circular or elliptical fault
233 (Fig. 2d) is often referred to as a ring fault segment or ring fault^{26,61}. Ring faults are

234 typically formed on top of magmatic reservoirs and can accompany the formation of
235 calderas. A slip along the whole ring fault is described by a vertical compensated linear
236 vector dipole (vCLVD)^{26,61}. Two types of vCLVD have been observed²⁵, characterised by a
237 vertical pressure (P) or a vertical tension (T) axis^{25,62}. These two mechanisms can result
238 from different configurations, depending on the ring fault geometry and the movement of
239 the inner crustal block: the first case (vertical P) can either be explained by the uplift of the
240 inner block along an outward dipping ring fault, or by its subsidence along an inward
241 dipping fault, while the opposite applies for the second case. The mechanism associated
242 with the slip of a ring segment includes double couple and non double couple
243 components⁶¹ and the resulting moment tensor can be potentially used to estimate the arc
244 angle and orientation of the ring fault segment⁶². There are several examples of Mw>5 ring
245 fault earthquakes²⁵, often characterised by slow processes or long rupture durations²⁶,
246 including some sites where a reversed motion has been observed at the time of uplift and
247 caldera collapse, such as at Bardarbunga volcano, Iceland⁶³⁻⁶⁵.

248

249 Besides ring faults, other physical processes, involving fluid flow and/or volumetric
250 changes, have been proposed to explain the observation of vCLVD moment tensors²⁶. The
251 first group concerns fluid transports and net volumetric changes involving
252 expanding/contracting cracks and conduits⁶⁶ as well as mass/volume exchange, for
253 example among a conduit and a sill⁶⁶ or between two magma chambers⁶⁷. Horizontal
254 tensile cracks, activated by quick magma injection or withdrawal, are also modelled by

255 vCLVD⁶⁸⁻⁶⁹. Fluid-driven cracks form and open a factor of 104 slower compared to rupture
256 of shear cracks, and they are expected to close even slower, most likely aseismically⁷⁰.
257 However, a sudden shear failure in the overburden, as observed e.g. in mining
258 environments⁷¹⁻⁷², can still produce the reversed vCLVD mechanism or volumetric
259 components⁷³.

260

261 **Dike-parallel joints**

262 One of the models proposed to explain focal mechanism reversal at neighbouring
263 locations in volcanic environments suggest these may occur at neighbouring locations at
264 the tip of a propagating dike or near dike constrictions²². The model, sketched in Fig. 2e,
265 hypothesises the activation of sub-parallel structures at the dike tip sides. While this model
266 may be questionable when a magma dike propagates within an undisturbed crustal
267 volumes, where fractures at the dike tip are expected to occur along 45° oriented
268 planes^{46,50}, the model could still hold in the case of pre-existing zone of weaknesses or en-
269 echelon structures in strongly heterogeneous stress field, for example due to previous
270 magmatic intrusion episodes, or through the asymmetric failure of solidified magma plugs
271 along magma conduits or channels²².

272

273 **Fluid injection**

274 There are multiple reports on induced microseismic events with opposite failure
275 mechanisms from hydraulic fracturing operations in shale gas reservoirs³⁴⁻³⁶. The authors

report on dip-slip mechanisms with a steep dipping and an almost horizontal nodal plane, which show both normal or reverse fault motions. The observation of these reversed events has been attributed to the presence of hydraulic fractures that alter the local stress field or directly impose additional strain³⁵, causing an opposite sense of slip. The following models require the presence of particularly oriented weak planes and pre-existing faults. In one model³⁵, the opposite slip occurs at shale bedding planes (Fig. 2f). While the opening of the vertical hydraulic fracture ($S_H = S_{max}$, $S_h = S_{min}$) itself is considered as an aseismic process, it may produce shear loading on the weaker bedding planes. As a consequence, events with opposite slip directions can be induced in two configurations (Fig. 2f): (a) on two sites of a single bedding plane separated by the hydraulic fracture or (b) on two closely-located bedding planes at the top and the bottom of the vertical hydraulic fracture, as observed via a clear depth separation for a stage at the Barnett shale^{36,74}. These induced shear events are limited to the vicinity of the hydraulic fracture because no regional shear stress is acting on the bedding planes in this setting³⁶. In the case of a horizontally-laying hydraulic fracture ($S_v = S_{min}$) opening parallel to the bedding plane, the model must be rotated by 90 degrees. Consequently, the additional stress at the fracture tips could produce a micro-graben structure with an opposite slip direction on possibly close-by, nearly vertical, pre-existing natural fractures³⁶.

Overshooting

296 In tectonic environments, a mechanism able to produce a stress reversal and the
297 activation of earthquakes with similar locations and heterogeneous focal mechanisms, can
298 be given by the occurrence of a large earthquake. Indeed, very diverse focal mechanisms,
299 including cases of focal mechanism reversals, have been observed both along transform
300 faults²⁷ and plate subductions²⁸⁻²⁹ after large earthquakes, such as the 1989 Loma Prieta,
301 USA, 2011 Tohoku-Oki, Japan, and 2014 Iquique, Chile, earthquakes. In all these reported
302 cases, event pairs with almost reversed focal mechanisms have been located close to
303 each other, either on the same fault or subduction interface, or pre-existing adjacent faults
304 with slightly deviating orientations⁷⁵. In both cases, this can be explained (Fig. 2g) by a
305 transient reversal of the stress condition, resulting from a complete stress drop and
306 dynamic overshoot²⁸.

308 Discussion

309 In this work we reported several observations of earthquake pairs with anti-correlated
310 waveforms. Our observations are quite heterogeneous. First, they sample very different
311 seismogenic environments, with seismicity either controlled by tectonic, volcanic or
312 anthropogenic processes. Further, the presented case studies concern a broad range of
313 magnitudes, inter-event times, and observational setups. A general conclusion is that not
314 only do anti-repeating earthquakes exist, but they can even be found in very different
315 seismogenic contexts.

316

317 Many of the observations shown in Fig. 1 can be directly explained by the proposed
318 source models, being controlled by spatiotemporal stress perturbation introduced by fluid
319 transfer. For example, parallel normal and thrust faulting at the North Mid Atlantic Ridge
320 (Fig. 1a) have been explained in response to a dike intrusion (Fig. 2a,b), with normal
321 faulting occurring shallow above the vertical dike and thrust faulting occurring at its both
322 sides³⁸. In the case of the Mayotte anti-repeaters (Fig. 1c), the seismogenic process is
323 likely related to the overall depletion of a deep magma reservoir¹³; it has been suggested
324 that pressure fluctuations within the depleting reservoir could promote short-term stress
325 transients in the overburden, accommodated by upward and downward movement of
326 trapdoor fault(s) (Fig. 2c) with short inter-event times¹³. The observation at the Äspö Rock
327 Laboratory (Fig. 1d) is most likely attributed to a local stress rotation induced by the growth
328 of a hydraulic fracture, a small scale equivalent to a dike intrusion (Fig. 2a,b). The
329 observation of heterogeneous focal mechanisms within the compact Bucaramanga nest,
330 including anti-repeaters (Fig. 1b), remains poorly understood¹². However, also in this case,
331 the transient presence of fluids, e.g. through dehydration processes at intermediate
332 depths, may have a seismogenic role.

333

334 For earthquake repeaters, highly correlating waveforms imply that their inter-source
335 distance is smaller than a quarter of a wavelength¹. The same threshold applies for anti-
336 repeaters: in our cases, such a spatial threshold reaches from tens of centimeters to tens
337 of kilometers (Tab. 1). High anti-correlation values and small inter-event distances below or

338 close to the respective quarter-wavelength criterion in all cases (Tab. 1) suggest anti-
339 repeaters. However, to resolve if the earthquakes rupture patches are overlapping, and
340 not just close, frequencies should be chosen high enough¹⁰: such conditions could be
341 fulfilled here for the Mayotte and Bucaramanga cases. Additional information from
342 accurate location might resolves inter-event distances better then waveform similarity by
343 not relying on empirical thresholds and scaling relation. One of those case is the example
344 from the Mid-Atlantic ridge, which is in fact a case of quasi anti-repeater associated with
345 the reverse motion of neighbouring faults³⁸. The physical models compiled in this study
346 also concern both true anti-repeaters and quasi-anti-repeaters. True anti-repeater could
347 occur, for example, along the same ring fault, in consequence of inflation and deflection
348 periods of an underground magma reservoir (Fig. 2d). Conversely, other models, such as
349 the triggering of normal vs thrust faulting above or on the side of a dike, only explain quasi
350 anti-repeaters. We like to point out that the separation of true and quasi anti-repeaters is
351 less critical at this point compared for repeating events, e.g. used to quantify fault creep or
352 predominantly aseismic processes: in both cases, stress transients cause a remarkable
353 change of local stress conditions.

354

355 Since the local stress conditions control the fault motion during an earthquake, a motion
356 reversal along the same fault segment would require a substantial temporal stress change.

357 Should the two reversed earthquakes occur along neighbouring structures, rather than a
358 single one, this would imply either a temporal change of the stress or, at least, a strong

stress heterogeneity in the focal region. Therefore, studying anti-repeaters is important to detect spatial and/or temporal anomalies of the stress condition. In the case of tectonically active regions, the stress anomaly can be due to the occurrence of a large earthquake (Fig. 2g), as found both for transform faults and subduction regions²⁷⁻²⁹. However, in most reported cases, including those occurring in volcanic environments or associated with injection-induced seismicity, the stress transient is rather attributed to fluid migration processes. In these cases, the observation of anti-repeaters provides indirect evidence for the presence of fluid and its migration. This may also apply to the case of intermediate and deep seismicity cases, which are often attributed to dehydration processes, e.g. for the Bucaramanga nest.

The minimum and the maximum of the cross-correlation of two waveforms depends on the frequency content and the chosen time window: higher frequencies, sampling smaller local structures, and longer time windows containing more noise reduce both values.

Additionally, the definition of a (very) high cross-correlation varies across different studies^{10,76}, as does the threshold for which waveforms are considered to be similar⁷⁷.

With a simple synthetic test (Fig. 3), we show that even relatively high maximum cross-correlation values (such as 0.8) can be misleading when omitting the negative part of the cross-correlation function or using the absolute value. Of course, the validity of not considering the negative part depends on the purpose of the study. Still, it is a loss of information that might have hindered broader attention to anti-correlated events/anti-

380 repeaters in the past. For the test, we calculated synthetic three-component waveforms
 381 (up to 4 Hz) for two co-located random double-couple mechanisms based on a regional
 382 velocity model¹³. We choose a geometrical setup that mimics the observational condition
 383 of the Mayotte case: the epicentral distance of the receiver is fixed at 30 km, while the
 384 event depth is randomly chosen from a uniform distribution between 1 and 50 km, as is the
 385 event azimuth relative to the receiver. The component-wise maximum and minimum cross-
 386 correlation values (without allowing for time shifts) are plotted against each other in Fig.
 387 3a. Dark red points in the upper triangle depict a clear correlation with a significant
 388 difference between the absolute values of $CC_{\min}$ and $CC_{\max}$. The lower triangle shows DC
 389 pairs which show anti-correlated waveforms. When considering only single components,
 390 $CC_{\max}$ can be as high as 0.85/0.9, but still $CC_{\min}$ is close to -1. Combining the three
 391 components by calculating their respective means helps isolate (anti-)repeaters more
 392 clearly, while single anti-correlated event pairs can still appear highly correlated (within the
 393 grey triangle). After all, we show that an (almost) perfect anti-repeater could be lost in
 394 favour of a less-well constraint repeater or not recognized at all if omitting the negative part
 395 of the cross-correlation. Additionally, even when considering both parts of the cross-
 396 correlation function, small differences between the absolute values of $CC_{\min}$ and $CC_{\max}$,
 397 which we refer here as differential cross-correlation coefficient, hinder an unambiguous
 398 identification of (anti-)repeaters. When studying both phenomena, we recommend setting
 399 a threshold for the differential cross correlation coefficient depending on waveform
 400 characteristics (e.g. signal duration and frequency). In the example shown in this study, the

401 differential cross correlation ranges between 0.08 and 0.35 (Tab. 1). The synthetic test
402 shows that identifying (anti-)repeaters is possible with only one three-component station.
403 However, single-station analyses might suffer from low signal-to-noise ratios on any
404 component depending on the radiation pattern of the studied earthquake mechanism. If
405 the data is available, repeaters and anti-repeaters should be identified using multiple
406 seismic records from stations around the epicentres since increased azimuthal coverage
407 provides more robust results⁷⁸.

408

409 **Conclusions**

410 In this work we proved the widespread existence of anti-repeating earthquakes, showing
411 highly anti-correlated waveforms in a multitude of seismological settings. Although
412 negative waveform cross correlations have been rarely considered in seismological
413 analysis, we illustrate that several such observations are already available. The reported
414 case studies show a wide variety of environments where seismic anti-repeaters can be
415 observed, including volcanic, tectonic and induced seismicity, as well as shallow and deep
416 seismicity. This implies that anti-repeaters may occur in almost any seismogenic context.
417 The set of reported case studies also concern a broad range of magnitudes, showing that
418 anti-repeating events can span, at least, from microseismicity associated to fluid injection
419 operations up to earthquakes of magnitudes Mw 6.0, e.g. at the Mid Atlantic ridge.
420 Differential times among anti-repeating event pairs are also very variable. In some cases,

421 as, for example, at Mayotte, they occur with short delays in the order of seconds to
422 minutes. In other cases, such as at Bucaramanga, the delay is in the order of years.

423

424 Besides reporting on different observations of anti-correlated events, we reviewed
425 previously proposed models. Both observations and models illustrate the presence of two
426 different scenarios. On one side, there are true anti-repeaters, which affect the same fault
427 or fault segment with a reverse motion, implying a process reversal; these can occur, for
428 example, in the case of trapdoor or ring-faulting in response to pressurisation or
429 depressurization of magmatic reservoirs and conduits. In many cases, however, we
430 observe so-called quasi anti-repeaters, which have a reversed focal mechanism but occur
431 on neighbouring structures. These earthquakes can be modelled, for example by the
432 reversed activation of parallel faults in response to magma dike intrusions.

433

434 Both true and quasi anti-repeaters denote the presence of strong spatial and/or temporal
435 stress perturbations, for example in response to a magmatic intrusion or to a large
436 earthquake. Thus, they can directly be used to detect stress perturbations in space and
437 time. In many cases, especially in the frame of volcanic and induced seismogenic
438 processes, they are directly controlled by fluid transfer. In these environments, the
439 identification of anti-repeater provides valuable information to track underground fluids and
440 their movements.

441

442 **Acknowledgements**

443 We are thankful to all institutes providing seismic data used in this study.

444

445 **Data availability**

446 Seismic data used in this study pertains to the following networks: RA (RESIF-RAP
447 Accelerometric Permanent Network 1995), CM⁷⁹, G⁸⁰. These data are open and available
448 at IRIS (Incorporated Research Institutions for Seismology), GEOFON (GEO-
449 FOrschungsNetz), ORFEUS EIDA (Observatories and Research Facilities for European
450 Seismology - European Integrated Data Archive) and/or the Réseau Sismologique et
451 Géodésique Français⁸¹ web services. Waveform data for the anti-repeaters recorded
452 during the injection experiments at the Äspö Hard Rock Laboratory are available via the
453 data publication⁸².

454

455 **Code availability**

456 All software used in this work is open source. The codes used to generate individual
457 results are available through the contact information from the original publications.

458 Requests for further materials should be directed to S.C. (simone.cesca@gfz-
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695

696 **Author contributions**

697 S.C. coordinated this project, conceived the manuscript and analysed seismological data.

698 P. N. performed the analysis of Äspö data. S.C. and P.N. prepared figures; P.N. prepared

699 tables. S.C., M.S., T.D. and S.I. drafted the manuscript. All authors reviewed the

700 manuscript.

701

702 **Competing interests**

703 The authors declare no competing interests.

704

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708 Figures and Tables

709

710 **Tab. 1: Anti-repeaters parameters**

Case	Difference		Bandpass Filter [Hz]	Dominant frequency [Hz]*	Shear wave velocity in source volume [m/s]	$\lambda/4$ [m]	Anti-CC/CC (mean of 3 components/ stations)
	Time	Space [m]					
Mid Atlantic Ridge	~ 4.5 d	45500	0.02-0.1	~ 0.05	3900	78000	-0.89/0.59
Bucaramanga	~ 3,5 d	11500	0.375-4.0	~ 0.5	4500 (*mantle global)	9000	-0.99/0.67
Mayotte	84 s	~ 600	0.4-4.0	~ 2.5	4000 (*lower crust)	1600	-0.92/0.70
Äspö HRL	6 s	0.45	3000-7000	~ 5,000	3200	0.64	-0.93/0.85

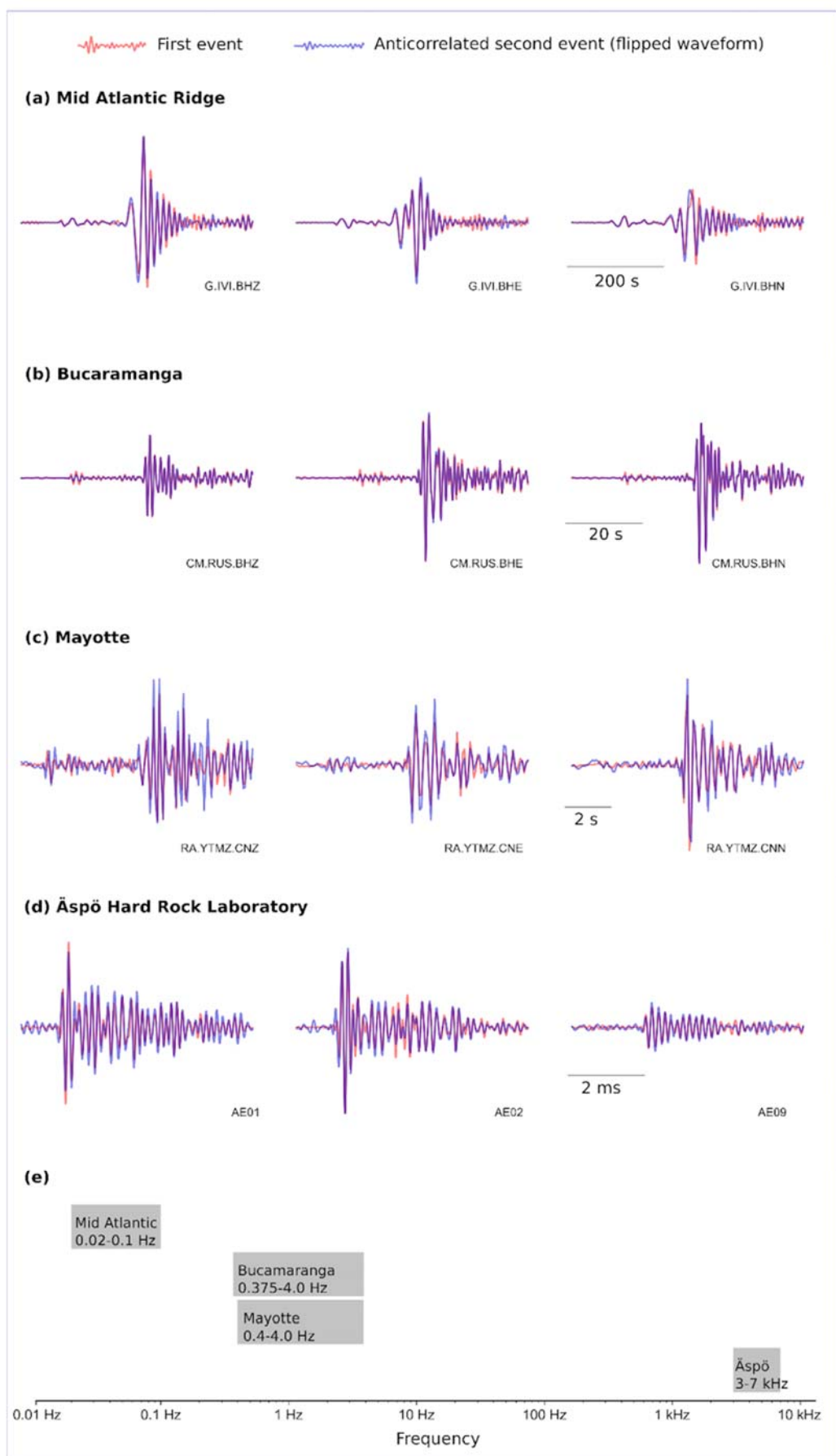
711

712 **Tab. 2: Earthquake parameters**

Date	Time	Region	Lat	Lon	Depth [km]	Magnitude	Reference
2022-09-26	09:59:57	Mid Atlantic Ridge	54.0141	-35.3224	6.3	Mw 5.7	Cesca et al. 2023
2022-10-01	01:18:55	Mid Atlantic Ridge	53.6602	-35.6690	4.9	Mw 6.0	Cesca et al. 2023
2018-08-31	18:21:55	Bucaramanga	6.8262	-73.1078	154.5	mb 4.0	ISC-REV
2020-09-04	04:58:19	Bucaramanga	6.7707	-73.0260	158.0	mb 4.4	NEIC
2018-08-20	21:34:15	Mayotte	~12.80	~45.43	~20	Mw 3.2	Cesca et al. 2022
2018-08-20	21:35:39	Mayotte	~12.80	~45.43	~20	Mw 3.0	Cesca et al. 2022
			X [m]	Y [m]	Z [m]		
2015-06-04	08:50:33.402	Äspö HRL	2402.7	7307.4	405.9	M _{AE} 3.13	Niemz et al. 2020
2015-06-04	08:50:39.482	Äspö HRL	2403.2	7307.2	405.9	M _{AE} 2.49	Niemz et al. 2020

713

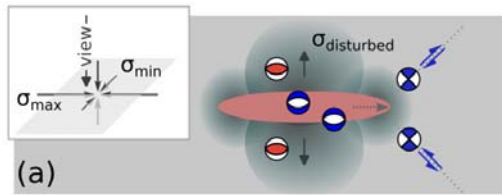
714



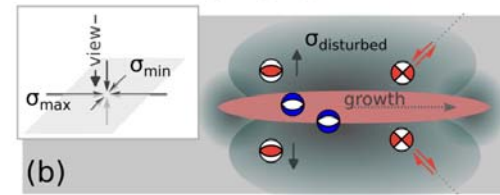
716 **Fig. 1: Examples of anti-repeaters.** Four cases are reported: **a**, Mid Atlantic Ridge, **b**,
717 Bucaramanga, Colombia, **c**, Mayotte, Comoro Islands, and **d**, Äspö Laboratory, Sweden.
718 For each observation we show three sets of traces, for different components or stations,
719 as reported in the bottom right of each plot. Raw waveforms (velocity in **a** and **b**,
720 acceleration in **c**, counts in **d**) are plotted, after applying a bandpass filter (as reported in
721 **e**). In each panel, two waveforms are plotted: the first event in red and the second one in
722 blue, after waveform flipping. Waveforms are normalised preserving the amplitude ratios
723 among different traces at the same site.

Local stress rotation

Dike intrusion



Further dike propagation

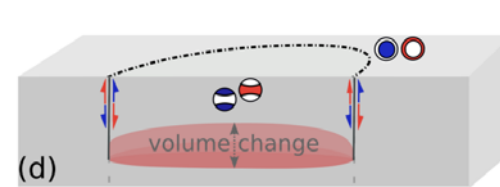


Opposite slip at pre-existing zones of weakness

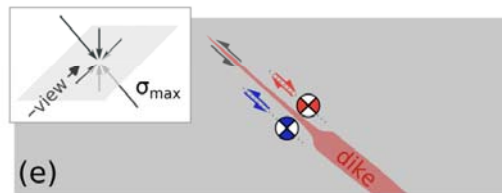
Trapdoor faulting



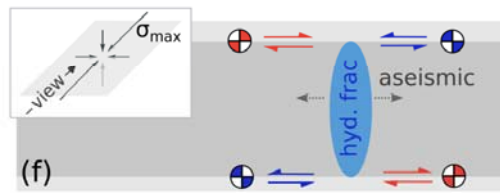
Ring faulting



Dike parallel joints



Bedding planes



Complete stress drop

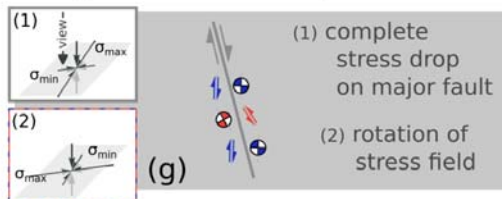


Fig. 2: Proposed conceptual models for anti-repeating events. **a** and **b**, Local stress rotation upon dike intrusion and growth^{19,50}, **c**, Trapdoor faulting⁵⁸, **d**, Ring faulting²⁶, **e**, Dike parallel joints²², **f**, Bedding plane slip³⁵⁻³⁶, **g**, Stress rotation after complete stress drop⁷⁵.

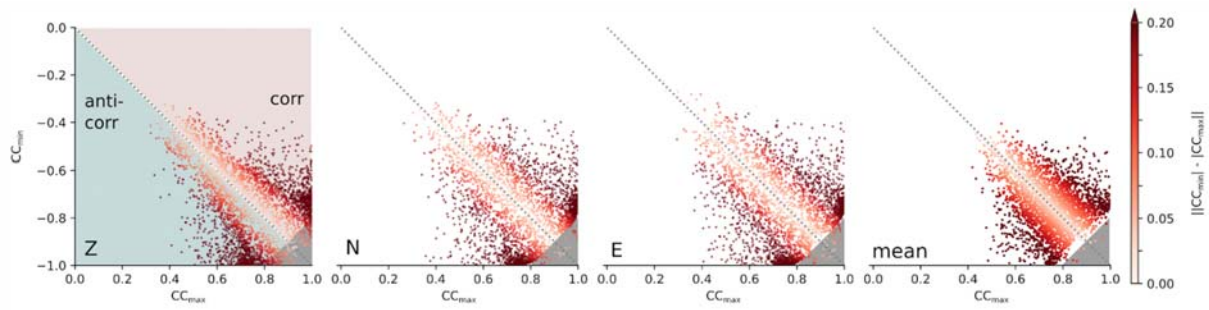


Fig. 3: Synthetic tests. A comparison of minimum and maximum CC for synthetic waveforms of 3000 random DCs randomly co-located at a distance of 30 km around a central receiver. CC_{min} is plotted over CC_{max} for three components and for their mean, colour-coded according to the difference of the absolute values of CC_{min} and CC_{max} . The lower triangle shows events which show higher anti-correlations (larger absolute CC_{min}), while higher correlation (larger absolute CC_{max}) are in the upper triangle. The critical region for the identification (anti-)repeaters is marked by a grey triangle.

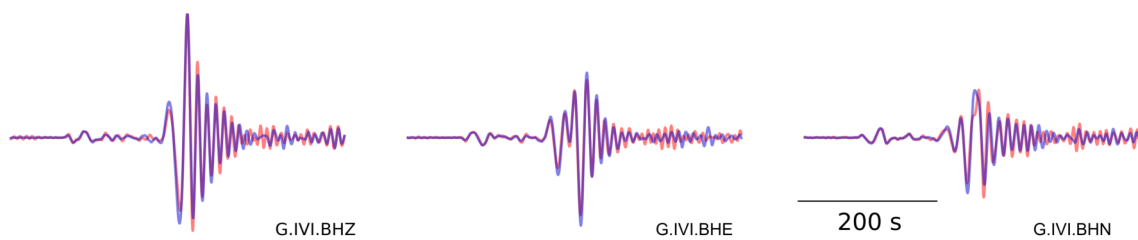
737 **Supplementary Material**

738 The supplementary material includes 4 Suppl. Figs. which complement the main text.

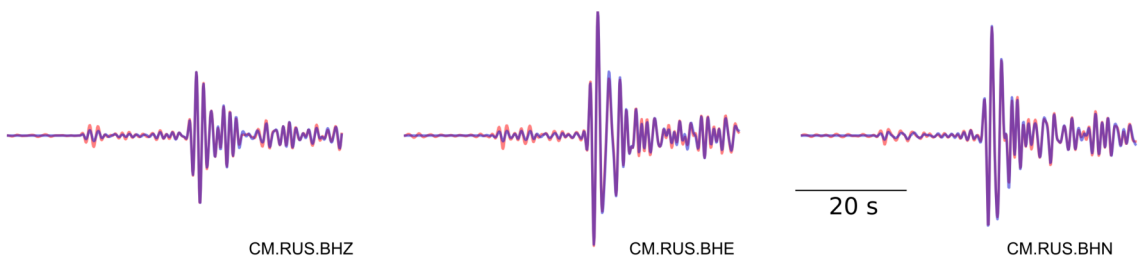
First event

Anticorrelated second event (flipped waveform)

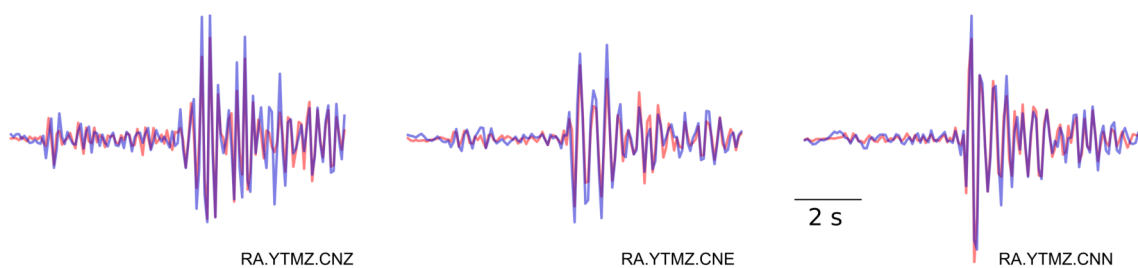
(a) Mid Atlantic Ridge



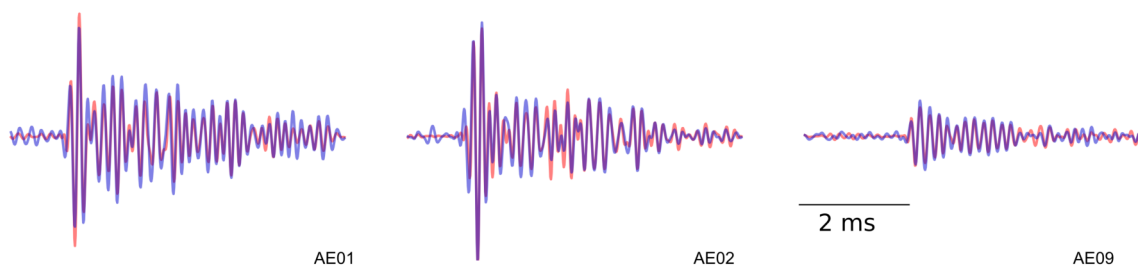
(b) Bucaramanga



(c) Mayotte



(d) Äspö Hard Rock Laboratory



(e)

Mid Atlantic
0.02-0.1 Hz

Bucamaranga
0.375-1.0 Hz

Mayotte
0.4-4.0 Hz

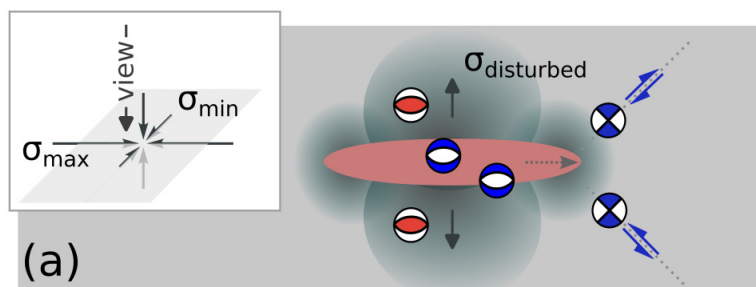
Äspö
3-7 kHz

0.01 Hz 0.1 Hz 1 Hz 10 Hz 100 Hz 1 kHz 10 kHz

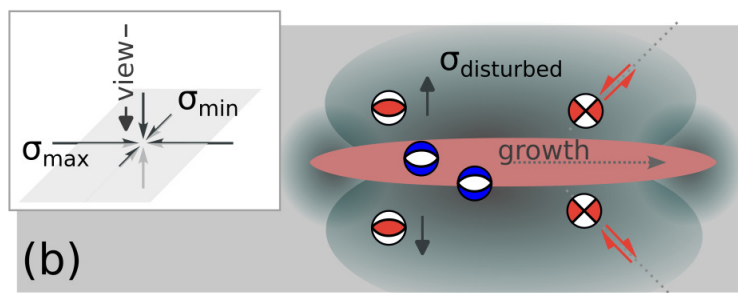
Frequency

Local stress rotation

Dike intrusion

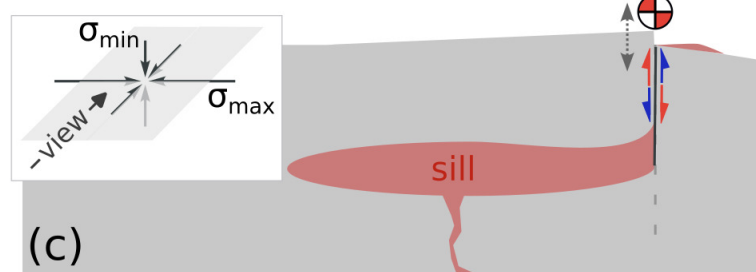


Further dike propagation

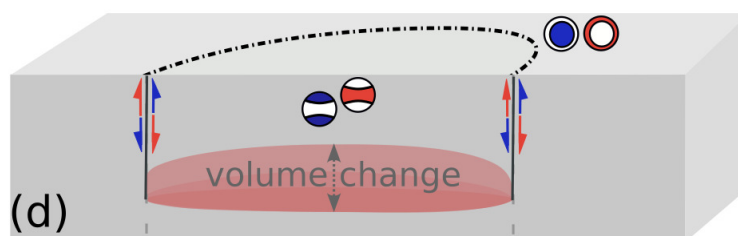


Opposite slip at pre-existing zones of weakness

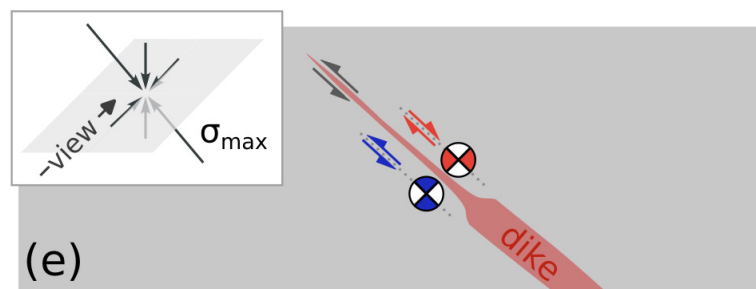
Trapdoor faulting



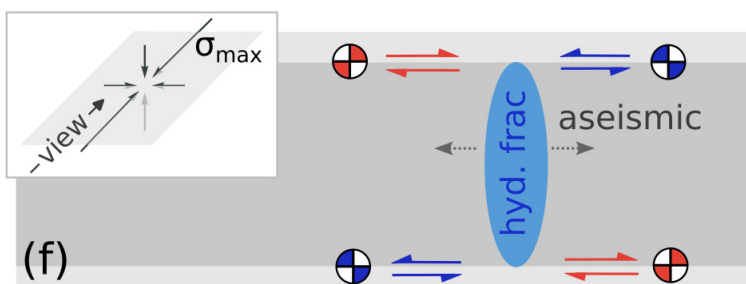
Ring faulting



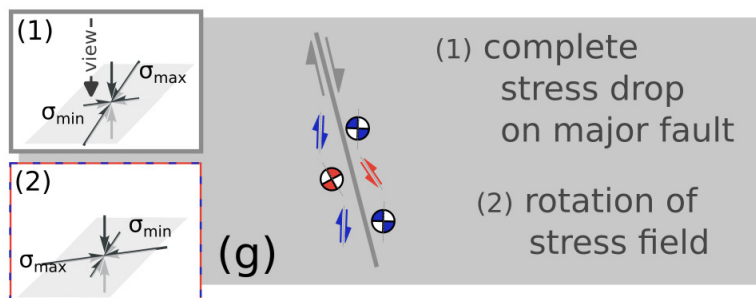
Dike parallel joints

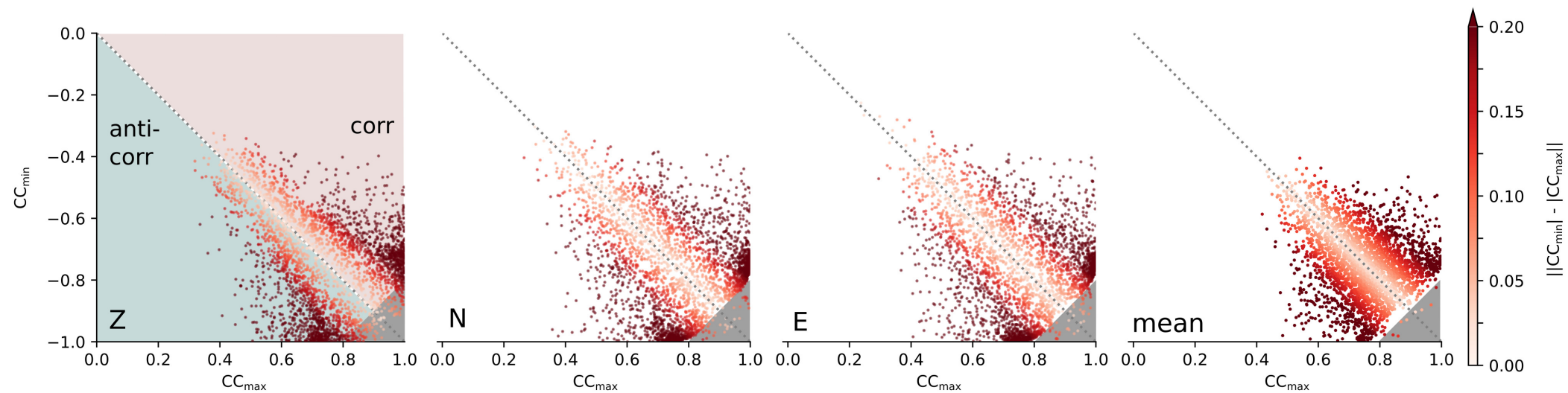


Bedding planes



Complete stress drop





Dear reviewers,

we are thankful for appreciating our work and providing constructive suggestions, which helped to improve our manuscript. We first discuss a few major issues, which raised comments by various reviewers, and then report a full list of point-to-point replies.

1. Definitions of repeaters and anti-repeaters

A first concern raised by reviewers deals with the definition of repeater (and thus of anti-repeater). To account for this comment, we have improved the manuscript by early introducing these definitions. We also clarified the physics-based concept of repeaters as the activation of a common/overlapping patch with same location and mechanism, the potential limitation of a waveform similarity analysis to detect repeaters and the potential use of additional approaches, such as hypocentral relocation to safely identify those. Identifying repeaters is indeed important, e.g. to accurately track slip at plate interfaces.

The same concept theoretically applies to anti-repeaters, too. However, we consider that both what we referred to as true and quasi-anti-repeaters are equally important to be detected, as both reveal spatial and/or temporal stress anomalies. Therefore, as explicitly stated in the manuscript, we relax the condition to detect only true anti-repeaters, and also aim at detecting quasi anti-repeaters. We now reiterate this choice in the introduction and discussion. The two families may be identified as ‘reverse mechanism earthquakes’, as suggested by reviewer #3, but we avoid such a definition, as it hides the spatial vicinity of their hypocenter, which is important for the discussion.

To consider reviewer comments, (i) we introduce anti-repeater and quasi-anti-repeater concepts earlier in the text, (ii) we explicitly define our target as the identification of both true and quasi-anti-repeaters, and (iii) in line with these changes, we also rephrased some concluding statements, clarifying that we proved the existence of highly anti-correlated waveforms in very different seismogenic environments.

2. Review of previous works

Reviewer #2 points out that most of the cited examples come from previous works of the paper author(s). This is true, but there is a clear reason for that. Indeed, the paper was based on our past seismological work, as the repeated observation of anti-correlating waveforms triggered our curiosity. Indeed the manuscript stays in between a scientific and a review paper. We submitted it as a ‘review’ paper, following the editor's suggestion.

Said that, it is honestly difficult to find many references on this type of observation, as they were rarely discussed. We improved the revised manuscript, following the reviewer’s suggestion, mentioning the suggested references and a few more. We broaden the review of previous works discussing either anti-correlated waveforms or reversed focal mechanisms at neighboring locations.

3. Further information on case studies

Some comments ask for additional information on the characteristics and patterns of anti-repeaters in the case studies presented in our work. We extended the information on these observational cases, but we consider that providing further information is beyond the scope of this paper, which we

shaped as a first publication discussing anti-repeaters through selected observations and models. A more comprehensive analysis of these datasets may be the content of future works.

Below we provide a point-to-point reply to all comments (original comments are in black, our reply in blue). We also provide a version of the manuscript with tracked changes.

Simone Cesca (on behalf of all coauthors)

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript entitled « Anti-repeating earthquakes and how to explain them » by Simone Cesca and collaborators, is dealing with particular cases of seismic waveform similarity between earthquakes. Repeaters, whose very close waveforms are interpreted as events rupturing the same fault area with the same focal mechanism, have already been relatively extensively studied, whereas only few studies are focusing regarding anti-repeaters. Anti-repeaters are earthquakes with anti-correlated waveforms, interpreted as generated in the same area or very close from each other (referred as true anti-repeaters and quasi anti-repeaters) but with opposite mechanisms.

The manuscript provides a convincing review of the contexts in which anti-repeaters events have been observed and a review of the conceptual models that may explain their occurrence. The aim is to try to explain how reversal focal mechanisms at the same location or neighbouring location can occur alternatively, at different time. Numerous relevant references permit to present the diversity of the contexts in which anti-repeaters have been reported (from volcanic context, including dike intrusion, trapdoor faulting or ring faulting, to intermediate depth seismicity or induced seismicity by injection), illustrated with some examples with a large range of magnitude, time delay, frequency content and context. A review of the conceptual models proposed to explain the occurrence of anti-repeaters allows the reader to understand the phenomenological implications in the case of anti-repeaters detections in different contexts. The authors also discuss the strategy and the methods of detection of anti-correlated waveforms for a large range of magnitudes and instrumental configurations.

Moreover, the manuscript is clear, well-written, easy to read, the arguments are balanced, relevant and well-documented.

I recommend this manuscript for publication as a nice and original review paper regarding an interesting type of observations, still little studied, despite the interest they represent for tracking perturbations of stress in space or time, that can also be considered in some contexts as indicators for potential fluid transfers.

Nevertheless, I'd like to suggest few minor corrections.

[We are thankful to the reviewer for the appreciation of our work.](#)

- Line 29 : References to some repeaters observed in a larger range of contexts than only California or Marmara could illustrate better the variability of the tectonic contexts where they have been studied (e.g. Greece...).
- L. 30 : add a reference.

[We added references for both comments.](#)

- Chapter « Observations » : could you provide, for each case, some elements of quantification, if not statistics, regarding the number of anti-repeaters events that were found (considering that it is dependent on the way the waveform similarity is quantified) ? For example, did you find numerous anti-repeaters in each case (e.g. how many anti-repeaters

have been found among how many checked events or did they appear to be unusual or sporadic events ?).

We extended a bit the information on each case study. However, a comprehensive analysis and robust statistics are beyond the scope of this overview paper and will be treated in following publications. See main reply #3.

- L. 95 : « deep » should be replaced by « intermediate depth ».

Corrected.

- L. 99 : even if it is not essential for the purpose of the manuscript, I would appreciate if a map would have been proposed for the 4 examples (resuming the location/station configuration), as a supplementary material (as soon as a supplementary figure is possible).

We added 4 maps in the supplementary material.

- L. 104 : verify the reference to the corresponding network. It would be nice to at least add the name of the network in the text (even though references of the origin of the data sets are present in the dedicated chapter).

Corrected.

- L. 104 : I would appreciate to know where the station is located. Regarding the range of distance (« ~1000 to 2000 »), does it illustrate the distance between the 2022 swarm and the closest available stations, or the stations used in this study?

We added a figure in the supplement to show the map. Furthermore, we improved the explanation in the revised manuscript. The range ~1000-2000 concerns the epicentral distances to stations used in the reference paper for relative location and moment tensor analysis. The waveform anti-correlation is shown for station G.IVI.00 (the supplementary figure has been corrected). All events in the sequence, with few exceptions, have either normal or thrust mechanisms with NS orientation. Waveforms are accordingly similar, given that the spatial extent of the swarm is much smaller than the epicentral distances. Waveform correlation and anti-correlation values still depend on the signal-to-noise ratios, which typically decrease with the magnitude.

- L. 113 : « less than 20 km in depth ». Could you be more precise, or could you give a range of depths ?

We now provide two depth ranges, as reported in the literature.

- L. 128 : precise « multiple earthquake pairs ». Did you detect similarity among the detected pairs (i.e. can some of them be considered as a family rather than just as pairs) ?

- L. 135 : in addition to quantifying the number of events, it would be interesting to know over what period of time the research was conducted ? Did anti-repeaters occurred in limited periods ?

We rephrased the text, as we do not aim at discussing the whole statistics of anti-repeaters at Mayotte. This will be a target for future work. For sure, as now mentioned in the text, the anti-repeaters discussed in this study sample a specific spatial cluster, which is active in a limited time frame. This is after the end of the crustal dike migration and in the early phase of reservoir depletion.

- L. 201 : the occurrence of strike-slip events and associated anti-repeaters is not introduced as precisely as normal/thrust faulting events was (L. 198-200)). For the sake of uniformity, at least a reference should be added.

The sentence was improved.

- L. 290: the case of a horizontally-laying hydraulic fracture should be added in Fig. 2

Done

- Chapter « Discussion » : Even if the discussion is well argued and rich, I would have appreciated some details on the portion of anti repeaters in the population of the studied earthquakes.

See our reply to comment #3, in the introduction of this rebuttal letter. We provide now more information in the description of each case study. However, this paper aims at introducing this type of observation (i.e. event with anti-correlated waveforms), but not at discussing their detail or the statistics for each case study, which may be a topic for future works.

- L. 368 : The case of intermediate-depth anti-repeaters is shorter on detail. Moreover, does some anti repeaters were found in other areas (e.g. Vrancea nest ?).

We now provide some more information based on the reference papers, including also one more reference. To our knowledge, there is so far no similar observation at Vrancea or other nests.

- L. 380 : Some details (e.g. tool ?) on the way the synthetic three-component waveforms were calculated could be added (as a supplementary material for example ?).

We provide additional information on the method and tools used to calculate the synthetics in the manuscript.

- L.385 to 397 : this part would benefit from further clarification for non-specialists.

We revised this part of the text.

- L. 415 : « deep » should be replaced by « intermediate depth »
- L. 425 : a space should be erased
- L. 447 : the name of CM and G networks should be detailed
- L. 450 : it should be written: «Résif – Réseau sismologique et géodésique français»
- L. 504 to be deleted

All corrected.

- Tab. 1 : For each case, I would have appreciated to see the number of anti-repeated events detected in the area with those parameters ? Where they unique ?

The information is only available for some of the reference works (e.g. at the North Mid-Atlantic-Ridge) and a detailed study of the other cases is beyond the scope of this manuscript. See also reply to major comment #3.

- Tab. 2 : For each case, I would have appreciated to see the distance events-station

We added this information in Tab. 1.

- Tab. 2 : Does a more precise depth is available for the Mayotte events ? Or could you provide an uncertainty value ?

The reference paper only mentions this rough estimate. The reason is simply that the event was only recorded at the closest seismic station on Mayotte, and the single station location approach provides a poor depth constraint.

- Figure 1 : few elements about the events could be added after the name of the areas (eg. Magnitudes and distance source-stations).
- Figure 2 : the case of a horizontally-laying hydraulic fracture could be added.
- Suppl. Fig. 1 : There may be a mistake in the name of the station (IVI or FUTU ?).

We improved all these figures and/or captions according to the reviewer's suggestions. Suppl. Fig. 1 has been corrected (we erroneously showed the waveforms at another station).

Reviewer #2 (Remarks to the Author):

Review of Anti-repeating earthquakes and how to explain them, by S. Cesca, P. Niemz, T. Dahm, and S. Ide.

This paper describes the phenomenon of “anti-repeating” earthquakes—signals that are highly negatively correlated and thus have reversed focal mechanisms and inverted waveforms. The authors summarize observations of such events seen in a variety of environments and discuss possible mechanisms for their formation. The paper is largely well written and clear, and the topic is important: this is a phenomenon of which the seismological community may be unaware, and this paper will do much to inform them.

[We are thankful for the positive statement that this manuscript makes an interesting and useful seismological contribution.](#)

That said, I have some concerns with the structure of the paper, as described below.

A primary question relates to whether the scope of the paper is sufficient or appropriate. The study describes in detail four examples of anti-repeaters, all of which were described in other studies, which is to be expected in a review paper. However, of the four primary examples, three were first described in papers written by the authors of this manuscript (Mid-Atlantic ridge: Cesca et al., 2023; Mayotte: Cesca et al., 2019; Apso Hard Rock Laboratory, Niemz et al., 2020). This leaves only the Bucaramanga nest as work that was not led by one of this study’s authors. The description of a review paper on the Communications Earth and Environment page states “The scope of a Review should be broad enough that it is not dominated by the work of a single research group, and particularly not by the authors' own work.” Given that there are not a ton of publications on this topic this may be difficult, but the manuscript can clearly be broadened to include other examples. In particular, the authors could expand on the results from the references below, many of which are briefly mentioned in the article:

- Rubin, A. M., Gillard, D., & Got, J. L. (1998). A reinterpretation of seismicity associated with the January 1983 dike intrusion at Kilauea Volcano, Hawaii. *Journal of Geophysical Research: Solid Earth*, 103(B5), 10003-10015.
- White, R. S., Drew, J., Martens, H. R., Key, J., Soosalu, H., & Jakobsdóttir, S. S. (2011). Dynamics of dyke intrusion in the mid-crust of Iceland. *Earth and Planetary Science Letters*, 304(3-4), 300-312.
- Shelly, D. R., & Hill, D. P. (2011). Migrating swarms of brittle-failure earthquakes in the lower crust beneath Mammoth Mountain, California. *Geophysical Research Letters*, 38(20).
- Hotovec-Ellis, A. J., Shelly, D. R., Hill, D. P., Pitt, A. M., Dawson, P. B., & Chouet, B. A. (2018). Deep fluid pathways beneath Mammoth Mountain, California, illuminated by migrating earthquake

swarms. Science advances, 4(8), eaat5258.

• Cassidy, J. F., Balfour, N., Hickson, C., Kao, H., White, R., Caplan-Auerbach, J., ... & McCormack, D. (2011). The 2007 Nazko, British Columbia, earthquake sequence: injection of magma deep in the crust beneath the Anahim Volcanic Belt. Bulletin of the Seismological Society of America, 101(4), 1732-1741.

We illustrated our argument on the extent of the review and the range of the discussed case studies (see reply to major issue #2). This is indeed simply driven by the lack of reports on anti-correlated waveforms. Most previous studies elaborated on flipped mechanisms in close vicinity to each other, which implies similar waveforms but is limited to larger events for which moment tensors or focal mechanisms can be obtained. By discussing flipped waveforms, we can include a broader range of seismic activity. We are very thankful to the reviewer for pointing out these references and we either included new citations or extended them in the revised manuscript.

Because so much of what is presented here was originally done by this study's authors, the manuscript sometimes blurs the lines between what was done in the original studies, and what is being presented for the first time here. For example, the authors state that for the Mid-Atlantic ridge data, "we identified anti-correlated waveforms on...station G.IVI.00". Was that work performed for this study or was in part of Cesca et al., 2023? Further, although it is not clear that any of these authors worked on the Bucaramanga nest, the paper states "here we perform a similar search for anti-correlated waveforms". This makes it sound as if new analysis was done for the present manuscript, but no methods are described (how was the search performed? What parameters were used to identify anti-repeaters?). The only place we have information about methods is hinted in the code availability section which reads "The codes used to generate individual results are available through the contact information from the original publications", which implies that all analysis was performed in the original studies. In short, I am confused by what is new here, and what summarizes existing work.

We apologize as obviously the text failed to clarify differences among new and previous results. We carefully checked the paper and improved the text accordingly.

In each of the four cases presented in this manuscript, the authors present a single example of a reversed pair, even though some of the works describe clusters of anti-repeaters. If the paper is summarizing previously presented work, then it seems that all of the results should be discussed, not just a selected quake/reversed quake pair. If new analysis is to be included, it would be interesting to use the number of anti-repeaters, as well as their temporal patterns to discriminate between the different models proposed within the paper.

We provide some more information on those case studies, but the situation is different case by case. A complete search for anti-repeaters and their statistics in each case study is beyond the scope of this work (see reply to main issue #3).

The authors distinguish between anti-repeaters (true repeaters whose slip direction has reverses), and quasi-anti-repeaters (events occurring proximal to one another with different senses of motion). This is a good and important distinction, as it has implications for the cause of these events. However, there is little discussion of how easily this can be resolved. The paper is clear about the quarter-wavelength rule and why it is useful (where possible) to evaluate similarity at high frequencies, but there isn't much discussion about how often locations are known with high enough certainty to distinguish proximal faults.

We extended this discussion to consider this comment, as well as in reply to comments by reviewer 3 (see reply to main issue #1).

I strongly agree with the authors that there is a need to advertise the presence of these events to the seismological community—if researchers are already looking for multiplets it's relatively easy to search for anti-repeaters as well. I suspect this is a situation in which such events are simply out there waiting to be discovered and observed, and we're just using the wrong tools to find them.

We share this consideration. In this sense our review of case studies is by no means complete, but probably providing just some first example. We added a sentence in this sense in the conclusions.

Comments specific to individual lines follow:

Line 34: Are there examples of studies that refer to events on different faults as multiplets? And as noted above, is their occurrence on different faults confirmed, or is it a question of location certainty?

We added a few references. In general, the term multiplet is used based on the observation of similar waveforms. The assessment of the geometry of activated faults or fault patches differs among references, but in the general case is either not discussed or hindered by location uncertainties. Consequently, we rephrased the sentence, focusing on the waveform similarity aspect only.

39-40: describes anti-repeaters as “earthquakes occurring at the same, or similar, location but with an opposite mechanism, manifested in highly anti-correlated seismic waveforms” This should be clarified—must they have inverted waveforms, or is a reversed mechanism sufficient? This also speaks to the location issue above: if the events are true repeaters (reverse slip on the same fault) we would expect inverted waveforms. But events can reverse mechanism with variability in waveform.

The text has been restructured and modified to reply to major comment #1.

Lines 58 and onward: this is one of the places where the authors use “we” in the context filtering and correlating waveforms, but no methods are shown or described here. If this reflects work done in a previous paper, this should be stated, and the use of “we” should be replaced by a citation to that original source.

We checked and improved the manuscript text to clarify when the analysis/results are attributed to previous works or performed here.

Line 66-68: good to define the concept of quasi-anti-repeaters, but it’s hard to know how easy that is to identify without really robust and high resolution locations.

Correct. The text has been modified following main comment #1, and the definition of true and quasi anti-repeaters is well introduced. With respect to their discrimination, we also improved the discussion and conclusions, mentioning - in particular - the challenges for a robust identification of true anti-repeaters.

Line 73: says that reversed focal mechanisms “imply anticorrelated waveforms”. This may not be the case if the size of the seismogenic volume is large (or the events are not on the same fault).

The sentence was rephrased, also considering suggestions by other reviewers.

Lines 102-103: Another use of “we identified”. Is that this study or the previous?

Rephrased and corrected.

Line 111: while the term “nest” appears to be widely used for intermediate depth earthquake clusters, it is a term with which I was totally unfamiliar. Given that the audience for this paper is likely to be broad, it might be good to add a clause defining this term.

We added one sentence and a reference to clarify the term nest.

Line 115: change “compact extension” to “compact extent” or “compact size” (“extension” may be confused with the stress field).

Line 116 states that the Bucaramanga site is a likely place to host anti-repeaters. This suggests that it is likely to cause anti-reversing behavior, which isn’t obvious. I think it’s more appropriate to say that it is a good place to look for such events (given the small size and variability in mechanism).

Yes. We corrected the text to account for both suggestions.

Line 118 and 119 again state that the authors did a search for anti-repeaters, and they show a single example. Prieto et al., however, show clusters of such events. Is there a reason the authors of this work chose to show a single example? Is there benefit to looking at a larger cluster?

We improved the text and mention now that Prieto et al. found families of events. In the frame of our paper, we think it is sufficient to show one example of anti-repeaters for each seismogenic environment.

Line 133: not sure why the S-P time matters here?

The sentence was rephrased, to make clear how these values can be used to discuss the inter-event separation.

Line 145: Again, it is unclear whether the authors of this study performed the cross-correlation analysis, or if this was done in the original study.

This was done in our study. We clarify it in the text.

Line 150: please define “highly correlated”

To be consistent with the other cases, we do not include quantitative cross-correlation values at this point. We deleted the qualitative statement ‘highly’.

Line 173-174: I’m not sure how this line fits into the discussion here (the use of “for instance” suggests it relates to the previous line, and I don’t see a connection).

Line 175: the phrasing “further differences in seismicity migration” is awkward and unclear.

We removed both sentences.

Line 179: I’m not sure what is meant by the “back tip” of a dike. Does this mean that the dike is propagating in one direction only? And does “eventually” refer to a time when the dike depressurizes and so is under compression? This isn’t clear to me.

We rephrased the sentence.

Line 200 calls these events anti-repeaters, but it sounds like they should be quasi-anti-repeaters?

Line 221: Change “time interevent” to “interevent time”

Both corrected.

Line 227-8: I’m not sure why tsunamis are mentioned here unless it’s to justify the need to search for anti-repeaters?

We removed the sentence.

Line 231 and onward: there’s a long discussion here about CLVDs and their mechanisms. I find the connection between this and anti-repeaters to be hard to follow. I get that this is a situation in which researchers could look for anti-repeaters via reversed CLVD mechanisms, but this seems to be only

briefly touched on here. I think the paragraph from lines 249-259 could probably be cut with no significant loss of information to the paper.

We followed the reviewer's suggestion and we removed the paragraph.

Line 262 mentions “focal mechanism reversal”. As noted earlier, this is important, but it’s not the same thing as full waveform inversion. In general I think the paper would benefit from more clarity between these two perspectives (the focal mechanism can be reversed for some event pairs that are not anti-repeaters).

The model has been proposed to explain reversed focal mechanisms at close locations, which could produce anti-correlated waveforms. We improved the text here.

Line 282 and 290: Abbreviations SH, Sh, Sv, Smin, and Smax are used here but not defined and not used elsewhere in the paper. I think this can be deleted.

Done.

Lines 305-6: These lines discuss triggering of anti-correlated quakes by larger events, and the paper cited describes different mechanisms near the Loma Prieta fault. My reading of that paper is that this results from very low friction and high pore pressure, not from “overshoot” (the topic of the paragraph).

Here we refer to a paper by Ide and co-authors on Tohoku; the reference to Loma Prieta, which was cited as an observation case, is now removed from this section to avoid misunderstandings.

Line 337 again discusses the question of whether anti-repeaters occur on the same fault or not. I think it would be worthwhile to comment on the likelihood that this can be resolved in a given dataset. Some discussion of average location uncertainty would be helpful for readers interested in looking for anti-repeaters in their own datasets.

We agree. The text has been significantly modified here, also in response to other suggestions.

Line 380 and onward: I struggled to understand what was done in this section. I appreciate that correlation coefficients vary significantly with different frequencies, durations, etc., and I’m glad the authors brought this up. But I am struggling to follow the description of the synthetic waveform tests. I think this section needs to be made more clear: what does it tell us if the difference between $C_{\max}$ and $C_{\min}$ is small or large? Note that this could be important for monochromatic signals, where cycle-skipping (or half-cycle skipping) would yield both a high $C_{\min}$ and $C_{\max}$.

We added a sentence at the beginning of this part of the discussion, which is hopefully useful to explain the aim of the synthetic test. We think this part of the discussion concerns a technical, but important aspect of the identification of (anti-)repeaters, which may have contributed to overlook some anti-repeaters in the past.

Line 388: What does DC mean here?

The sentence was rephrased and the acronym removed.

Line 425: need a space between “presence” and “of”

Corrected

Line 457 describes that the code is available via the contact info from the original studies?

We rephrased: codes (and data) used to generate figures in this manuscript are available upon requests to the authors. Codes of previous studies are out of our control, and their availability stated for each case in the relevant reference.

In summary, I think this is an important topic and I'm glad the authors have written this manuscript, but I have concerns about the structure and completeness of the material presented.

You are welcome to include my name with this review:

Jackie Caplan-Auerbach

Western Washington University

We are pleased to do so. We are thankful for the careful and constructive review.

Reviewer #3 (Remarks to the Author):

The paper discusses the evidence of repeating events but with reverse polarity, what they call anti-repeating earthquakes. The topic is interesting and I agree a review paper on these events is warranted, but I think the paper is not there yet, it requires significant work.

Major concerns

1) The definition of an anti-repeater.

There have been a number of recent papers on repeating earthquakes. In particular, a lot of attention has been put into a strict definition of what a repeater really means. I think the definition is these are ruptures on the same fault patch. But how do we define that two events occur on the same patch? Well, earthquake location is one (even relative locations), the size of the fault patch, and the waveform similarity.

The new papers have argued that waveform similarity alone is not an appropriate criteria. The introduction on this contribution is vague in the discussion of the definition of a repeating event. It obviously applies to anti-repeating events. In various places in the text the waveform similarity is used as a criteria, and in other places the patch size and rupture location is discussed. The authors should be very clear about this.

Later in the examples, a more relaxed definition is used, based mostly on waveform similarity. The authors do not discuss earthquake location much, at least not in all examples. And finally, because the determination of similarity is based on a certain frequency range, empirically determined, no discussion about the choice of frequency band is given. For example, given a certain frequency range, and a preliminary velocity model, the wavelength could be discussed and relate it to the eventual patch size or earthquake location uncertainties. None of this is done.

Finally, later in the text, the authors use two definitions, a true anti-repeater and a quasi-anti-repeater. I tend to agree that such terms are fine and needed because of the limited data available, but this needs to be clearly stated in the text.

From my point of view, I think the paper should use the term reverse polarity events, and one special case of those would be an anti-repeater when location, patch size, etc pass a certain criteria. I know the literature has not done this (including myself) but since this paper could be the first to review such types of events, I think being thorough would be nice.

[We recognize this as a major concern and we have elaborated the reply at the beginning of this letter. Please refer to reply to main issue #1](#)

2) The examples

These are nice examples. But I think the examples are solely showing waveform similarity.

Because the case for a repeating earthquake requires not only waveform similarity but being over the same patch, in Figure 1e) , where the authors have the frequency band, can you also add what that frequency band represents in terms of the corresponding size of the patch or wavelength that we are using to correlate the waveforms? In the intro, the authors say they filter below the corner frequency, which makes sense, but how far below.

In fact, if I were to look at the Bucaramanga nest events, with source radii is of the order of 1 km or less for a M5.0, the wavelengths are of that same order? Please show or discuss this.

Since we are interested in both anti-repeaters and quasi-anti-repeaters, we aim at first discuss the waveform similarity. We now also mention the additional information on accurate location in order to assess if the ruptures overlapped. In a couple of cases, location information would suggest quasi anti-repeaters affecting neighbouring or parallel faults. For the other cases, the information on the location is limited and/or location uncertainties larger than the event separation, so that it is not possible to prove if these occur on the same patch or not. We believe this will be often the case also for future observations, in the lack of local dense dedicated networks; we added such a statement in the conclusions. We improved the discussion of each case study as suggested.

3) The models to explain anti-repeaters. Most of the models presented, explain reverse polarity events on distinct fault planes. Some models explain true anti-repeaters, the explanation is needed here.

I think the models presented are the best part of this contribution. They are not new, but are cleverly presented as examples where you would expect reverse polarity events in very close fault planes. I really like that.

But I also think that the models show cases where we are dealing with anti-repeating events, that can be expected to occur in the same fault plane, while in other cases the polarity of the events is reversed but occur in different or distinct fault planes. I understand in real life it is very difficult to determine if two events with high CC are occurring in the same fault plane or not, but the models do not have that problem. The authors can directly say whether this are examples of true repeats or quasi-repeats.

True. We have improved the discussion of the cited models in terms of true and quasi anti-repeaters.

The examples of dikes or fluids with volume increase or decrease, and overshooting are examples of true anti-repeaters. This is great. But they should correlate with the volume increase, or complete stress drop. But other cases, the model suggest that different fault planes are involved and thus are not anti-repeats. This is fine, the model is useful, but I think the authors can do a better work at helping the reader or future work to interpret the waveform polarity reversals with the available tectonic setting information.

We agree that the physical models beyond some of our observations can explain true anti-repeaters, whereas others are explained with quasi-anti-repeaters. Actually, for some processes such as seismicity induced by dike intrusions, both true and quasi-anti-repeaters may occur. We believe this becomes more clear in the revised manuscript, where these concepts are introduced earlier in the text. Additionally, we extended the discussion to illustrate which physical processes can explain both types of observations.

Good points to highlight

4) Positive and negative CCs

I think the authors have tried to add to the discussion two things that I would like to see improve but should in any case not be forgotten if a revised version is requested.

By looking only at positive CC or the absolute value, significant information may have been missed in past work. I agree and I think this is a highlight to keep in mind.

Thanks. We keep this part in the revised manuscript.

The second is that real data might have both high positive CCs as well as large negative CCs. How to decide? Is a simple threshold enough? Probably not.

The results suggest that using multiple components is better. Great.

Also in this case, this aspect remains in the revised manuscript. We tried to rephrase some sentences to make the point more clear to the reader.

Second, that sometimes you can have large positive CC and large negative CCs. But here I think the authors should be more thorough discussing how to decide what is a significant anti-repeat. This is a problem people have discussed a lot, called cycle-skipping. Even looking only at positive CCs. So, this is also true, and even more complex when looking at polarity.

We added a paragraph discussing cycle skipping with references to previously suggested criteria for identifying cycle skipping. We also point out that this problem is present for the event pairs with light red colored points in our synthetic test (Fig. 3).

It would be good to add some note on the statistics of CC. The CC robustness, or difference between two CC values depends on the length of the time series used. There is a very robust theory of the Z-transform of the cross-correlation and the statistically significant difference between two estimates of CC. Most of the seismology literature has neglected statistics in CCs.

VanDecar and Crosson, 1990 use the z-transform and calculate mean, standard deviations and confidence statistics to estimate qualities of relative lag times under the assumption that the cross-

correlation function constitutes a random process. That is convenient but might not be appropriate. A rigorous testing of the significance would require knowing the distribution of CC differences to compare it to, which is not straight forward since the distribution itself again depends on the frequency content and the number of samples of the seismogram. We think that a detailed discussion of this problem merits its own paper and we intend to keep the focus of this study on the observations and possible models.

We use the word significance in the submitted version of the paper which gave rise to the expectation that we intend to calculate a significance based on the assumption of a normal distribution. This was not our intention since we only present example cases to create awareness for the presence of anti-repeating events in seismic sequences. We checked the examples manually.

We added the sample number of the cross-correlated traces in the discussion (~1000 in each example observation) and a short discussion on the influence of waveform length and complexity in the manuscript.

The high sample number assures significance when assuming that the assumption of a normal distribution holds.

5) Conclusions

Not sure you proved that "we proved the widespread existence of anti-repeating earthquakes". You documented a number of anti-repeating events in various tectonic settings. This is relevant, but you have not proved this.

We rephrased the text.

Line 434 - You make conclusions on true and quasi anti-repeaters, but the definitions are not clear.

These definitions are now explicit in the introduction.

Here below we report the comments in the annotated manuscript and our replies.

L. 19. It is important to understand the authors definition of repeater. High waveform cross-correlation is not enough, as recent papers have highlighted.

We improved the abstract and introduce all definitions there and early in the introduction

L. 25-26 This is in fact a poor definition of repeating earthquakes. Highly similar waveforms, yes, but that should not be enough to state that two events are repeaters.

The most recent literature (Gao, Waldhauser) have done an increasingly better job at closing the definition, and have stated that only waveform similarity might be a biased definition or at least incomplete definition.

I just started reading the paper, so not sure how much this definition affects the overall study.

L. 27 This is the interpretation, but in some cases you can do a better job than just similarity.

We improved this section and the whole manuscript. Definitions are given, with reference to recent papers, and the role of waveform similarity and accurate locations described. See also reply to main comment #1.

L. 29-30. Any references for these? Refs 1-8 don't deal with subduction zones.

L. 34. Give examples of people using this definition of multiplets

L. 36. There are more references about this, Gao has two recent contribution and Waldhauser does discuss this as well. They should be added here.

We include references where suggested.

L. 38. I disagree. The standard definition of repeaters, according to Uchida and Burgman is events with identical location and geometry (see abstract). In section 2, they even state that "there is no standard definition of repeaters". Proposed definitions rely on overlapping rupture areas and/or waveform similarity.

L.39-40. This is confusing. What criteria are you going to use? Waveform anti-similarity? Or same or close location? Or both? This is not clear right now, and the text seems to mix these two criteria so far.

We modified this part of the text. See reply to major comment #1.

L. 48. I agree here. This is a good point. In particular because the cross-correlation function can have large positive and negative lobes, in some cases of similar amplitude. Which is taken? Why? See for example the early papers of Peter Shearer where they discuss cycle skipping.

We agree. As suggested by the reviewer in his/her general recommendation on our work, we preserved and improved the part of the discussion dedicated to the importance of considering positive and negative CC values. As for the reference to cycle skipping (e.g. Diehl et al, 2007), there is obviously some similarity with our concern, but the type of application and the overall approach are different, as he mostly focused on single phases and we typically work here with longer windows (1000 samples) containing full waveforms ensuring that the identification of anti-repeaters is robust. Additionally we described and applied a time-idepented criterion suggested by Diehl etal, 2017.

L. 62-63 I would bring this concept above, so that it is clear that you are considering a relaxed view of (anti)repeaters.

In the revised manuscript we introduce this concept earlier. See also reply to main comment #1.

L. 89-90. This may be the key aspect of the paper.

L. 90-91. This, on the other hand, at least from the intro may be the weak part of the paper.

We rephrased the final part of the introduction to account for these suggestions.

L.95-96. The way this is presented is not very nice. Is there a different way of presenting these examples?

We are unsure what is suggested here, and we believe that the other reviewers appreciated this section. The overview of observed earthquake pairs with anti-correlated waveforms in very different seismogenic environments is useful to illustrate different examples and to show how these observations may be done in different contexts.

L. 118-119. Are these stations local? Regional? Teleseismic?

The information on the epicentral distances has been included for all datasets, now also supported by new supplementary figures, in reply to multiple requests by different reviewers.

L. 124. In Figure 1, show the CC values obtained for the three examples. And maybe show an overall CC is you have for a combination of stations. If the authors agree that a criteria is not only one station, but multiple ones, then this can be shown.

Indeed we report the CC values in Tab. 1. These are either obtained using multiple components of one station, or multiple stations. For the specific case of Mayotte, these events were observed with a single station, and signals not recorded at other stations at larger distances because of the weak earthquake magnitudes.

L. 152 Because the case for a repeating earthquake requires not only waveform similarity but being over the same patch, in Figure 1e), where the authors have the frequency band, can you also add what that frequency band represents in terms of the corresponding size of the patch or wavelength that we are using to correlate the waveforms? In the intro, the authors say they filter below the corner frequency, which makes sense, but how far below.

In fact, if i were to look at the Bucaramanga nest events, with source radii is of the order of 1 km or less for a M5.0, the wavelengths are of that same order? Please show or discuss this.

We see the point of the reviewer, although the relevant text is rather some sentences before. We clearly state that the conditions we adopt are less strict than those typically applied to search for repeaters. The consequence, as explicitly stated in the revised manuscript, is that "... these smoother conditions imply that not all discussed cases may be strictly considered anti-repeaters, but some

may correspond to quasi anti-repeaters and, in other cases, a discrimination is not possible based on the available data.”

L. 157-158 Although this is true, please elaborate for the average reader. Saying something like, "if rupture slip direction occurs over the exactly the same patch, a temporal stress ..."

Corrected.

L. 165-168. The cartoons are useful, and the coloring makes sense. But here I would like to make it clear to the reader in which cases rupture would be expected in the same patch, compared to rupture along closeby, but distinct faults. Maybe we cannot differentiate which plane has ruptured seismologically, but the model does make that difference clear.

We agree and we improved the text describing these models, clarifying which model can explain the activation of the same or rather neighboring/parallel patches.

L. 178-179. This is a good example. So , here you might expect normal and reverse faulting on potentially the same fault planes? They would have a distinct temporal behavior right? This kind of discussion of what is expected, can be used in the future for a more clear criteria, and I think this kind of a paper should help the researchers in the future to look into temporal behavior of the anti-repeaters.

L. 203-204 This is something to highlight.

We have modified both these paragraphs in reply to these and other reviewers' comments.

L. 214-217. That is a great example. But something to look for in other settings. Again, I would highlight this.

L. 224-225. Here, again some sort of temporal behavior related to growth and degrowth is potentially useful.

We improved both sentences, as suggested.

L. 246-247. In this case, again, the reverse polarity occurs when net volumetric changes happen?

For sure the reverse polarity occurs during inflation/depletion stages, which are accompanied by reversed volume changes and, typically, by vertical surface deformation of different sign. This does not necessarily implies that the moment tensor would include any isotropic component, as the volume change may occur aseismically: indeed, if we model the extended ring fault as a superposition of shear faulting (double couple) mechanisms along a ring-like surface, the resulting moment tensor would have no isotropic component (but a large CLVD, as often observed in these cases). We have not changed the text here, as the discussion goes too far from the focus of the discussion.

L. 263-264. In this case, anti repeaters occur along subparallel but distinct fault planes?

Correct. We now mention this.

L. 265. hypothesizes?

Corrected.

L. 284. All these at neighbouring but distinct fault planes, right?

Correct. We now mention this explicitly.

L. 304-306. This is a very good example of anti-repeating by overshoot.

We now mention the anti-repeating case.

L. 330-332. I agree this is not understood at all, but which of the models should apply here? How can dehydration be related to this?

We removed the sentence concerning dehydration, as a direct link with the proposed models is missing.

L. 339-341. I think you need to be more quantitative here. There has been significant work done in the last few years on repeating earthquakes, so be more specific. See my comment on Figure 1e.

The entire paragraph has been modified, also considering suggestions by other reviewers.

L. 357-359. This is unclear to me. Some of your models show that a simple geological setting can have opposite rupture in neighbouring faults, without the temporal component. And yes, the stress is heterogeneous but the geological setting is simple.

We modified the sentence and linked it to the proposed models for quasi anti-repeaters.

L. 375. I fail to understand what this figure is trying to say. I understand it is difficult to decide, even with $CC=0.8$ that an event is a repeater versus an anti-repeater because the negative peak might not have been taken into account. But the figure is not a very good example of this. Also, even particular events might have high CC values, with sidelobes that are as large as the main peak in the CC function, so the problems of cycle-skipping need even more careful consideration. This has not been discussed in the text at all.

The figure aims exactly at illustrating that two events may have high positive CC values, and even higher (in absolute sense) negative values. This implies that, if negative CC values are ignored (as sometimes done when discussing repeating earthquakes) these two events may be erroneously considered repeaters, when they could actually be anti-repeaters. We are sure that the figure is illustrative for this purpose. However, we agree that the problem may even be more complex. In the revised version of the manuscript, we added that small differential cross-correlations (light red colours in Fig. 3) can point to cycle skipping. We also added a paragraph on cycle skipping (as described above).

L. 379. I agree with this.

Ok

L. 387-388. Why not show an example trace of the CC function?

We included an example showing waveforms and the cross-correlation function for the synthetic test in the supplement.

L. 398-400. Be more specific. For example: When dealing with repeater/anti-repeater, it is important to set a threshold between the maximum positive CC and the maximum negative CC, such that a robust determination of a repeater/antirepeater is statistically significant ... Three components is available really help ...

We modified the text as suggested.

L. 405-407. It would be good to add some notes on the statistics of CC. The CC robustness, or difference between two CC values depends on the length of the time series used. There is a very robust theory of the Z-transform of the cross-correlation and the statistically significant difference between two estimates of CC. Most literature in seismology has neglected statistics in CCs.

This point was addressed in our reply to the general remarks (see above).

L. 410. Not sure you proved this. You documented a number of anti-repeating events in various tectonic settings. This is relevant, but you have not proved this.

We modified the sentence.

L. 434. You use these two terms broadly without defining them at the beginning.

The manuscript has been significantly improved to account for this issue. The definitions are now given early in the introduction.

L. 456-457. Not sure what the policy of the journal is, but at least the examples could be shared directly, at least the ones showing the waveforms of Figure 1. And maybe the waveforms of Figure 3. But depends on the journal's policy.

All data used are openly available as mentioned in the 'Data availability' section. Here the 'Code availability' is discussed. In our case, this can be only the scripts we used for the preparation of figures, the estimation of cross-correlation and the synthetic test. All is available upon request, as stated. Should the editor consider that these scripts have to be uploaded to a freely accessible repository, we will do so.

24th Jan 24

Dear Dr Cesca,

Your manuscript titled "Anti-repeating earthquakes and how to explain them" has now been seen by our reviewers, whose comments appear below (Reviewer #3 indicated simply that they approve of publication). 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.

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<https://www.nature.com/commsenv/>
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors, Cesca et al., responded convincingly to the comments, questions and suggestions of the reports. The manuscript became clearer, better argued and constructed and it benefits also to some figures improvements. Some clue points were carefully detailed. However, few suggestions were not taken into account considering that they were out of the topic of the manuscript, it is well argued in the rebuttal letter. In particular, it was suggested that the case studies would be more detailed, the authors extended the information on the observations but in a limited extension, considering that to go further would be out of the scope of the paper, which can be considered as review paper regarding a rarely focused topics : anti-repeaters. I consider that their arguments is relevant and that the paper could be published as it is.

I have just a last point to suggest to the authors : regarding the Mayotte case, several papers were published since the first papers cited by Cesca et al. . Mercury et al. (2022) provided revised locations for events occurring in the early period of the unrest and eruption, other papers confirm the fact that most of the Mayotte events occurred under the Moho (e.g. Foix et al., 2021 ; Dofal et al., 2022 ; Lavayssière et al., 2021), and not « deep in the crust » as written by Cesca et al. The description and analysis of the seismic sequence could be refreshed, at least the authors could verify whether the location of the anti repeaters they identify could have been improved by Mercury et al. (2022). As the case studies are described in order to illustrate how anti repeaters can be observed in various contexts, I do not suggest a complete new analysis of the Mayotte case (which would be out of the aim of the paper), but the authors could just check whether, in the focus of their paper, certain new elements provided by recent papers could improve their interpretation of the anti repeaters identified in Mayotte.

However, the paper should be published, it is an interesting review on a little-known subject that

should be of great value to the seismological community.

Reviewer #2 (Remarks to the Author):

This is my second review of this paper and I find the revised version to be substantially improved. I've tried to restrict my comments here to focus on whether the authors adequately addressed the concerns I brought up in the first review, with one or two small edits.

The few comments that I have are minor--a couple of typos/phrasing issues:

Line 90: "similat" should be "similar"

Line 121: Is "NS" north-south? Please clarify.

Line 241: Phrasing is awkward. Maybe replace "can occur in consequence of..." with "can occur as a consequence of..."

Line 463: change "monotonous" to "monotonic"

Line 471: change "data is available" to "data are available".

My only real suggestion for clarity is in the section related to the synthetics. It might be helpful to emphasize the fact that CCmin is a reflection of the negative values, not the smallest correlation. This took me a while to understand, so I was struggling with grasping Figure 3.

Overall, I think the paper has been well revised and I am pleased to recommend it for publication.

Dear reviewers,

we considered the last minor comments in the revised version of our manuscript. Below you find point-to-point replies to those comments.

Reviewer #1 (Remarks to the Author):

The authors, Cesca et al., responded convincingly to the comments, questions and suggestions of the reports. The manuscript became clearer, better argued and constructed and it benefits also to some figures improvements. Some clue points were carefully detailed. However, few suggestions were not taken into account considering that they were out of the topic of the manuscript, it is well argued in the rebuttal letter. In particular, it was suggested that the case studies would be more detailed, the authors extended the information on the observations but in a limited extension, considering that to go further would be out of the scope of the paper, which can be considered as review paper regarding a rarely focused topic: anti-repeaters. I consider that their arguments are relevant and that the paper could be published as it is.

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However, the paper should be published, it is an interesting review on a little-known subject that should be of great value to the seismological community.

Thanks for the appreciation to our work. We followed the remaining suggestion and improved the description of the Mayotte case. We removed the former sentence on earthquakes “deep in the crust”, which actually related specifically to the anti-repeater pairs, and not to the whole seismicity associated to the Mayotte seismo-volcanic unrest. Mercury et al. (2022) does not locate the pair of anti-repeater, but – according to their differential time - they fall in the cluster located closer to Mayotte, the so-called proximal cluster. According to Mercury et al. (2022) the depths of the earthquakes in this cluster are mostly ranging 25-45 km, but they are shallower (4-25 km) at the time of the observed anti-repeater pair.

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We corrected the text at all these points.

My only real suggestion for clarity is in the section related to the synthetics. It might be helpful to emphasize the fact that CCmin is a reflection of the negative values, not the smallest correlation.

This took me a while to understand, so I was struggling with grasping Figure 3.

We improved the definition of CCmin, adding the following statement: "Since we consider the full cross-correlation function, the minimum cross-correlation value (CCmin) is the amplitude of the largest negative lobe of the cross-correlation function, not the lowest correlation."

Overall, I think the paper has been well revised and I am pleased to recommend it for publication.

We are thankful for the accurate, constructive reviews.