Letter to the Reviewers of the Manuscript

A repeating earthquake catalog for Northern Chile

Dear Mathilde Radiguet, dear Blandine Gardonio and dear Reviewer B,

thank you for the careful reviews of our manuscript and your comments. We appreciate your considerations, and in the following, we will give a point to point response to the raised questions and suggestions.

Reviewer A

This article presents a catalog of repeating earthquakes constructed for Northern Chile taking advantage of a recent regional seismicity catalog. The authors used the earthquakes present in the catalog as templates to search for repeating earthquakes in the continuous signal by performing template matching. They detect more 10,637 repeaters grouped into 3,152 families. They categorize these particular earthquakes according to their recurrence times into different families : quasi-periodic, burst, decay, repeated burst or aperiodic.

They also use a relationship to link the magnitude of the repeaters to the slip. In the end, they produce yearly maps of slip rate for the entire zone. Two mega-thrusts earthquakes occurred in this area : the Tocopilla M7.7 earthquake in 2007 and the Iquique M8.1 earthquake in 2014. The authors present how these two major events affected their repeater families.

I found that this paper is very well written and clear. The results can be of major interests for the scientific community working on this section of the Chilean margin. However, I think that the paper lacks important details and that some parts should be further investigated. I think that the relationship that defines magnitude of the newly detected earthquakes must be computed again to be sure that it is well suited for the area. Furthermore, the spatial distribution of repeating earthquakes and the different recurrence types must be presented with more details, especially for the earthquakes detected in a structure in the shallow part of the subduction zone, between -71,5 and -70,5 easting since repeating earthquakes are thought to be on the interface, it is very surprising to see so many groups within the subducting slab.

-> Dear Blandine Gardonio, thank you for your comments.
We have now added a new figure (Fig. S3 in the Supplement) to demonstrate the validity of Eq. (2) for computing the magnitudes of the additionally detected earthquakes. Here, we plot the logarithmic amplitude ratio versus the magnitude difference for all event pair combinations, where both the template and the detected event are included in the original IPOC catalog and the magnitudes are taken from the catalog (these magnitudes are calibrated for the study area, see Sippl et al., 2023b, for details). The fig-

ure shows that the data points align well along the bisecting line, i.e. the amplitude ratios are very consistent with the cataloged magnitude differences, and we conclude that it is justified to use Eq. (2) for computing the magnitudes of the newly detected events. This relatively simple approach works here, because the compared waveforms in our RE case study are highly similar.

We have followed many of your suggestions as specified in detail in the following. Please note that the main objective of this paper is the construction of a high-quality, as complete as possible, repeating earthquake (RE) catalog for Northern Chile, including a description of the methodology applied and the main general characteristics of the RE series. We make the complete list of REs including the calculated parameters available. This will provide a valuable source for continuative studies, as also underlined by Reviewer B. We agree that the analysis of specific features would be very interesting, but we think that an in-depth processing is beyond the scope of this paper, and we prefer to shift it to more detailed, future investigations. We hope you find this acceptable.

Seismicity Data

- I think that the number of station is missing here. I understand that this number fluctuates with time according to the station availability but the minimum and maximum number should be given in this paragraph.

-> Yes, we mention them it now.

- Furthermore, in Figure S1, I think that it would be more interesting to show the station availability according to their latitudes rather than by sorting them with data duration. It will clearly help the reader to see which zones are well covered or not.

-> We have changed the order accordingly.

- It would be nice to remind the reader of the magnitude of completeness of the catalog used in this section, even if the article by Sippl et al., (2023a) is cited.

-> Since we apply template matching to the continuous data, the magnitude of completeness is not so critical for our approach. Yet, of course, it affects which repeater series can be found in the first place. There is no overall M_c given by the authors of the IPOC catalog (Sippl et al, 2023), probably due to its spatial variation. For their earlier catalog from 2018, they give a M_c of 2.7, but this is estimated by Hainzl et al. 2019. The plot of the magnitude distribution of the repeating earthquakes (Fig. 3 in our manuscript) suggests that this value is rather conservative, and the RE series are complete down to smaller magnitudes.

Method

- It is not clear to me why the authors chose to use the entire 180,000 earthquakes from the catalog as templates. My guess is that some earthquakes in this catalog were close by enough to be gathered and characterized by one waveform. This would greatly decrease the number of computation needed for template matching.

-> The main motivation to apply our computationally exhaustive approach was to minimize the potential missing of any repeating events, because this would directly affect the completeness and quantitative analysis of the cumulative slip of the RE series. For RE detection, grouping of catalog events would be restricted to relatively few, very similar events with a cross correlation coefficient cc > 0.95, but even then, temporal variations in station availability, seismic noise and other factors could lead to reducing the detectability. One important and maybe surprising finding of our study is, that almost 50% of the finally detected repeating events were not included in the original catalog, i.e., these events would have been missed if we had restricted ourselves to correlations of the catalog events only, instead of searching systematically the complete continuous data. This also indicates the importance of using the data as exhaustively as possible for RE studies. We have added a corresponding phrase in the manuscript.

- I understand that the chosen criteria for defining repeating earthquakes can be seen as restrictive, namely having both P and S phases, a frequency band of 1-8Hz and a threshold of cc$\geq$0.95. However, could you precise why you chose a pairing at a minimum of two stations and not three ? Having three stations would be of great use to relocate the seismicity in a relative way.

-> That is a good point. We decided to finally accept a minimum of only two stations and not three, because the station spacing of the IPOC network is rather sparse in relation to the mostly small magnitude earthquakes (M$\approx$2-3 and even smaller), and seismic waveform quality and cc-values decrease with distance. To compensate for this, we selected the relative long time windows including both the P and the S wave coda.

- Could you please detail what would be the results in terms of number of repeaters detected and number of families if three stations are chosen instead of 2?

-> The number would, of course, be smaller, but we have not done a detailed comparison. We performed some tests and found a number of minimum 2 stations with a cc$>$0.95 to be the best compromise. We visually inspected the waveforms of the RE groups identified by 2 stations, and did not find erroneously grouped events. On the other hand, when using a cc$>$0.95 criterion on minimum 3 stations, we would clearly miss some repeaters.

This may be illustrated by the RE series 2426 shown in Figure 5 in the manuscript. Here, we can see an extremely regular series (defined by the 2 stations criterion). Magnitudes are always similar (step hight is equal), and the inter-event times increase, until they occur in a regular interval. Only in 2018, there appears to be a too long waiting time. This is because the closest station(s): PSGCX, PB11 have data gaps (Fig. S1). We need to fall back to more distant stations for this event, and here, the cc-value does not meet the cc>0.95 criterion anymore. If we used 3 stations instead, this would be even more often the case, and we would miss significantly more repeating events. Now, we could decrease the cc threshold, but this would include more quasi-REs (adjacent events, but not true REs). Hence, we decided that a minimum of 2 stations is the best compromise for our case study. We have slightly extended this point now in the manuscript.

- The magnitude definition needs some clarification and in-depth test. Equation (2) must be tested with your templates and other earthquakes present in the catalog that they will detect in order to make sure that this relationship is correct. Since the rest of the paper is based on computing the slip with the magnitude, equation (2) should be treated with great attention. You could show the plot of the difference in magnitude between the template and its detections versus the amplitude ratio between template and detection to define the proper amplitude ratio calibration.

-> Please see our detailed response to the general comments above. We have performed the proposed testing and included the corresponding plot in Fig. S3 in the supplement of the revised manuscript.

Results

- It is not clear to me why the authors chose to have a criterion on the Mstd to define the quasi period groups. It has been shown that repeating earthquakes can see their magnitude increasing after mega-thrust earthquakes. I think it would be interesting to see if you still see the periodicity even when removing this criterion on Mstd or not.

-> We decided to follow here the nomenclature proposed by Waldhauser and Schaff, JGR, 2021, and for consistency, we computed this value.

- I think that the classification into different recurrence types is interesting but not really used and presented in-depth in this paper. It would be interesting for the authors to elaborate on when and where the different types occur. Are they found at a particular place of the subduction zone or are they found everywhere ? Looking at Figures S7 and S8 I feel that the burst-type are more frequent before Iquique for example. Could you elaborate on this ?

-> That is definitely interesting, and we think that such an analysis is valuable, but beyond the scope of this article (please see also our reply to your general comments above). Nevertheless, we plot a new additional figure in the supplement, where groups are color-coded by type.

- Also, the authors mention that burst types are found " at shallow to medium crustal depths ", could you add a cross-section to explicit this ? Several groups are given line 176 but they are not labeled in Figures S3-S8 so it is not easy to follow, could you clarify this ?

-> We have included a corresponding new figure in the Supplement to make this clearer (Figure S10 in the revised manuscript).

- In the end, dc label dominates which is not very surprising because of the seismicity context of this area but I think that they might be all located close-by Iquique earthquake. Could you make maps for the different recurrence types ?

-> Yes; please see our new Figure S10.

- In the main text, l. 184, you mention groups 29 and 1669 as rb type without showing any figure to detail your point. Could you elaborate on this ?

-> These series are visible and labeled in Figures S7 and S8. We have added that to the text.

- I think that Figure 6 is interesting but should be discussed in more details. Are there GNSS data to compare with ?

-> We agree. We do not have this data, but we intend to work on this in the future. This could be part of an advanced study which we think is beyond the scope of this manuscript, that is intended to provide for the first time the methodology and construction of a RE catalog for the region and an overview of the main features (please see also the general comments above).

- One lack of this paper is a discussion on the different structures highlighted with the repeating earthquakes in Figure 1 in the cross section view: one in the west and the other one at greater depth where there is a large number of repeaters that are not on the interface. I think it is important to discuss about it and give more details on that.

-> You are completely right, this is highly interesting. Again, we see this subject as worthy of a detailed, separated study, and it cannot be covered in this article.

Figures

- Figure 1 : this figure is not really clear. I think that the color are too dark and it lacks clarity. The colors chosen for the sea should be lighter in order to better sea the points of repeaters. The names of the stations are not very visible either. Same remark for the two cross-sections : the gray dots should be lighter in order to clearly see the dark blue dots. Precise what RES mean in the caption or main text (I assume Repeating Earthquake Sequence). Which slab model is used in this figure ? Could you add the reference ? Could you add the depth contours.

-> We have edited the figure and caption accordingly.

- Figure 3 : Please add the magnitude of completeness for the IPOC catalog.

-> Please see our response to your previous comment on the M_c of the IPOC catalog.

- Figure 4C : the green circle indicates the group clD64 instead of clD62.

-> Thanks! Corrected!

- Figure 6 : Could you add the depth contours and put larger red stars for the Iquique and Tocopilla earthquakes hypocenters ?

-> Certainly! We have done that.

- Figure S1 : could you plot sorted according to the locations instead of the available data to give an idea on the coverage quality ? There is an $'SX'$ in the figure caption.

-> We have done that. Thank you.

- Figures S3 to S8 : it is not clear to me why the authors chose to stack the cumulative slip. It would be correct if the groups where close enough in space as they are indicative of local slip at the plate interface. Either the authors group close RES and stack them or they should show only Figure S7 and S8 with the largest groups.

-> This is a misunderstanding. We do not stack the slip, but we shift each series vertically by an (arbitrary) offset of 20cm slip in order to make them visually distinguishable. We have added an explanation in the figure caption. We have adopted this representation style from comparable previous RE studies, e.g. Igarashi et al., JGR, 2003 (their Fig. 7).

- Figures S9 to S13 : a colorbar is missing

-> We have added the colorbar.

Reviewer B

This paper describes a large-scale data analysis to construct a repeating earthquake catalog for Chile north of 18° latitude. This is appropriately pitched as a valuable resource to aid future investigations, in addition to the initial analysis presented currently. Overall, the analysis seems solid and well documented. I have a few minor suggestions, mostly to improve the presentation, as documented below.

Specific comments:

- Abstract: The first sentence describes that repeating earthquakes occur on the same fault patch, but the analysis as presented doesn't actually impose this constraint, instead relying on waveform correlation coefficients alone. I would suggest removing this from the abstract (or elaborating to clarify) to reduce potential confusion.

-> You are right, we have changed this to '... **are assumed to** occur reiteratively on the same fault-patch...'. Given our relatively strict criteria imposed on the waveform similarity (compare e.g. Uchida and Bürgmann, 2019), we still hold that our detected RE series comply with this general definition of RE. We also tested for some well recorded RE series their locations using differential P and S times and found overlapping rupture areas (using also their stress drops), but we finally did not use the locations as a criterion due to the generally sparse station geometry and deep and offshore hypocenters.

- Method section: can you discuss how merging of families works? I suppose two repeating earthquake families that are initially separate will merge if an event is found that meets the correlation threshold with members of both families? Are there any other subtleties in this process?

-> No, that is exacly it. Each event only has to meet the criteria with one of a given group. Hence, if two groups share one event, they will be joined.

- Figure 1: It's quite hard to see the blue dots offshore on top of the blue bathymetry. I would suggest removing the bathymetric shading or lightening it substantially.

-> We have changed the color scheme accordingly.

- Figure 1: The coastline (solid black line) and country boarder(?) (dotted line), continue outside the map boundary. Please fix.

-> We have done that. However, in case the editor allows, we have now removed the restriction for the background seismicity catalog to show its full extent and highlight that here are no repeaters outside the box boundaries.

- Line 113: what does it mean to "compare well to Mw"? Does this mean the magnitudes are very similar, or that they just scale together? Please clarify.

-> They are very similar, and we use them as 'Mw'. We have changed the phrase accordingly.

- Figure 2 caption: "...each with 30 members..." I guess this should be 20 members?

-> Yes, thanks.

- Figure 4 caption: "The time window (for waveform cross-correlation) starts one second before the p pick..." Please clarify as indicated - as stated it sounds like the plotted time window is being described.

-> Thanks. Indeed, we wanted to describe the plotted time window here. We have changed the caption.

- Figure 5: There's mention of a possible missing event in the caption - perhaps also indicate this in the figure itself? Also, it might be helpful to include a brief discussion of possible missing events and their impact on the catalog in the main text.

-> Accepted. We have also included a brief comment in the text.

- Figures S3-S7: I understand the vertical axis represents total sip for a given repeating earthquake family, but how is the offset between each family set? From Figure S3, I initially thought it was adding up slip sequentially in each family, but from Figure S7 it's obvious that families are overlapping on these plots. Some additional explanation/clarification would be helpful.

-> Reviewer A raised a similar concern (see also our corresponding response above). Only for a better graphical representation, the lines are gradually offset by a value of 20cm slip on the vertical axis. If a series has higher cumulative slip than its plotted neighbor, curves may cross, eventually. We have added a description in the caption of the old Figure S3 (Fig. S4 in the revised Supplement file), accordingly.

- Figures S9-S13: I was initially confused by the caption - it would be helpful to add "size": "Increased-size reprints.."

-> Thank you, we have corrected this.

Additional Changes

Please note that we have made a few changes in addition to the comments by the editor and the reviewers.

- The most important change is the integration of the recent data from the year 2024. We have already agreed on that with the editor. This update affects all numbers and figures, but does not change any interpretation.
- The template matching was performed using a passband of 1-4Hz not 1-8Hz, as stated earlier.

We hope that we have answered all your questions satisfactorily.

Best regards
Jonas Folesky, Jörn Kummerow & Rens Hofman