Comment on cp-2021-103

Anonymous Referee #1

Referee comment on "Abrupt climate changes and the astronomical theory" by Denis-Didier Rousseau et al., Clim. Past Discuss., https://doi.org/10.5194/cp-2021-103-RC1, 2021

We thank Reviewer 1 for his comments. Our replies are in blue below.

In this manuscript, Rousseau and colleagues present a small review of millennial scale variability in the North Atlantic, with a particular focus on DO events. They use recurrence plots to determine the main transition times in the past 3 million years, and also to link millennial scale variability in the last glacial period to Bond cycles.

The review section is unexpected in CP, but could make sense as a contribution for this special issue. I have no major comments on that section and will leave this to the editor.

> *Although the title of the manuscript is "Abrupt climate changes and the astronomical theory," we didn't intend to submit a complete review paper on the astronomical theory, which is the object of the entire Special Issue. Instead, we just wanted to sketch the evolution of ideas on the specific aspect of abrupt climate changes through a selected subset of papers, while injecting some of our own thinking and recent results. Such a selection cannot be entirely devoid of personal preferences.*

On the research side, the use of recurrence plots to identify specific transition is an interesting approach. The advances presented are not very substantial when compared to standard CP papers;

> *Our paper is a contribution to the CP Special Issue dedicated to the celebration of the centennial of MM's 1920 book. As such, this paper is based on the invited presentation given during the centennial symposium and is part of a series of papers on the detection of abrupt transitions by using two distinct but complementary methods: a modified Kolmogorov-Smirnov (KS) method and the recurrence plot (RP) method used in the paper at hand.*

in my second major comment I suggest some aspect that could be fleshed out a bit. My main problem with this manuscript is the seemingly arbitrary way in which the transitions in the recurrence plots are determined (see major comment below). I wonder if the results are robust against small changes in parameter selection. I would like to see a sensitivity analysis before I recommend publication of this manuscript.

> *Thanks to Reviewer #1 for pointing out this important issue, which was not included in the original manuscript. Following their recommendation, we have performed a recurrence rate (RR) analysis, which corresponds Reviewer #1's request for a sensitivity analysis. The results were plotted along with the original recurrence plot. The plotted values correspond to the mean for different window lengths ranging from 1 kyr to 15 kyr. The selection of the transitions of interest relies therefore on the definition of a threshold that we choose to be the standard deviation of RR prominence, which is 0.089 for the U1308 benthic $\delta^{18}O$, 0.127 for the U1308 bulk carbonate $\delta^{18}O$ and 0.173 for NGRIP $\delta^{18}O$. The modified figure is attached to this reply and will be included in the final manuscript if the paper is accepted.*

Major comments:

- The choice of transition in the recurrence plots is not explained or justified. In line 166

and 167, the authors refer to Eckmann et al., 1987 and Marwan et al., 2013 to determine "sufficiently close". That is not acceptable, as a publication should include all necessary information to replicate the results. The authors should explain in detail what choices they made to produce the red lines in the recurrence plots.

We agree with Reviewer #1 that just referring to these papers — while necessary and useful to the reader unaware of the recurrence analysis literature — is not a sufficient explanation of the choices made in identifying the abrupt transitions we discussed. To explain these choices, as mentioned previously, we have performed an RR analysis using different windows, and plotted the mean values under the recurrence plot. The minima of the RR plot correspond to the abrupt transitions of interest and applying the RR prominence analysis, we determined the major rapid changes to be discussed. They are marked on the figure by pink crosses. The statistics of the RR minima are given in a new table, also attached to this reply and to be included in the final manuscript, if accepted.

An emblematic example of this problem is Figure 4. Looking at the recurrence plot in figure 4b I see no justification for the line at 32 kaBP, it seems very arbitrary. The same goes for the line at 78 kaBP; between 70 and 78 kaBP there seem to be three more transitions that could reasonably have been drawn. The question arises about the sensitivity of the results to small variations in the parameters of the algorithm chosen to identify transitions. An uncertainty/sensitivity analysis needs to be added for each RP.

See above. The RR analysis allowed us to refine the dates of the major transitions previously identified in the original manuscript. Concerning NGRIP $\delta^{18}O$, the RR analysis has identified 7 major transitions (RR prominence above the standard deviation highlighted in yellow in the new table) and 6 more could be considered in the discussion (RR prominence close to the standard deviation in highlighted in green). This leads us to remove the former lines at 32 ka and 78 ka, which correspond to minima with an RR prominence that is too low compared to the standard deviation; see the new table attached. Between 70 and 80 ka, the RR analysis identified one major transition at 72.3 ka, and two minor ones at 74.2 and 76.4 ka, respectively.

The sentence in line 305 is unclear. Are the authors defining new GIs based on the recurrence plot? If so how are they defined?

No, we don't define new GIs based on the recurrence plot.

If instead they are talking about the GI numbers in Figure 4a, which ones do they mean? There are several numbers in each interval defined by the red lines. I think the authors may have missed an opportunity to make a clear contribution here.

We have rephrased the sentence using the results of the RR analysis. Still, the longest GIs from the NGRIP $\delta^{18}O$ record are labeled in the upper panel of Figures 4 and 5.

This paragraph is the only one of the chapter that appears to be more than a review, and the relationship between GI duration and sea-level is very interesting. A scatter plot of sea-level (or sea-level trend) vs. GI duration would make their point much clearer and add a bit more results to this chapter.

We have redrawn Figure 4: first by presenting it in a format similar to Figures 2 and 3, i.e., with the original record in the upper panel (a), the recurrence plot in the middle (b), and the recurrence rate

in the lower panel (c), with the pink crosses identifying the selected minima with a prominence threshold higher than the standard deviation. Moreover, in Figure 5 we changed the RR curve to the global mean sea-level curve to argue in favor of our hypothesis of longer GIs being linked to "stable sea levels". Thank you for these very constructive suggestions.

Minor comments:

Lines 12-13: "relatively" used twice in one sentence

Changed "relatively short time" to "rather short time"

Line 16: "constant" is the wrong word here since these are periodic variations. Maybe "regular"?

OK, changed; thank you.

Line 98: It is unclear what "those" stands for in the second part of the sentence. I imagine it must refer to the shorter periodicities mentioned in the first part? Please clarify.

"Those" here refers to "transitions". We have changed "those" accordingly.

Line 99: I'm not sure "affected" is the right word here. Maybe something like "the frequency of abrupt changes is in part modulated by…"

We have changed the sentence as follows: "We show that abrupt climate changes are still resulting, albeit indirectly, from changes in insolation and […]"

Line 131-132: As I understand this sentence, it now says that during the late Pliocene the ice sheets over Greenland and Scandinavia were larger than during the Quaternary. That is not the message of the Naafs et al. 2013 paper. Please clarify.

Sorry for this statement's lack of clarity. Indeed, ice sheets over Greenland and North America were not larger during the late Pliocene than during the Quaternary. The sentence should read instead "Naafs et al. (2013) report the occurrence of minor IRD events attributed mainly to Greenland and Fennoscandian glaciers, indicating that the ice sheets over these regions were more prominent than during the later Quaternary, when North American ice sheets were considerably larger"

Line 141-143: Yes, but Barker's record starts at 800 kaBP without any information about the occurrence of millennial scale variability before that. I think it is important to make clear that we don't know if millennial-scale variability (i.e. DO events) started during the MPR or not.

We have corrected the sentence, which reads now as follows: "At about the same time, the synthetic Greenland $\delta^{18}O$ reconstruction — which starts, however, at 800 ka — indicates the occurrence of millennial variability expressed by DO-like events (Barker et al., 2011)."

Line 154-155: This sentence is too vague, as ice sheet extent was very large also during MIS6 and LGM. It also doesn't convey much important information. I suggest rephrasing it or deleting it.

We have rephrased the sentence as indeed the southern edge of the NH ice sheets reached, during MIS 12 and 16, a position similar to that reconstructed for MIS6. Indeed, the Batchelor et al. (2019) reconstructions show that the Laurentide (LIS), Eurasian (EIS) and Greenland (GIS) ice sheets had

areas that were fairly similar during MIS 16, 12, 6, and again the same values during MIS 2 for LIS and GIS (Batchelor et al. 2019 Suppl. Data).
The sentence reads now as follows: "During the interval 1 Ma – 0.4 Ma, Northern Hemisphere ice sheets reached a southernmost extent during MIS 16 and 12 that was similar to the one reached during MIS6 (Batchelor et al., 2019)".

Line 184: I think it would be helpful to explain in one or two sentences what a "drift topology" is here, with deeper insights being referred to Marwan et al.

The end of the sentence explains what the drift topology relates to. In fact, this is a particular pattern introduced by the Eckmann et al. (1987) paper cited above. However, we have updated the sentence as follows: "recurrence analysis shows a drift topology (Marwan et al., 2007) that characterizes a monotonic trend in time,[…]".

Line 186: Please refer to Figure 2a at the end of this sentence already.

Done.

Line 196-197: This sentence seems unnecessarily complicated. I suggest "Our analysis further identifies the steps at 0.9 Ma, 1.25 Ma, and 2.75 Ma (with 1.25 step also noticed in the $\delta^{18}O$)."

We have corrected the sentence following Reviewer #1's suggestion.

Line 204: The sea-level change increased since the value of the change is not higher

Correct, thank you. We rephrased the sentence as follows: " After 1.25 Ma, the sea level changes increased to about 70–120 m below their present day values,"

Lines 208-211: That is only true for the glacial maxima. The glacials themselves have all kind of different orbital configurations due to their long duration.

Correct, thank you. We rephrased the sentence as follows: "The "Milanković glacials," which correspond to the odd marine isotope stages determined in the U1308 core and in many others, have maxima that are characterized by low eccentricity and obliquity,.."

Line 221: You could reference Figure 2 here since it's the same plot.

No. The paragraph relates to IRD and therefore we must refer to Figure 3, which shows the recurrence plot of the bulk carbonate $\delta^{18}O$.

Lines 224-225: Not every cold period is a Heinrich Event.

We agree with Reviewer #1's statement, which is consistent with our manuscript's sentence that "The former are manifested by IRD events, some of which are significantly stronger, and represent the previously mentioned HEs and correspond to massive discharges of icebergs into the North Atlantic." Hence we keep the sentence as it is.

Line 261: In the text above, the "canonical" DOs were those described by Dansgaard.

We rephrased the sentence as follows: "[…] all the canonical events described by Dansgaard et al. (1993) and identified in Rasmussen et al. (2014),…"

Line 333: "event" is included in HE. Please provide a definition separating HEs from regular IRD events.

*We have removed "events". HEs are defined previously in lines 224-225 and IRDs are defined line 118, where we added after ice-rafted debris "*continental detrital material eroded by the ice sheets,"

Line 350: "prevailed" may not be the best word choice here. How about "existed"?

"Prevail" is correct English but maybe less familiar, since Reviewer #1 doesn't like it. So we accept the suggestion.

Line 354-355: It's not clear what "these results" refers to here. I'm guessing the authors mean the relationship between sea-level and GI duration? Please clarify.

We were referring to the 0.9 Ma or 1.5 Ma dates. Therefore, we have rephrased the sentence as follows: " Whether a younger start date of 0.9 Ma or an older one of 1.5 Ma is posited, these dates show that the Northern Hemisphere ice sheets played a significant […]"

Line 368-373: This mechanism was already posited by Shaffer et al. in 2004 (https://doi.org/10.1029/2004GL020968)

Thank you for mentioning this reference. The model of Shaffer et al. (2004) did propose already that ocean subsurface warming during the DOs may be at the origin of ice rafting events, due to ice shelf melting and break up. However, these authors did not model the Northern Hemisphere ice sheets, which are the iceberg providers. We repeat here their conclusion, as follows: "Clearly, more simulations with more comprehensive models and more high-resolution paleodata are needed to test the proposed mechanisms for coupling of DO cycles and ice rafting events. For example, a better understanding of ice sheet–ice shelf dynamics is needed, not only to predict the future of the Western Antarctic ice sheet (Oppenheimer, 1998], but also to better interpret past climate variability". This is exactly what Ziemen et al (2019) did by modeling the evolution of the Northern Hemisphere ice sheet dynamics during HEs as a two-stage mechanism described in much greater detail and comparing with proxies in a way that Shaffer and co-authors did not do." This is the reason that we wish to maintain our description of the state of affairs.

Figure 1: In paleoclimatic sciences and in this manuscript as well for most of the figures, the "Age" scale on the x-axis increases in values towards the right. I would advise the authors to either flip the figure around to make it consistent with the rest of the figures, or to use "time" instead as an x-axis with negative numbers if you want to keep the present on the right side.

We have homogenized all the x-axes of the figures; thank you.

Figures 5 and 6: x-axis has again been reversed, please flip the figure around or use "time" with negative numbers.

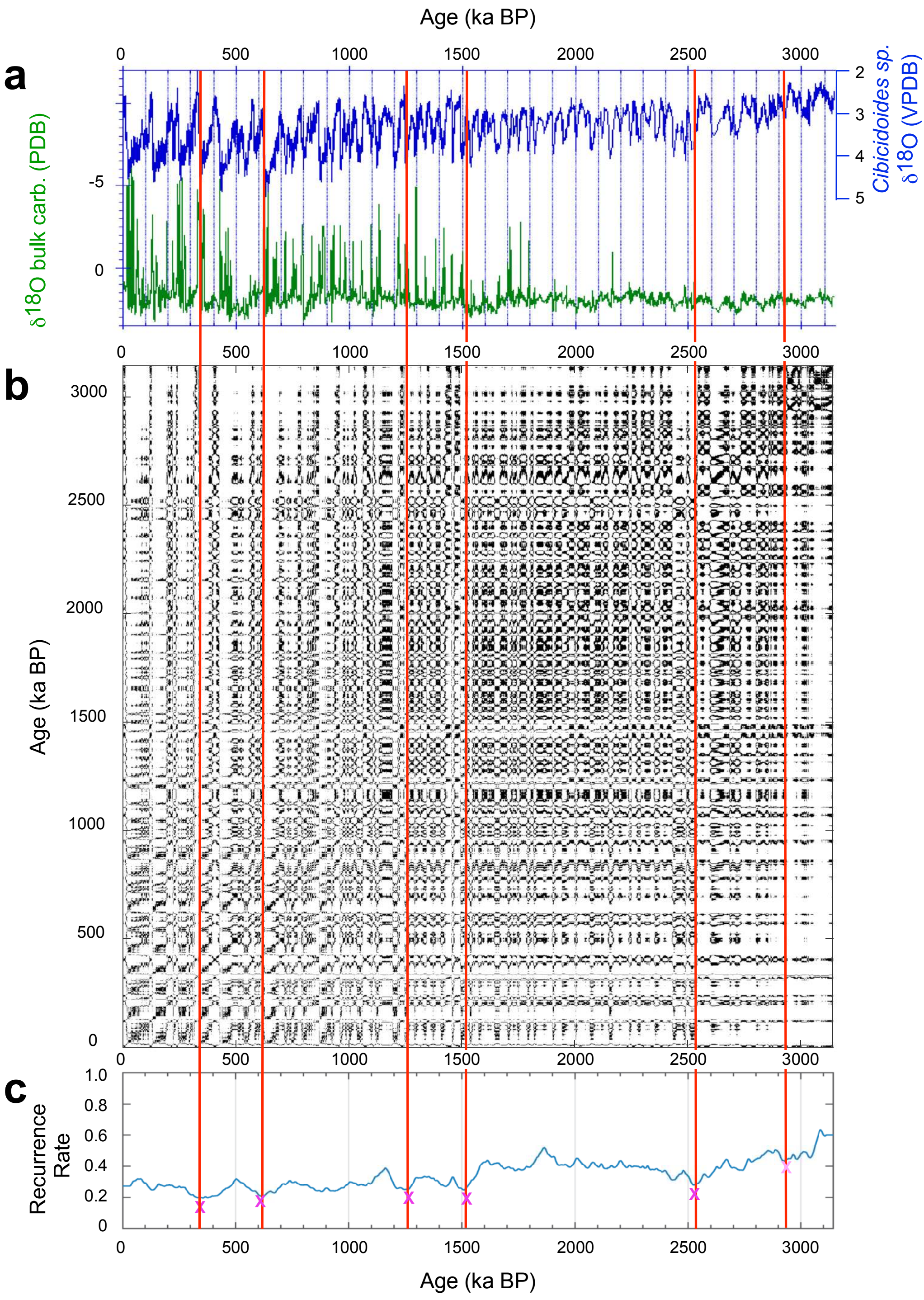
Done; thank you.

Table 2: "Last" is already included "LGM".

Corrected.

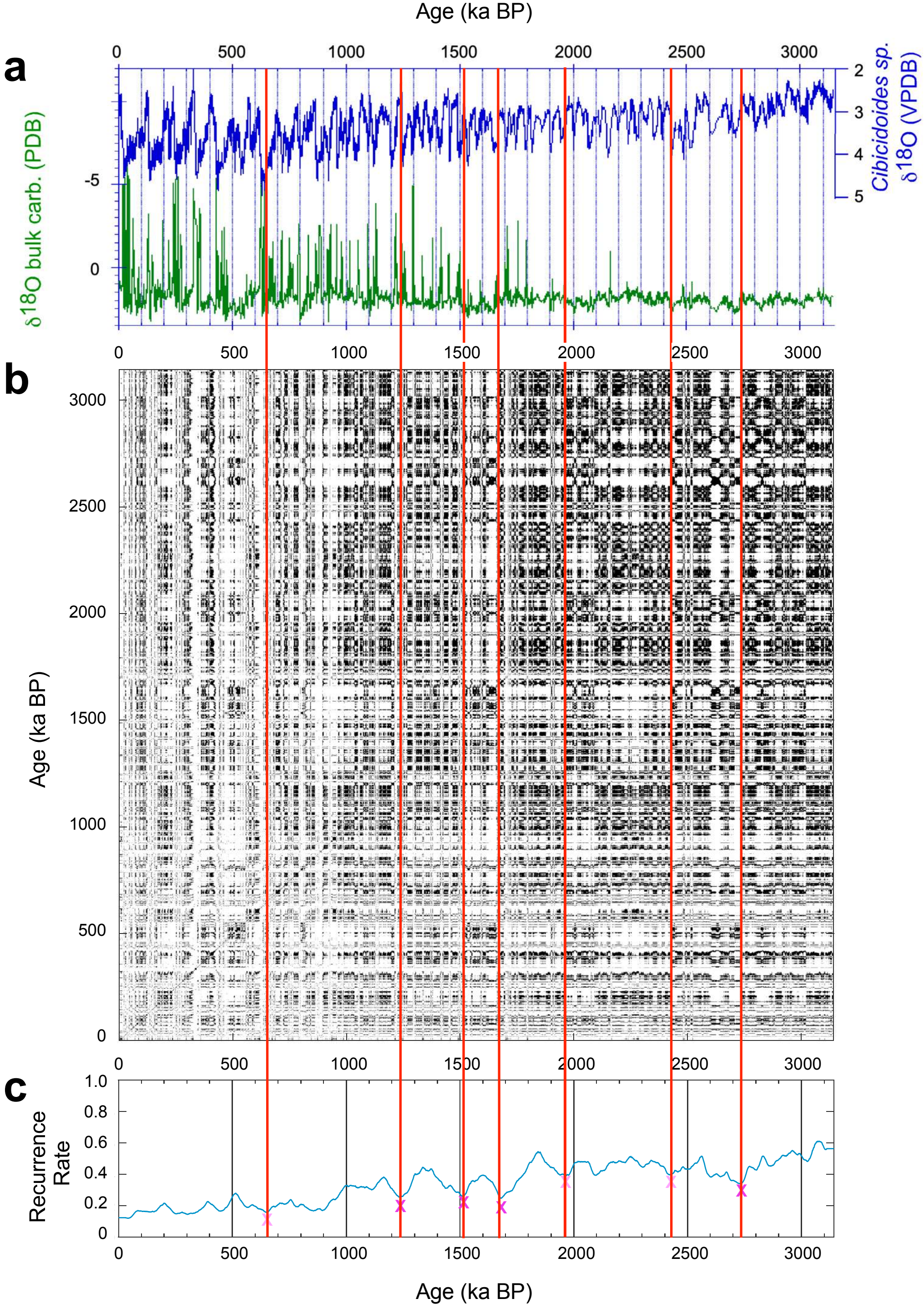
revised Fig. 2

Recurrence U1308 benthic $\delta^{18}0$

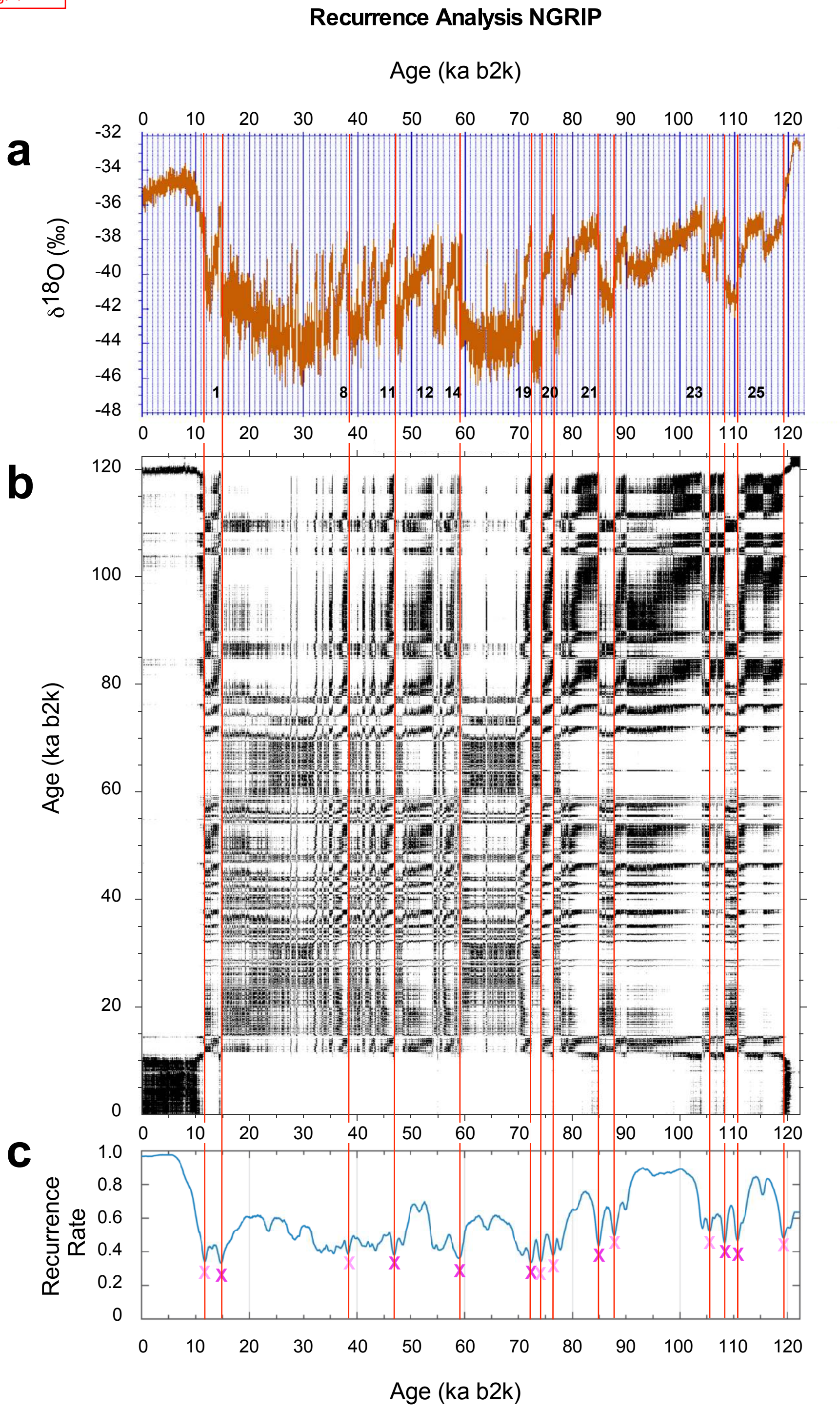


revised Fig. 3

Recurrence U1308 bulk carbonate $\delta^{18}0$



revised Fig. 4



New table with RR statistics

U1308 d18O window: 60-250 ka		U1308 bulk carbonate d18O window: 60-250 ka		NGRIP d18O window: 1-15 ka	
ka BP	RR prominence	ka BP	RR prominence	ka BP	RR prominence
2524	0,237961909	2732	0,203635512	14,8	0,568283951
1510	0,141692156	1681	0,19748231	108,3	0,395308193
354	0,123972802	1510	0,134913563	72,3	0,360963901
614	0,111549228	1234	0,127527323	84,9	0,322903841
1248	0,086921423	1966	0,124987183	58,9	0,257118924
2925	0,070682017	653	0,122240332	47	0,237895536
879	0,070551594	2421	0,117588056	110,7	0,206818254
2741	0,069641012	2095	0,088280537	87,8	0,16889445
1736	0,066365778	856	0,071821212	119,3	0,152040996
1428	0,06113048	303	0,070869172	74,2	0,130837523
2430	0,059878276	3026	0,069861461	38,3	0,129318102
1975	0,056834027	2865	0,064225819	76,4	0,124855727
2141	0,050670749	447	0,06097431	105,5	0,101968333
132	0,039569208	2304	0,044156783	11,7	0,098720815
3041	0,037467965	2605	0,03210594	115,5	0,096423259
2054	0,037279365	1112	0,028449744	55,4	0,092962617
2984	0,0297718	2802	0,023338937	43,5	0,088814624
1073	0,023585616			28,4	0,085818524
				64,3	0,081859835
				23,6	0,079906839
				35,6	0,078988928
				77,8	0,068334382
				104,2	0,059038137
				33,3	0,047249467
				51,6	0,046485061
				70,7	0,045081655
				89,9	0,044750327
				95,3	0,042344854
				48,6	0,0386483
				41,5	0,02814942
				54,5	0,021946771