Title: Towards the systematic reconnaissance of seismic signals from glaciers and ice sheets - Part A: Event detection for cryoseismology
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General statement, in reply to Part A Reviewer 1:

We're very grateful for the thorough review, and we'll pay close attention to providing clarification on the detailed points that are raised. With regard to the overview intentions of our Part A and Part B contributions (respectively, catalogue generation and event reconnaissance) we see that it will be important to make small additions or rewords some parts of the abstract and introduction to make it clear that our approach has a distinct innovation, in that it takes a 'catch-all' approach to events, and noise bursts, within the seismic wavefield as a whole. Hence, we deliberately don't pre-select the events we wish to have in the catalogue as implied by some of the R1 comments. We instead capture the vast majority of events (broadly defined) and event-like noise bursts that occur (Part A); and then undertake a reconnaissance of these using unsupervised learning (Part B). Given that this workflow differs to some previous literature, we see that we need to more clearly outline the thinking behind our approach, and we're of course happy to do this.

We note that Part A R2, Part B R1 and Part B R2 all returned very positive reviews, so we're encouraged that our approach is likely to be of high utility.

Below, the R1 comments are copied in grey. Author Comments continue in blue.

This manuscript present a new algorithm to detect seismic events. The method is based on the classical sta/lta detection method. It runs the algorithm using a wide range of time windows (tSTA and tLTA) to build a hybrid detection function. This method allows to detect a wide variety of seismic signals covering a huge range of signal durations (0.1 - 10000 s).
We (the authors) confirm that these overview statements are correct.

The method is applied to a dataset from the Whillans Ice Stream. However, this manuscript does not provide new information on the source of these seismic signals.
The purpose of the m/s under discussion, Part A, is event detection specifically designed to capture seismic events and event-like noise sources in the difficult case of the glacial environment, it is not our aim in this part to investigate the source of the signals. Part B examines the source of the signals, so we refer the reviewer to this second contribution. We're very sorry that this key piece of information wasn't evident to the reviewer at the outset (although it is mentioned later by the reviewer in a positive light), and we we'll accordingly add an improved explanation (as per the general statement above).

Most possible "stick-slip" events are already known (Pratt et al, 2014) and their correlation with tides has already been extensively discussed.
Yes, we agree. We are presenting a semi-automated workflow across the Part A and Part B contributions, hence, we show that the new workflow concurs with previous work where the signals were manually identified and analysed.

I am rather disappointed by this paper. First, it is purely methodological with no result on glacial processes.
As noted previously, the purpose of the m/s under discussion, Part A, is event detection, it is not our aim in this part to investigate the source of the signals. Part B examines the source of the signals, so we refer the reviewer to this second contribution. See also the general statement – we're happy to outline more clearly the general thinking behind our approach.

The method could also be applied in many fields of seismology (landslides, volcanoes, ..) that also exhibit a large variety of seismic signals. It could thus better fit in a journal on seismology.
The glacier environment calls for analysis of the widest range of signal types, which is why we developed the 'Part A' algorithm for glaciology, further, the Part A followed by Part B workflow demands that the journal is focussed on glaciology. We agree that we could explain the application to a wide range of signal types more clearly, and will accordingly clarify our existing explanation.

Second, I am not fully convinced by the advantages of the method compared to other methods. The main advantage is to automatize what many researchers do by trial and errors.
The advantage of this method is that it produces a 'catch-all' event catalogue. It automates the process for many signal types and is scalable to large datasets, with repeatable results. In contrast, a trial and error approach could only be attempted for a small number of signal types over a modest dataset, further, a trial and error approach would not be so repeatable/consistent if/when carried out by different analysis over different seasons. We agree that we could emphasise the benefit of repeatability more strongly, and will accordingly add an improved explanation.

Many researchers adapt the time windows of the STA/LTA methods (Short and Long Time Average of seismic energy) in order to detect most events that can be observed by eye when looking at seismograms and spectrograms, while simultanouesly decreasing the rate of "false detections", ie, anthropogenic and environnemental noise, teleseisms or other types of events different from what they look for. But I think that this first step of looking at seismic data (on a small subset of the dataset) is essential to discover different types of events and to select signal of interest.
We agree that the data analysis should progress to extracting the signals of interest. We do this in Part B, aided by an unsupervised learning approach to expand the range of signals that can be identified. We hope that our proposed clarifications as above (general statement, and pointing the reader to Part B) will make this clearer.

Also, the method only considers two parameters (tSTA and tLTA) but does not discuss the other parameters: the minimum ratio of short and long-term energy used to define an event and the frequency band.
Our experience is that varying the parameters mentioned results in a full catalogue. We are happy to add a note in the discussion section on this point.

I guess the authors do not filter the data, while it could be an efficient way to remove noise events and to detect weaker events by selecting the frequency of interest and where the signal/noise ratio is largest.

We do not use conventional frequency-based filtering, because we are searching for events across a range of frequencies. In preliminary investigations, we also found that conventional frequency-based filtering often led to artificial event detection with our method. We do, however, pre-process the data by taking the Euclidean norm of the three-component amplitudes such that weaker signals are able to be captured by the algorithm. We are happy to add a clarification on this point.

I feel that the method allows to detect more events but most of these events are maybe noise, such increasing the work of event classification, which is the most difficult task.
We agree that we now capture many noise-like events. This is an advantage in the glacier environment, because many such signals have an ice-related source. We are happy to add a clarification on the advantage of this point. We agree that event classification is important, hence the workflow that we demonstrate in Part B.

I believe that a simpler STA/LTA method with well chosen parameter could be almost as efficient than the proposed multi-STA/LTA algorithm, while reducing the number of "false detections". At least, the authors need to demonstrate that their method detects more events but without increasing the fraction of false detections.
We take a slightly different approach, and are deliberately building a catalogue that does include a variety of signal types. The process of associating events across multiple stations ensures that only a very small number of truly spurious events enter the catalogue, although we agree that there could be a small number of co-incidental event associations. We are happy to add a clarification on this point.

The multi-STA/LTA algorithm is compared with the standard STA/LTA method, but only for the two extreme models (very short or very long time windows, l232). Why not using all models or the average model?
We compare the multi-STA/LTA algorithm with one short and one long STA/LTA model to demonstrate the benefits of the catch-all approach over individual applications of the standard approach, which are not typically averaged.

The manuscript is often hard to read and understand, many points should be clarified (see minor points below).

The manuscript stops when things could start being really interesting.
It is indeed a great shame that Part B wasn't seen by this reviewer at the outset. We hope that the concerns that arose have been addressed in response to previous comments.

What are the newly discovered "stick-slip" events? Why were they not detected before? Are they weaker than the others or do they have a different waveform? Could you try to locate these new events?
We agree that this information is hard to find. We include in the Electronic Supplement further descriptions for how the Stick-slip and Teleseism labels were verified by analyst (event_detection_for_cryoseismology/labelled_catalogues/README.txt). For the ease of access, we've copied that description below:

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There are 146 events in the prototype catalogue labelled by analyst (RL) as
stick-slip.

Of the 146 events, 136 fall within an assumed 30-minute duration of previously
identified start times (Pratt, 2014), labelled 'STICK-SLIP, PRATT14 '. The
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remaining 10 events have been hypothesized as stick-slips by an analyst during manual appraisal. These are labelled ‘STICK-SLIP, PRATT14, additional.

Our assessment of whether an event looks to be stick-slip is based on the expected rupture propagation shape shown previously on the Whillans Ice Stream (Pratt, 2014). From the literature, we can expect “three separate pulses of abrupt ice velocity change during a slip event, each corresponding to the passage of a rupture front” (Pratt, 2014). These temporally-correlated ruptures are referred to as Rupture 1, Rupture 2, and Rupture 3 in descriptions below.

Of the 136 STICK-SLIP, PRATT14, 3 events that fit the requirement of occurring within Pratt, 2014 events do not correspond to visualisable ruptures. Event 20101227T172108Z potentially occurs during a third stick-slip, but it is not verifiable because of the occurrence of a coincident low-frequency event. Events 20110119T154436Z and 20101222T154843Z trigger on and off before the initial stick-slip rupture, so are likely stick-slip related but not an actual stick-slip rupture-type event. However, due to temporal correlation, we keep these 3 events in the STICK-SLIP, PRATT14 label.

For the remaining rupture-type 133 STICK-SLIP, PRATT14 events, 50 events occur during Rupture 1, 42 events during Rupture 2, 26 events clearly encompass at least Ruptures 1 and 2, and 15 events are recorded more than once in the catalogue.

Of the 10 ‘STICK-SLIP, PRATT14, additional’ events, 6 events have uncertainty in the assigned stick-slip label upon further examination. Event IDs 20101221T040052Z, 20101221T180558Z, 20110109T145339Z, 20110122T012709Z, 20110125T004320Z, 20110126T205028Z have coinciding teleseisms and/or other low-frequency signals that confused the seismogram and spectrogram review during the manual appraisal.

For the remaining rupture-type 4 ‘STICK-SLIP, PRATT14, additional’ events, 2 events are during Rupture 1, 1 event is during Rupture 2, and 1 event clearly encompass at least Ruptures 1 and 2. The stick-slip start times that we would contribute as additional to the Pratt, 2014 catalogue are:

Start time (i.e. ref_time in UTC)	Related event ID (Rupture #)
2010-12-15T02:02:38.887027Z	20101215T020238Z (Rupture 2)
2010-12-19T06:23:36.107027Z	20101219T062336Z (Rupture 1)
2011-01-18T21:12:15.817027Z	20110118T211215Z (Rupture 1)
2011-01-19T00:50:15.682027Z	20110119T005015Z (Rupture 1)

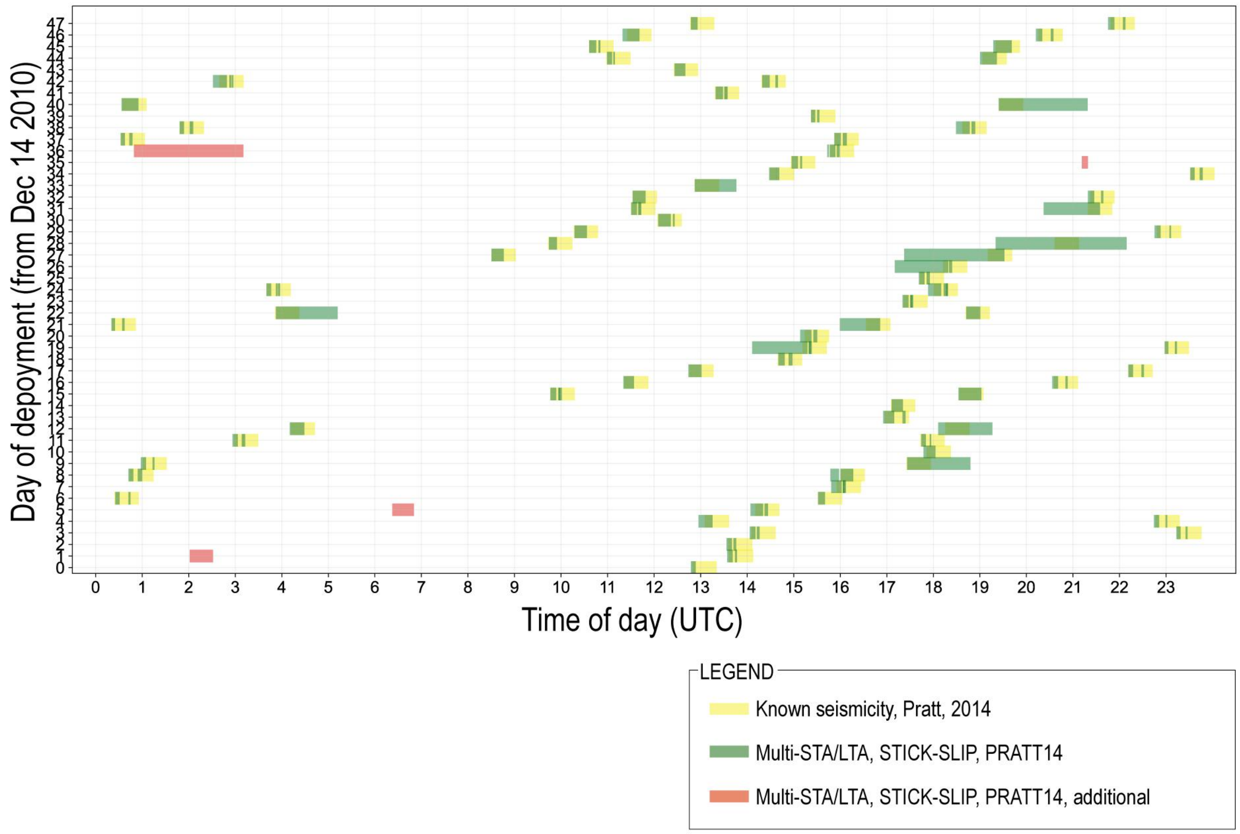

Figure1: Comparison of Whillans Ice Stream stick-slip events previously known (Pratt, 2014) and newly-detected using the multi-STA/LTA, by time of day of rupture and day of the 2010–2011 austral summer deployment. All known Pratt, 2014 events (yellow rectangles; 30-minute set lengths) are detected using the multi-STA/LTA detection algorithm, overlaid as rectangles shown from starttime to duration of event (green rectangles). Additional stick-slips are overlaid (red: verified, grey with red outline; unverified). The temporal context reveals patterns in stick-slip behavior and provides further validation of stick-slip label assignments.

What are the "tremor-like" signals mentionnent on l326?

We will refer to Part B, where the tremor events are further described, and can clarify the use of the word tremor accordingly in Part A.

Details and minor points:

Figure 1. Plots (a) and (b) could be removed, all information is also on the other subplots.

We were asked by the editor to include this figure, and we prefer to keep the subplots separate to provide a background to the STA/LTA algorithm for readers new to such detailed aspects of seismology (as usable in glacier research). We could perhaps combine (a) and (b), as a compromise that would also support a clear explanation.

Algorithm description, section 2.1.
The classical recursive STA/LTA algorithm should be described (even it is described in the cited references) as it is the base of the multiSTA/LTA method.
We will expand the caption of Figure 1 to provide the background explanation, so this is directly available to readers, and make better use of the subplots (a) and (b) that we wish to retain.

l118. What are the values of the minimum STA/LTA thresholds (trigger and detrigger) used to define an event? How are they chosen? Why not optimizing these parameters as done for the time windows? Fig 1 suggests the threshold is fixed at 3 and is the same to trigger an detrigger an event. Did you try other values?
We agree that the choice of trigger and detrigger value is not clearly outlined in the m/s and supplement. We apologise for that oversight, and will add a short clarification in the text. We note that the low confidence events follow the same patterns as the high confidence events, so inclusion or exclusion of the very lowest confidence events is not critical to ongoing usage of this (or any similar) catalogue.

For the reviewer's understanding: The trigger and detrigger value we use in the illustrative example in Fig. 1 differs from that chosen for the rest of the paper. In Fig.1, the trigger value is 3 and the detrigger value is 0.5, which were picked to show the best comparison between event detections for this example waveform. In the application of multi-STA/LTA on the Whillans Ice Stream (Sect. 2–4), the trigger value is 3 and the detrigger value is 1. Referring to the application of multi-STA/LTA, we did test multiple solutions of the trigger and detrigger to ensure that the number and nature of triggers was reasonable in a visual inspection. In principle, the related variables: trigger pairing and the number of seismometers required for a valid detection, could be constrained using a Monte Carlo simulation. However, we optimise these parameters visually, instead of as done for the time windows, due to the need for a wide view across several representative days. As above, we'll add an abridged version of this explanation.

I don't understand eq. (1) and point (3) (l116). Is the hybrid function the average (as in eq(1)) or the maximum value (l116) of all single-parameters STA/LTA functions?
Many thanks for bringing this to our attention. We confirm that point (3) states that we take the maximum of the characteristic functions (which we do) but the equation shows a summation. We will correct this. The maximum function is used rather than a summation to avoid reinforcing detections from the time windows in the middle of are range of parameters (which will likely have detections in multiple nearby windows) in preference to those at the extreme of our range of parameters.

l133. I don't understand what represents epsilon?
We agree that the description of epsilon requires further clarification in the text. The purpose of the epsilon parameter is to ensure computational efficiency by not calculating more windows than necessary. The parameter is a tolerance value that ensures the most spread out of the sta or lta windows is not spaced closer than a factor of epsilon (i.e. we do not go smaller than this tolerance).

Section 3.2 should be moved to the "method" section 2. It describes how the catalogue is compiled and is not specific to the Whillans Ice Stream catalogue.
We will keep Section 3.2 as is to maintain the linear workflow, but will consider the naming of the relevant subsections to improve clarity.

l194: I don't understand this sentence: " The reference time precedes this arrival time by half the network time for the N closest seismometers." What is the "network time"? What is the value of N?

We agree that N, and the network time are definitions generally, are not currently defined in the text and that will be added. N is the coincident trigger threshold and the 'network time' is the travel time for a seismic wave between the most distant seismometers in that group.

l195 "We also take into account that multi-STA/LTA will decompose events into smaller events based on amplitude variations." I think this is a drawback of the method; and a simpler STA/LTA method with well chosen parameters and with a detrigger threshold lower than the trigger threshold may avoid this problem. You should describe in more details how you merge "overlapping events" into one event to obtain the correct event duration.
We address the background to this concern firstly in our general statement (above), and emphasise that we turn this challenge into an advantage: we are able to explore the complex and varied glacier seismic wavefield in a systematic way and this wavefield includes signals with a lower signal to noise ratio than in conventional analysis. Secondly, we are happy to provide clarification on our carefully thought-through procedure with regard to overlapping events.

l213 "Taking uncertainties in start time into account, we label 140 events as stick-slip. Four of those events are determined as additional to the Pratt et al. (2014) catalogue from a manual reconnaissance." How do you know that these 4 events are "stick-slip"? Could you show examples of a newly detected "stick-slip" event and a known stick-slip event?
We refer R1 to the above reference of the Electronic Supplement and included description of our procedure for stick-slip manual identification.

l219 "What means "a.u.": arbitrary unit?
We are happy to add the meaning of a.u. into Sect 3

l267 "The distribution of the peak amplitude occurrences provides source mechanism information". Could you specify which "source mechanism information"? Do you mean the Gutenberg-Richer b-value?
Yes, we are referring here to the GR b-value. We will clarify the text and reference to the Weiss, 1997 citation.

l268 "However, in cryoseismology, the actual magnitude cannot be determined because the material strength, slip distance, and area of slipped fault are usually indiscernible." I don't think this is a big issue and a major source of uncertainty on magnitudes. The problem is even worse for earthquakes that occur at depth were material properties are less constrained.
We're happy to modify the sentence to '… are usually less discernible than for crustal earthquakes.'

l271 "The maximum of the occurrences ". Do you mean the maximum of the distribution of event amplitudes?
There are several similar sentences where I was not sure to understand what the authors mean.
We are happy to clarify the use of the word choice of occurrence with a reference to Fig. 5.

l287 "As a drawback to this approach, a small number of event groups might be catalogued under a single energetic reference event even though the source mechanisms could be different." Yes indeed, many processes produce a wide range of signal peak amplitudes (Gutenberg-Richter law). I think that the event duration or frequency content is more useful to identify the source process.
Our intention with this sentence is simply to acknowledge that a small number of events might coincide. As previously noted, the reconnaissance of source processes is discussed in Part B.

l289 "It is possible that events in other locations of interest for cryoseismology have event types with substantially different seismic signatures than those of the WIS (on which our simulated waveform population was based). " Yes, indeed. For instance, basal stick-slip events have duration ranging between 0.1s and 1000 s and frequencies between 0.01 Hz and 1000 Hz (see Podolskiy and Walter 2016 for a review).
Thanks for this suggestion – this is a good example to note. We will add a half-sentence accordingly.

Fig 6 "The multi-STA/LTA algorithm combines advantages of the other algorithms, as it is able to match, and improve upon, the detections achieved by RECmin". But are all detections real events or is there a significant fraction of false detections (noise)?
Our general statement (at the top of this reply) addresses this point, and we are happy to add a clarification that our definition of events is broadly defined, and includes noise-like bursts, which likely have a glacier process origin (including the adjacent ice shelf, in the case of the WIS).

Fig S3: The signal with a frequency of 0.01 Hz is consistent with stick-slip, but it could also be a teleseism
We agree that there is potential that this is true. However, we carefully confirmed the label using Pratt's catalogue and our own method for flagging potential teleseisms.

Fig S5: Why filtering the signal? At least the spectrogram should be shown for the raw unfiltered signal.
We chose to filter the signal because the low frequency rumblings were hiding any discernible signal in the illustrative figure. Adding the raw spectrogram to the panel won't be informative in this case, so we prefer to add a note to the figure caption in view of transparency.

l303 "we have manually identified events of stick-slip origin": could you explain how you distinguished "stick-slip" events from other types of events?
See the above extract Electronic Supplement and included description of our procedure for stick-slip manual identification. We're happy to add a clearer pointer to this.

l306 "The general trend between peak amplitude and duration (7, top) and energy and duration (7, bottom) of events is consistent with the positive linear association expected from cryogenic sources " This is very general and true for many different source types. So it is not useful for classifying events.
We agree that in the figure the overlapping linearity by event types is shown; however, the ability to analyse events in a multi-dimensional feature space is useful for the multi-dimensional machine learning technique applied in Part B.

l325 "The events of lower energies,..., that occur for long durations (bottom) suggest the presence of harmonic tremors in the catalogue." This could be interesting! Could you show an exemple of seismic signal and spectrogram ? What could be the source (slow-slip event, water flow, storm ...)?
We will refer to Part B, where the tremor events are further described, and can clarify the use of the word tremor accordingly in Part A.

Section 4.2.1. The correlation with tides and temperature is interesting and is a good way to investigate the source mechanisms. But it should be done after classifying events in different types, ie, removing known stick-slip and teleseisms.
We agree in general, and that it is relevant to retain stick-slips, but teleseisms are likely to occur without any association to local tides, hence, they might slightly lessen any tidal or other association, but are not likely to impact any conclusion or insight drawn on this point.

Rather than amplitude, I think that frequency content (average frequency and width of the spectrum) and signal duration could be better parameters to discriminate source mechanisms.
See companion paper, Part B, for further discussion on this point.

Fig 7. You could show only plot (a) as it contains almost all information shown by the other plots.
We prefer to retain the separate plots to allow the reader to view the content with better clarity.

l361: "Further, the production of near-comprehensive, reproducible event catalogues is a critical step towards standardized glacier monitoring as comparative studies between locations are enabled." I agree that comprehensive and reproducible catalogs are valuable, but I think that standard methods (simple STA/LTA or template matching) can already produce such catalogs.
We address this point in our general statement, which hopefully explains why our algorithm and extended catalogue is a valuable additional approach, especially in reconnaissance analysis of the complex wavefield and variety of events that it contains. We would be enthusiastic about a template matching approach for more detailed analysis of a specific event type, and are happy to add clarification to the discussion accordingly.

I think that each glacier is different and that all algorithms and parameters need to be adjusted for each case study. I also think that using different methods may allow to detect events that are still unknown. The main problem is not the detection of events, that can be easily automated and reproduced by others.
We address this point in our general statement, and hope that our workflow Part A and Part B will allow a more general approach that yields additional insight.

The classification of events is much more tricky and subjective, often done "by eye" without objective criteria. I understand that this is the goal of your companion paper (l373) and I am very interested to see how a fully automatic machine learning method can perform.
This is the first mention of the Part B paper by this reviewer, so we refer to our general statement, and hope that other readers will now understand the intentions behind our workflow at the outset.

l370 "The new catalogue will find utility in guiding conventional glacier seismology." Can you explain how?
We again refer to our general statement, and will add clarification at this point.

L408 "We find a partial association of seismicity with the tidal cycle,". This is not a surprise since the catalog contain many already identified stick-slip events that are known to be driven by tides.
In 3.2.1 we discuss that the majority of events in the catalogue are not stick-slip nor teleseisms. Of the 1856 events (broadly defined) 140 are stick-slip and 68 are teleseisms making up 11% of the catalogue.

L12, L409 " We find a slight association with ice surface temperature, as an indicative example of one atmospheric observable.". I don't see such a correlation when looking at Fig 9. This "association" should be quantified and tested using a statistical test.
We confirm that we chose our words carefully, in this instance, and are happy to add a clarification that a longer time series would be needed to support a statistical test or more robust statement.

L414 "semi-automated approach". When reaching the conclusion I still don't clearly understand which part of the detection method is not automatic?
We use the term ‘semi-automated’ as the (automated) ‘multi-‘ algorithm is not applied in isolation, but is done so alongside some actions of a human analyst. This have been described in the article, and include the pre-testing of algorithm parameters. More generally, the Part A, Part B workflow is best described as

‘semi-automated’ because some external information is included in the analysis, such as the likely times of arrivals from teleseismic events. The essence is that a much-extended reconnaissance of the seismic wavefield by a human is enabled by the ‘catch-all’ catalogue generation followed by the unsupervised learning.