Near-real-time matched-filtering for the development of dense earthquake catalogs during sequences of seismicity

Chamberlain Calum[1], Townend John[2], and Gerstenberger Matt[3]

[1]Victoria University of Wellington
[2]Victoria University Wellington
[3]GNS Science-Institute of Geological and Nuclear Sciences Ltd

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Abstract

Conventional earthquake detection methods suffer significant degradations in completeness during high-rate sequences such as aftershock sequences or volcanic swarms. Missed earthquakes during the early periods of aftershock sequences can affect aftershock forecasts and hazard estimates. Missed events during volcanic unrest sequences can impact rate estimations, leading to the sequence being mis-characterized. Much recent work has addressed how matched-filters can be used to overcome some aspects of catalog incompleteness during high-rate sequences, by detecting similar events using cross-correlation. Here we describe the application of open-source (GPL v3.0) software to the near-real-time implementation of matched-filter earthquake detection. Our software (RT-EQcorrscan) is written in Python, and leverages the extensive Obspy package, as well as EQcorrscan and Obsplus to provide matched-filter methods and database handling respectively. RT-EQcorrscan is designed to be modular, so that users can readily utilize only the components they require, or make use of pre-built command-line utilities controlled by simple that can handle thousands of templates over tens of channels of seismic data within the processing capacity (memory and CPU usage) of a standard desktop personal computer. Detections are made within a few seconds of data arriving, with latency due to data delivery and a requirement for full network move-out. At the same time, RT-EQcorrscan has an overarching "Reactor" module to listen to a web-service and respond to new events. If an event occurs that meets user-defined criteria, the Reactor will initiate a near-real-time matched-filter process encompassing the region surrounding the trigger event. Subsequent trigger events in different regions can also be handled with threaded operations. This system is backed-up by a constantly updating template database built on Obsplus, allowing groups of templates to be rapidly deployed. In this presentation we will discuss the key implementation details, as well as showcasing some examples of the system in operation.

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RT-EQcorrscan

github.com/eqcorrscan/RT-EQcorrscan

- Generate dense matched-filter derived catalogues in near real-time
- React to trigger events (e.g. large magnitude or high-rate)
- Run thousands of templates in < 8GB RAM

Well-suited to:

- *Aftershock sequences,*
- *Swarms,*
- *Volcanic unrest,*
- *Repeating earthquakes,*
- *Low-frequency earthquakes*

Motivation

- Energy detectors miss many events during high-rate sequences due to saturation (overlapping waveforms) and high-background amplitudes.
- Matched-filters are better suited to detect during high-rate sequences, but are not generally used in real-time.
- Previous work has shown that matched-filter catalogues can reduce catalogue completeness by ~1 unit (e.g. Warren-Smith et al., (2018), Peng & Zhao (2009), Kato & Obara (2014), and others).
- Aftershock forecasts rely on general statistics until catalogues have sufficient information to derive sequence-specific statistics. The 2016 Kaikoura M7.8 earthquake had a lower rate than the general NZ parameters used in early forecasts (Kaiser et al., 2017) and early forecasts did not fit well.
- Real-time matched-filters may provide **more complete catalogues sooner** allowing for **better forecasting** early in aftershock sequences.

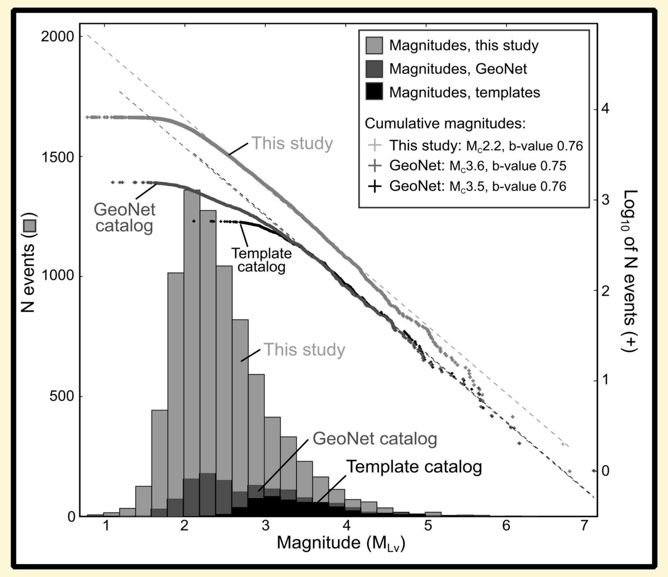


Figure: Magnitude-frequency plot for the Te Araroa aftershock sequence, from Warren-Smith et al., (2018). "This study" used matched-filters to detect additional aftershocks, lowering the completeness by 1.4 units, as well as adding events above the GeoNet (NZ national) completeness. All catalogues have similar b-values.

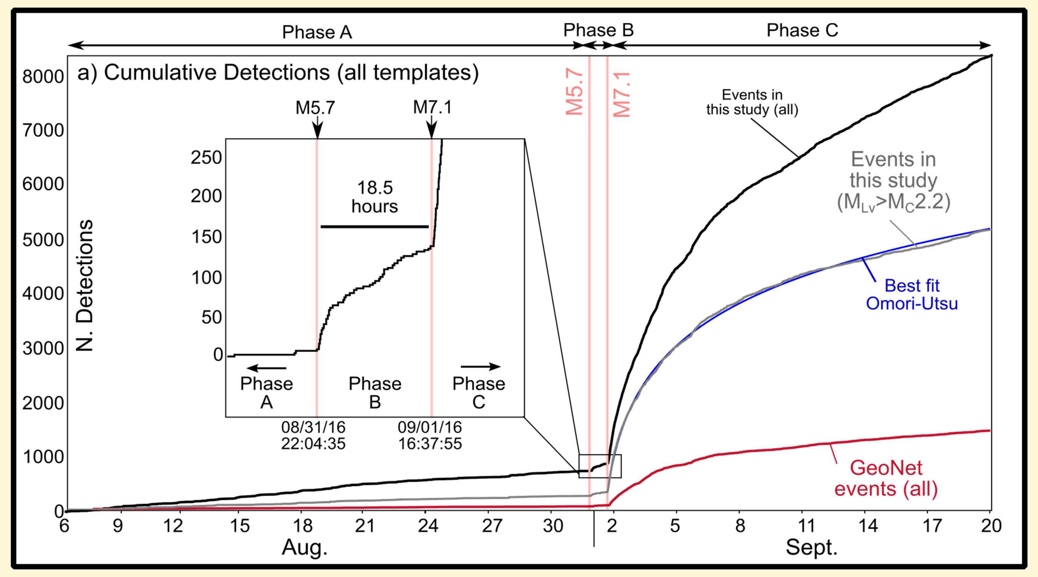
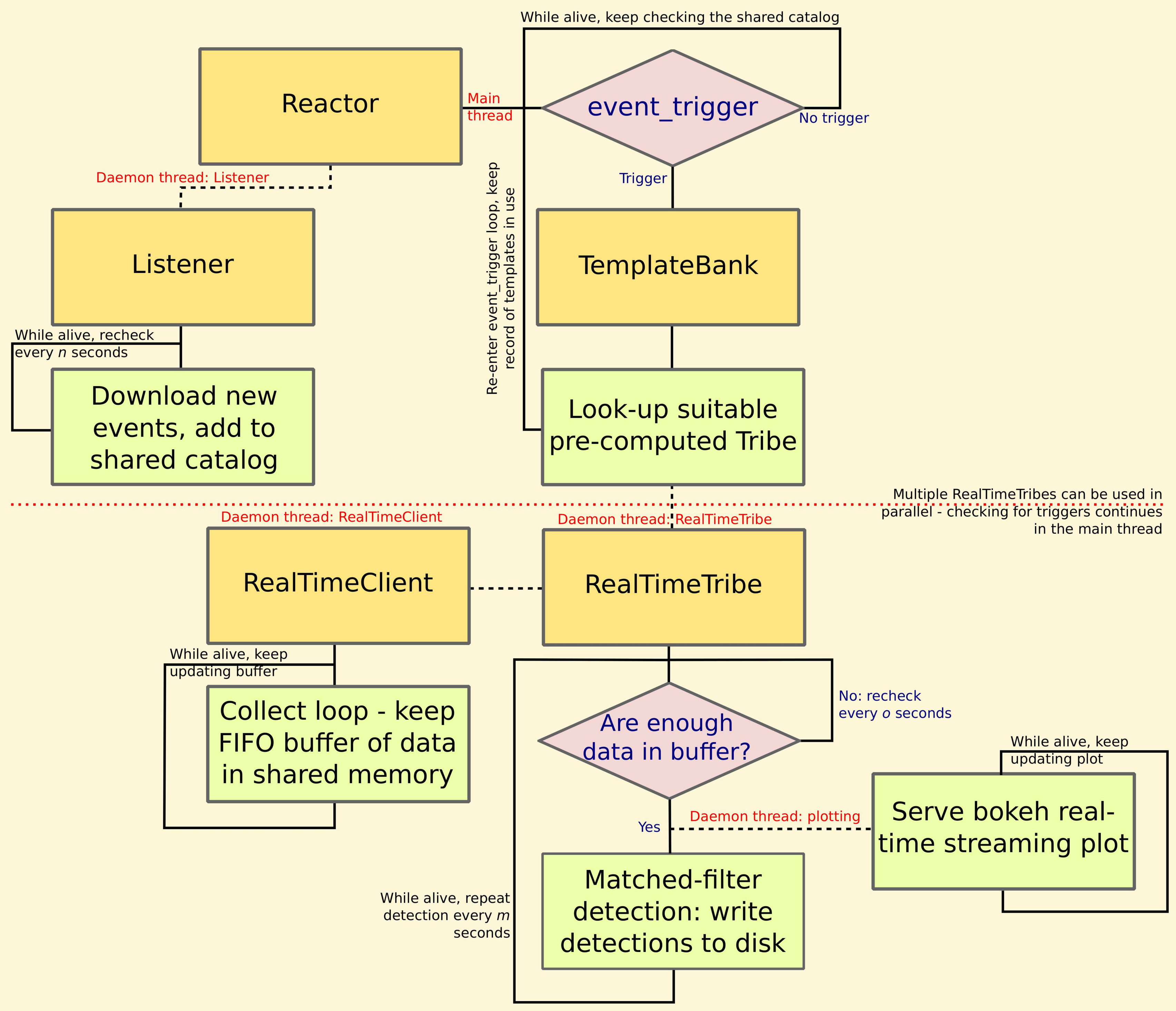


Figure: Cumulative detections for the Te Araroa aftershock sequence, from Warren-Smith et al., (2018). Matched-filter catalogues are well described by Omori-Utsu type decay. Because the matched-filter catalogue is more complete than the "standard" GeoNet catalogue, sequence-specific statistics can be reliably derived sooner in the sequence, potentially allowing for robust sequence-specific forecasts early in aftershocks sequences.

Implementation

Reactor
Governing process: interacts with *Listener* and *TemplateBank*. Checks whether any new events collected by *Listener* meet the user-defined triggering thresholds. If triggered, spawns a child *RealTimeTribe* process for that trigger. Continues operating while *RealTimeTribe* runs matched-filter detectors.

TemplateBank
The database manager built on Obsplus (Chambers et al.). When the *Listener* collects new events they are added to the *TemplateBank* on disk. When the *Reactor* is triggered, templates from a suitable region defined by basic magnitude-distance scaling relationship are read into memory as a *RealTimeTribe*.



Listener
Query an updating event database (e.g. FDSN service) every *n* seconds to check for new events. If new events are registered, create new *Template* and add to *TemplateBank*.

RealTimeClient
Stream data from a streaming service into a FIFO (First In First Out) custom Numpy buffer in shared memory. Commonly this listens to a SeedLink server, using the Obspy (Megies et al., 2011) Seedlink wrappers.

RealTimeTribe
Near-real-time wrapper of an EQcorrscan *Tribe* (Chamberlain et al., 2018). Manages parallel data preparation, correlation, peak-finding, converting detection-times to Obspy (Megies et al., 2011) *Events*, writing out of detections and can spawn a real-time streaming plot using bokeh. Conducts operations faster than real-time for at-least 4k templates on AMD 2600X, in < 8GB RAM. Correlations computed in the frequency-domain every *m* seconds rather than truly real-time.

Plotting

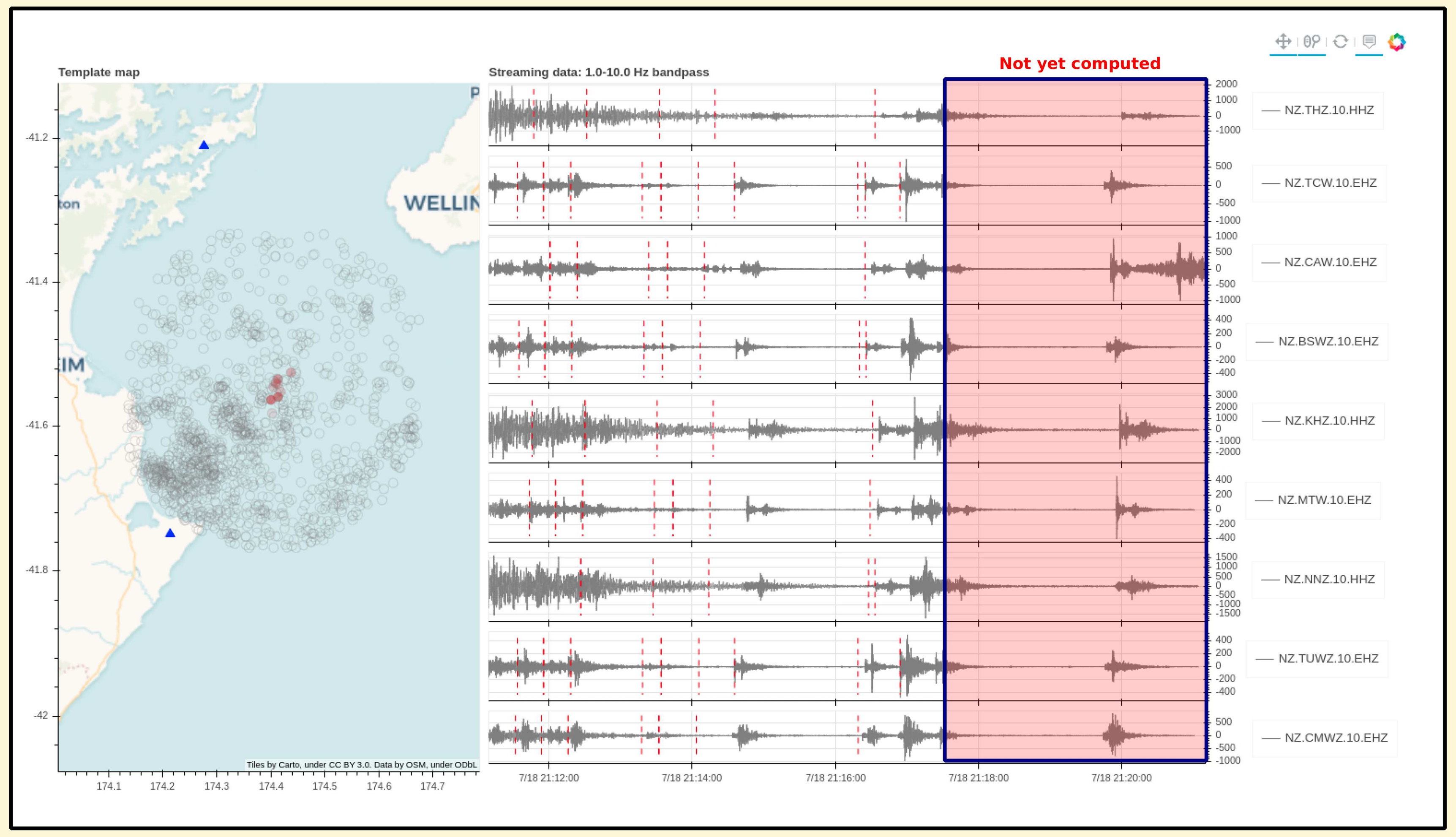
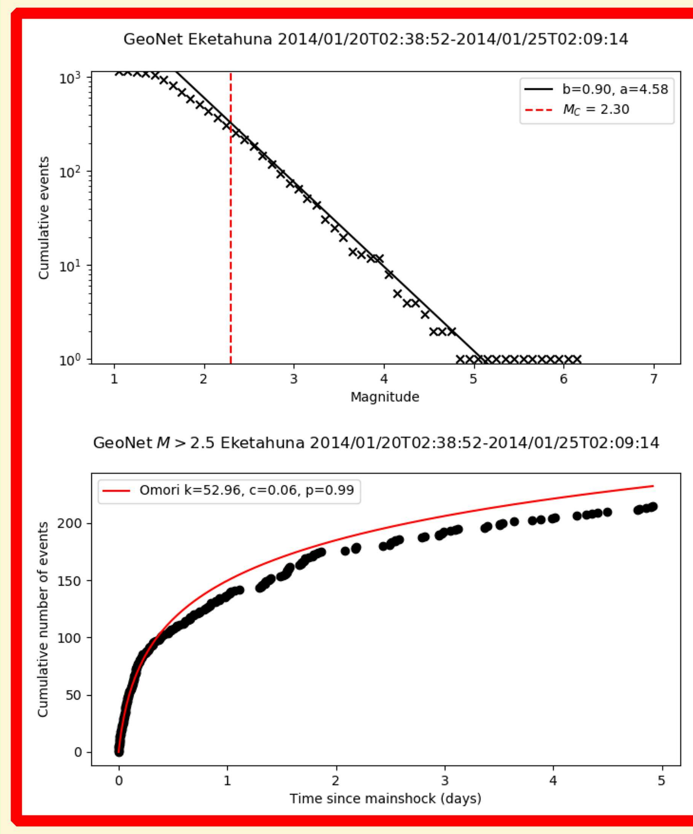


Figure: Interactive streaming plot using bokeh (docs.bokeh.org). **Left:** Map of stations in use (blue triangles), and templates deployed (open circles). The map is movable and zoomable. When a template detects an event it turns red, this colour fades with time. **Right:** Real-time streaming data from seed-link server. Data are filtered prior to plotting. Red vertical lines highlight detection times. Note that detections lag ~3 minutes behind real-time.

Application to aftershock detection

2014 Eketahuna M6.2 Normal Faulting:
Interaction of slab earthquake and slow-slip episode (SSE). SSE was stopped by the earthquake (Wallace et al., 2014), and aftershock sequence was unusually quiet after the first 6 hours.

2013 Cook-Strait earthquakes:
Two crustal M5.7 and M5.8 earthquakes preceded two M6.6 earthquakes in the Cook Strait region between North and South Island, New Zealand (Hamling et al., 2014).

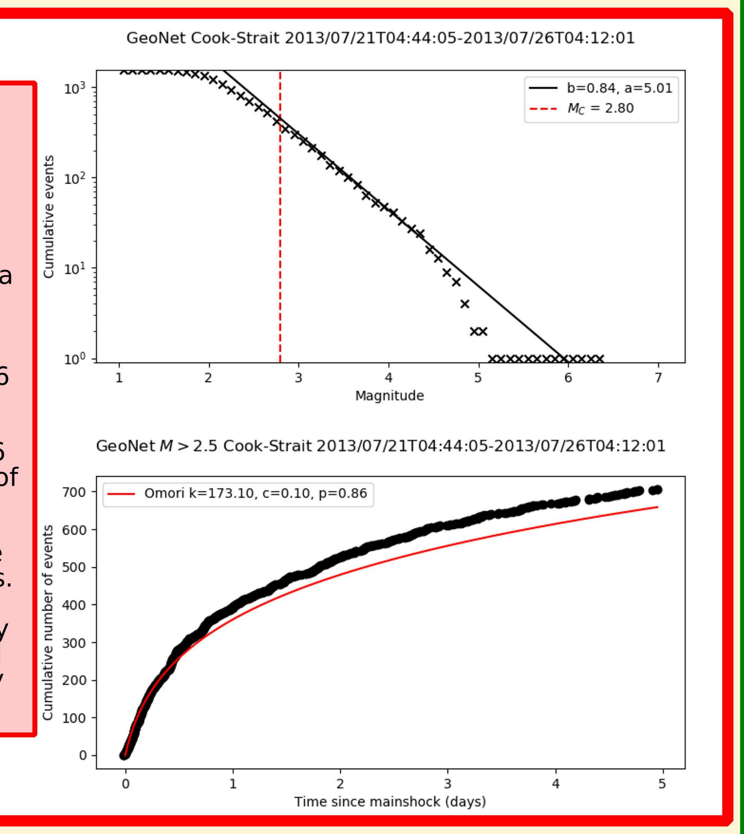


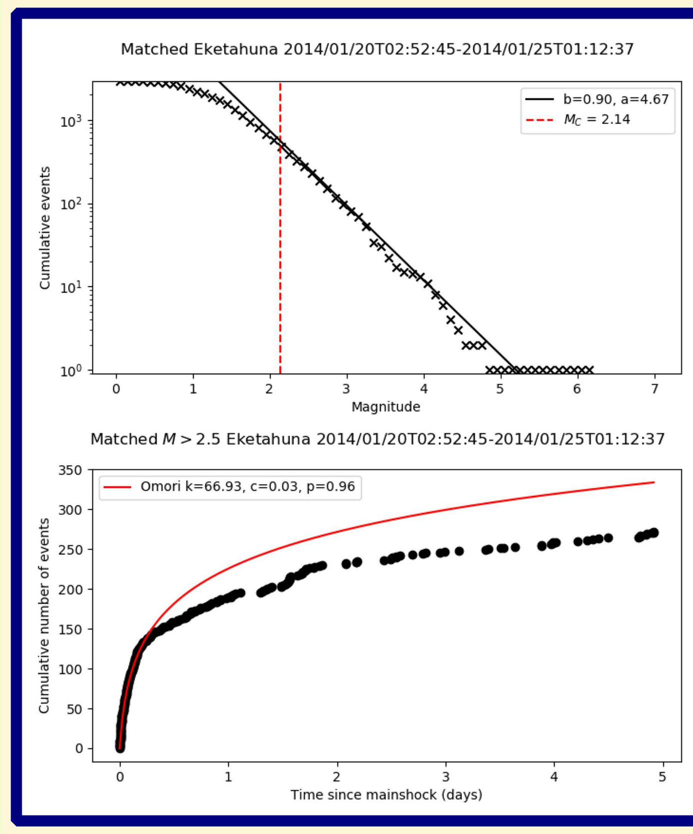
GeoNet catalogues downloaded via the FDSN service.

The Eketahuna sequence (left) is affected by nearby slow-slip, resulting in a non-Omori type sequence.

The Cook-Strait M6.6 mainshock was proceeded ~25 days later by another M6.6 earthquake. The lack of high-magnitude aftershocks may be related to this, or the two M>5.5 foreshocks.

Completeness is fit by "goodness-of-fit" and Omori parameters by iterative inversion.

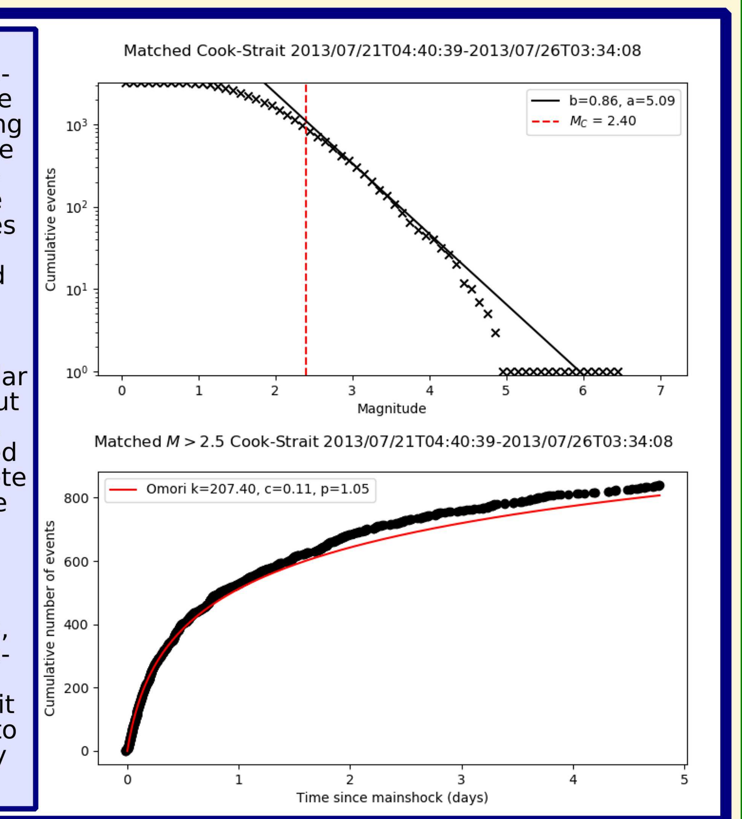




Matched-Filter catalogues after five-days. Catalogues are generated hourly using templates prior to the start of that hour to simulate a real-time situation. Magnitudes are computed by correlation weighted relative amplitude estimation.

Eketahuna (left): similar b-value to GeoNet, but lower completeness. Note higher estimated k due to more complete catalogue during the early (Omori-type) sequence.

Cook-Strait (right): Lower completeness, and slightly higher b-value than GeoNet. higher k and better fit to Omori decay due to more complete early catalogue.



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