Earth and Planetary Science Letters 484 (2018) 111–123

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Focal mechanisms and inter-event times of low-frequency earthquakes reveal quasi-continuous deformation and triggered slow slip on the deep Alpine Fault

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ARTICLE INFO

Article history:
Received 25 September 2017
Received in revised form 8 December 2017
Accepted 8 December 2017
Available online xxxx
Editor: P. Shearer

Keywords:
slow deformation
low-frequency earthquake
matched-filtering
Alpine Fault
New Zealand
focal mechanism

ABSTRACT

Characterising the seismicity associated with slow deformation in the vicinity of the Alpine Fault may provide constraints on the stresses acting on a major transpressive margin prior to an anticipated great (≥M8) earthquake. Here, we use recently detected tremor and low-frequency earthquakes (LFEs) to examine how slow tectonic deformation is loading the Alpine Fault late in its typical ∼300-yr seismic cycle. We analyse a continuous seismic dataset recorded between 2009 and 2016 using a network of 10–13 short-period seismometers, the Southern Alps Microearthquake Borehole Array. Fourteen primary LFE templates are used in an iterative matched-filter and stacking routine, allowing the detection of similar signals corresponding to LFE families sharing common locations. This yields an 8-yr catalogue containing 10,000 LFEs that are combined for each of the 14 LFE families using phase-weighted stacking to produce signals with the highest possible signal-to-noise ratios. We show that LFEs occur almost continuously during the 8-yr study period and highlight two types of LFE distributions: (1) discrete behaviour with an inter-event time exceeding 2 min; (2) burst-like behaviour with an inter-event time below 2 min. We interpret the discrete events as small-scale frequent deformation on the deep extent of the Alpine Fault and LFE bursts (corresponding in most cases to known episodes of tremor or large regional earthquakes) as brief periods of increased slip activity indicative of slow slip. We compute improved non-linear earthquake locations using a 3-D velocity model. LFEs occur below the seismogenic zone at depths of 17–42 km, on or near the hypothesised deep extent of the Alpine Fault. The first estimates of LFE focal mechanisms associated with continental faulting, in conjunction with recurrence intervals, are consistent with quasi-continuous shear faulting on the deep extent of the Alpine Fault.

1. Introduction

Slow earthquakes are transient-slip phenomena hypothesised to play an important role in the seismic cycle as they involve stress transfers between stably sliding and locked portions of a fault (Wech and Creager, 2011). Slow earthquakes generally manifest as short- to long-term (days–months) geodetic transients (Dragert et al., 2001) with (e.g. Frank et al., 2013) or without contemporaneous non-volcanic tremor (e.g. Wech and Bartlow, 2014). Tremor signals correlated both spatially and temporally with slow slip events were first documented on the deep portion of the Cascadia subduction zone (Rogers and Dragert, 2003) and interpreted to be the seismic manifestation of deep slow slip on the fault interface (Obara, 2002). However, slow slip has been observed without concurrent tremor, in Cascadia and elsewhere (Delahaye et al., 2009 and references therein); and tremor has also been detected without observable slow slip (e.g. Guilhem and Nadeau, 2012). Even though incomplete detection of tremor or slow-slip might explain those occurrences, this nonetheless emphasises that the mechanisms involved in tremor generation require further elucidation.

Low-intensity, long-duration tremor signals without impulsive P- and S-wave arrivals were first observed at subduction zones (Obara, 2002; Rogers and Dragert, 2003) but later reported at major strike-slip fault zones (e.g. Nadeau and Dolenc, 2005; Wech et al., 2012; Aiken et al., 2013). Several studies show tremor to occur on the plate interface in the rheological transition zone between stick-slip (in the brittle seismogenic zone) and stable sliding (in the ductile downdip portion of the fault; e.g. Beroza and Ide, 2011). Two principal mechanisms have been proposed to explain the inferred weakening of the plate interface at depth: (1) an increase in temperature; or (2) trapped fluids at the plate interface and resulting high pore pressures (Shelly et al., 2006).

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https://doi.org/10.1016/j.epsl.2017.12.021
0012-821X/

Shelly et al. (2007) demonstrated that tremor can be decomposed into a swarm of discrete low-frequency earthquakes (LFEs). LFEs are commonly interpreted as the rupture of small asperities within otherwise aseismically slipping regions of a fault (e.g. Ide, 2008). Each LFE source generates multiple events constituting a LFE family. In this study, we capitalise on the repeating nature of LFEs to construct a continuous catalogue of LFE seismicity associated with the central Alpine Fault using an iterative matched-filter routine (Shelly et al., 2007). In this context, matched-filtering is the process of correlating the waveforms of a known template event (e.g. the phases of a LFE) with continuous seismic data to detect near-repeats of the template event. In the following we refer to all the detections made by a single template as being part of a single "family" of detections.

Tremor was first documented on the Alpine Fault by Wech et al. (2012) using data recorded by the Southern Alps Microearthquake Borehole Array (SAMBA) (Boese et al., 2012). Wech et al. (2012) reported tremor occurring in 12 separate episodes between March 2009 and October 2011, in the lower crust (between 25–45 km), south of the SAMBA network. They interpreted tremor to represent slow slip occurring on the deep extent of the Alpine Fault in a region of elevated fluid content. LFEs were subsequently identified by Chamberlain et al. (2014) by visual inspection of seismic data spanning periods of tremor. Fourteen LFEs were identified and used as primary templates in a matched-filter routine to detect similar events occurring throughout a 36 month period from 26 March 2009 to 2 April 2012. Following an initial detection run, the 10% of detections with the highest signal-to-noise ratios were stacked linearly to generate a new template. This process was repeated until the number of detections stabilised. Despite this, few P- and S-wave arrival times could be picked accurately, and P-wave polarities could not be determined. As a consequence of the resulting large uncertainties in hypocentral depths and the absence of source parameters, interpreting Alpine Fault tremor and LFE observations in terms of slip on the fault itself remained inconclusive.

Here, we use an additional 4 yrs of data and present the longest continuous record of LFEs beneath the New Zealand Southern Alps to date (spanning an almost 8-yr period). Using templates manually identified by Chamberlain et al. (2014) and a matched-filter detection technique, we detect 10,000 events occurring in 14 families between 26 March 2009 and 22 October 2016. We implement a phase-weighted stacking method (Schimmel and Paulssen, 1997; Thurber et al., 2014) instead of linear stacking within the matched-filter routine to emphasise coherent signals resulting in higher signal-to-noise ratio stacks. This facilitates more accurate picks, which in turn allow for the generation of refined hypocentre locations and the calculation of reliable focal mechanism parameters with which to examine the state of stress in the vicinity of the LFEs. We study inter-event times and document an almost-constant background rate of LFE generation punctuated by distinctive short-term rate increases corresponding to known periods of tremor or large ($M_w > 5$) regional earthquakes.

2. Tectonic setting

The Alpine Fault is an 850 km-long dextral-reverse transpressional fault and is the principal locus of deformation within the Australia–Pacific plate boundary in the South Island of New Zealand (Fig. 1). An average of 70–75% of total plate displacement (equivalent to a fault-parallel slip rate of 39 mm/yr and a convergence rate of 7–9 mm/yr) is accommodated by the central part of the Alpine Fault (Norris and Cooper, 2001). The convergent motion results in an area of enhanced uplift with rates of 5–8 mm/yr (Beavan et al., 2002; Lamb and Smith, 2013) that corresponds to the region of the highest peaks in the central Southern Alps (Little et al., 2005).

Paleoseismic studies suggest that M_w 7–8 earthquakes rupture the central Alpine Fault every 271 ± 73 yrs (Sutherland et al., 2007; Howarth et al., 2016), with the most recent major event inferred to have occurred in 1717 A.D. (Wells et al., 1999). In other words, the Alpine Fault is late in its typical earthquake cycle, making it an ideal place to study the processes leading up to a large earthquake.

Drilling into the hanging wall of the Alpine Fault was undertaken as part of the Deep Fault Drilling Project to better understand the ambient conditions, rock properties, and geophysical phenomena within an active fault zone prior to a large earthquake (e.g. Sutherland et al., 2017). The most recent phase of drilling revealed a pore-fluid pressure gradient exceeding 9 ± 1% above hydrostatic levels and an extreme geothermal gradient of 125 ± 55 °C/km within the fault hanging wall (Sutherland et al., 2017). Those observations reinforce the hypothesis that rapid uplift and exhumation near the Alpine Fault have raised isotherms, thus weakening the crust and focusing deformation along the fault.

3. Methods

3.1. LFE detection

We use the waveforms of fourteen LFEs identified by Chamberlain et al. (2014) as primary templates in an iterative stacking and cross-correlation routine to identify similar events following the approach used by Shelly et al. (2007). We use the EQcorrscan Python package to compute matched-filter detections (Chamberlain et al., in press). Each template is constructed using a 6 s window beginning 0.5 s before the S-pick to ensure that it encompasses the S-phase arrival and coda. Each template and the dataset as a whole are resampled to 100 Hz and bandpass-filtered at 2–8 Hz, which corresponds to the LFEs' peak frequency band (Chamberlain et al., 2014). We correlate each template with the data recorded at each station on all three channels at 0.01 s intervals. The minimum inter-event trigger time for individual families is fixed at 6 s. A detection is made when the cross-correlation sum across the network exceeds a threshold value. Here, we use a threshold of eight times the median absolute deviation of the day-long cross-correlation sum, which has to be composed of correlations from at-least 15 channels. This threshold minimises the number of falsely detected events per day per template to 0–3 (Chamberlain et al., 2014).

After an initial detection run, we linearly stack the 20% of detections with the highest cross-correlation sum to generate a set of refined templates with higher signal-to-noise ratios (e.g. Fig. 1S in Supplementary Material). We then employ each new template in the matched-filter routine and iterate until the final template has a sufficiently high signal-to-noise ratio for us to pick reliable arrival times (requiring 2–4 iterations, depending on the template). After each iteration, the number of detections for most families increases significantly. Furthermore, the use of a higher signal-to-noise ratio template results in the detection of a greater number of relatively higher signal-to-noise ratio events between each iteration. This change in signal-to-noise ratio is reflected in the 20% best correlated detections that includes a larger number of high signal-to-noise ratio detections after each iteration, thus refining the template between iterations. We extend the final stacked waveform to 20 s-length to include both P and S arrivals for picking purposes (the resulting stack being a 20 s-long record with the S-arrival at ∼10 s). Finally, we apply phase-weighted stacking, described below, to the last iteration's detections.

3.2. LFE location

The majority of earthquake location methods are based on the arrival times of distinctive impulsive seismic phases. An inherent