

Real-time Failure Forecasting in Triaxially Stressed Sandstones

A. Crippen; A. F. Bell; A. Curtis; I. G. Main
The University of Edinburgh, School of GeoSciences



THE UNIVERSITY
of EDINBURGH

Introduction and Project Goals

We seek to create codes that can forecast laboratory brittle failure events in real-time using precursory signals such as accelerations in strain-rate and acoustic emissions (AE) events. These signals follow power-law spatial, temporal, and size distributions leading to catastrophic failure (Bell et al., 2011a,b; Brantut et al., 2013). This distribution can be modeled using Voight's relation [1988] of a geophysical precursor, Ω , to its rate for constant temperature and stress. When adjusting constants for real earth conditions the relation takes the form of a power-law increase in precursory signals with time:

$$\frac{d\Omega}{dt} = \kappa (t_f - t)^{-p}$$

This behavior is seen in the real earth before volcanic eruptions, laboratory deformation experiments, and occasionally earthquakes (Heap et al., 2009a,b; Bell et al., 2011a,b; Bouchon et al., 2013). The solution to Voight's relation is a singularity, commonly interpreted as failure time. Thus, modeling these precursors is believed to be the key to failure forecasting. This has been applied retrospectively to volcanic-tectonic earthquake and laboratory failure data to create 'hindcasts' (Bell et al., 2011a,b). However, this method faces issues when switching to real-time application: it has a retrospective bias (we know an event actually happened) and cannot adapt to false positive event triggers in real-time. We apply Voight's relation retrospectively to synthetic earthquake and real laboratory data. We explore additional forecasting techniques to adjust for real-time use. **Our ultimate objective is to create a forecasting model that can be applied to real-time laboratory failure events that may or may not actually happen.**

Laboratory set-up and Experiments

The rock deformation laboratory in the Grant Institute consists of a triaxial hydraulic deformation rig capable of conducting constant strain rate and constant load experiments with a ram capable of producing 10 tons of pressure (Image 1). We chose sandstone samples due to their strong heterogeneity, making them highly susceptible to microcracking and ideal for monitoring AEs. Samples are cored, thoroughly cleaned and sonicated before being loaded into the metal chamber (Image 2) and filled with fluid to maintain pore pressure. Piezoelectric transducers are placed above and below the sample to monitor AE events and perform velocity surveys (Image 3). The AE sensors are connected to Richter and Cecchi Trigger Hit Count units in order to combine whole waveform real-time data and triggered event data for monitoring. LVDT units are placed next to the sample and connected by a metal plate to measure minute changes in length to monitor deformation and changes in strain rate. The sample is loaded at a constant rate until failure (Image 4).



Image 2. Metal chamber mounted on rig with LVDT units running parallel

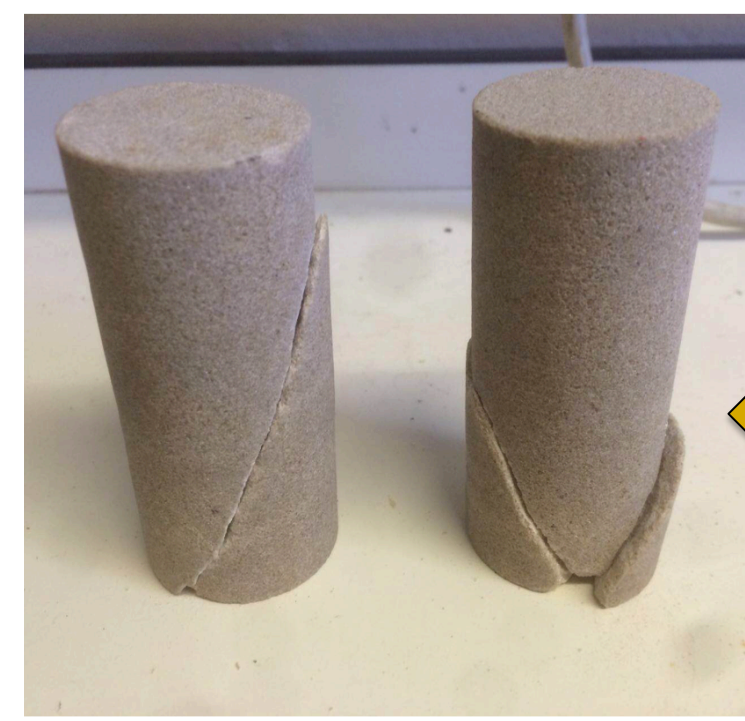


Image 4. 38mm diameter, 90mm tall sandstone cores after deformation

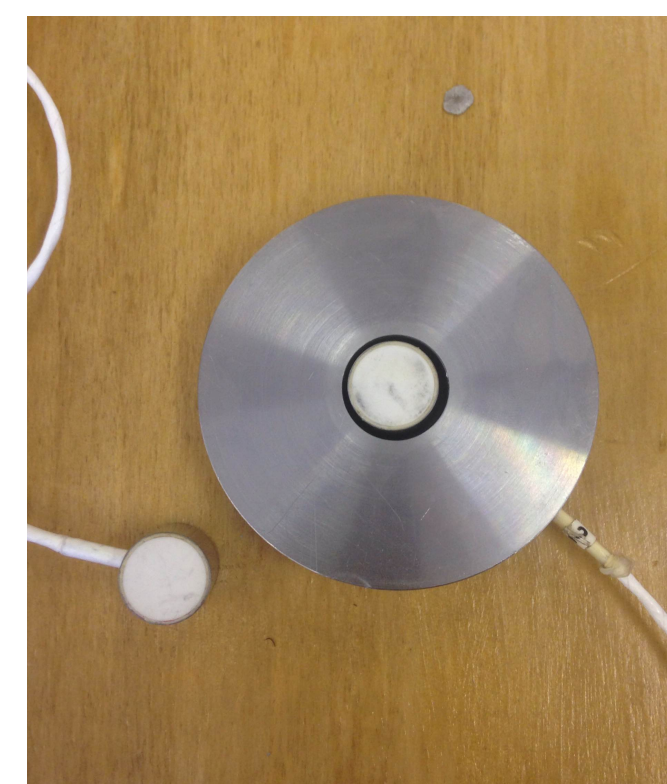


Image 3. AE sensors, alone (left) and in a metal casing for the ram stack (right)



Image 1. Triaxial hydraulic deformation rig with oil flow control panel and chamber

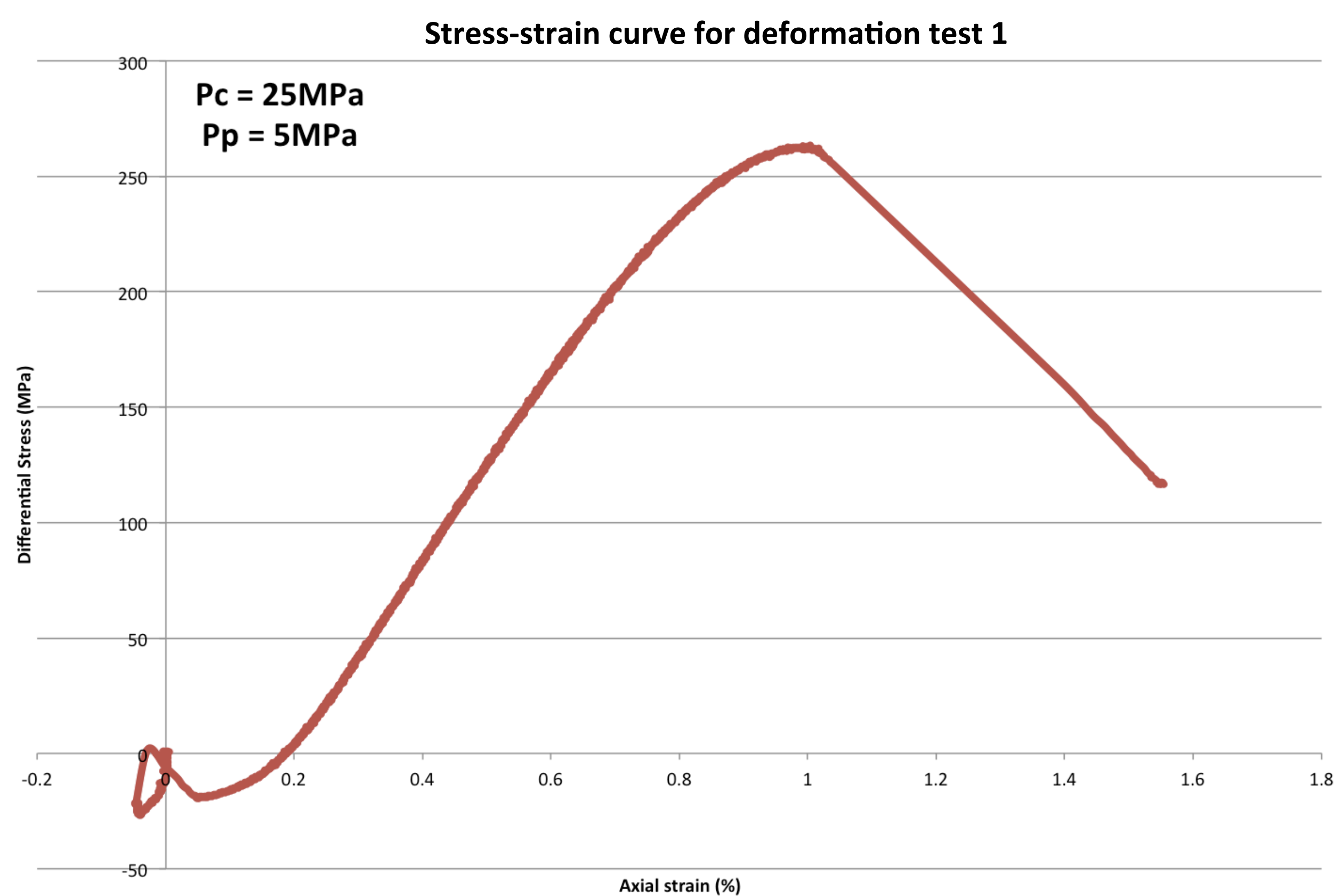


Figure 1. Stress-strain curve for sandstone deformation test 1. Effective pressure was set to 30MPa and a constant strain rate of $1.0 \times 10^{-5} \text{ s}^{-1}$. Comparing many of these curves along with AE energy with time will allow us to adjust forecasting methods based on the medium property changes leading up to failure

Forecasting Models and Hindcasts

Synthetic Volcano-tectonic (VT) earthquake data was created using a poisson generator and thinning process using an inverse Omori rate. Voight's relation was fitted to the data using a BFGS optimization method to solve for system parameters including failure time.

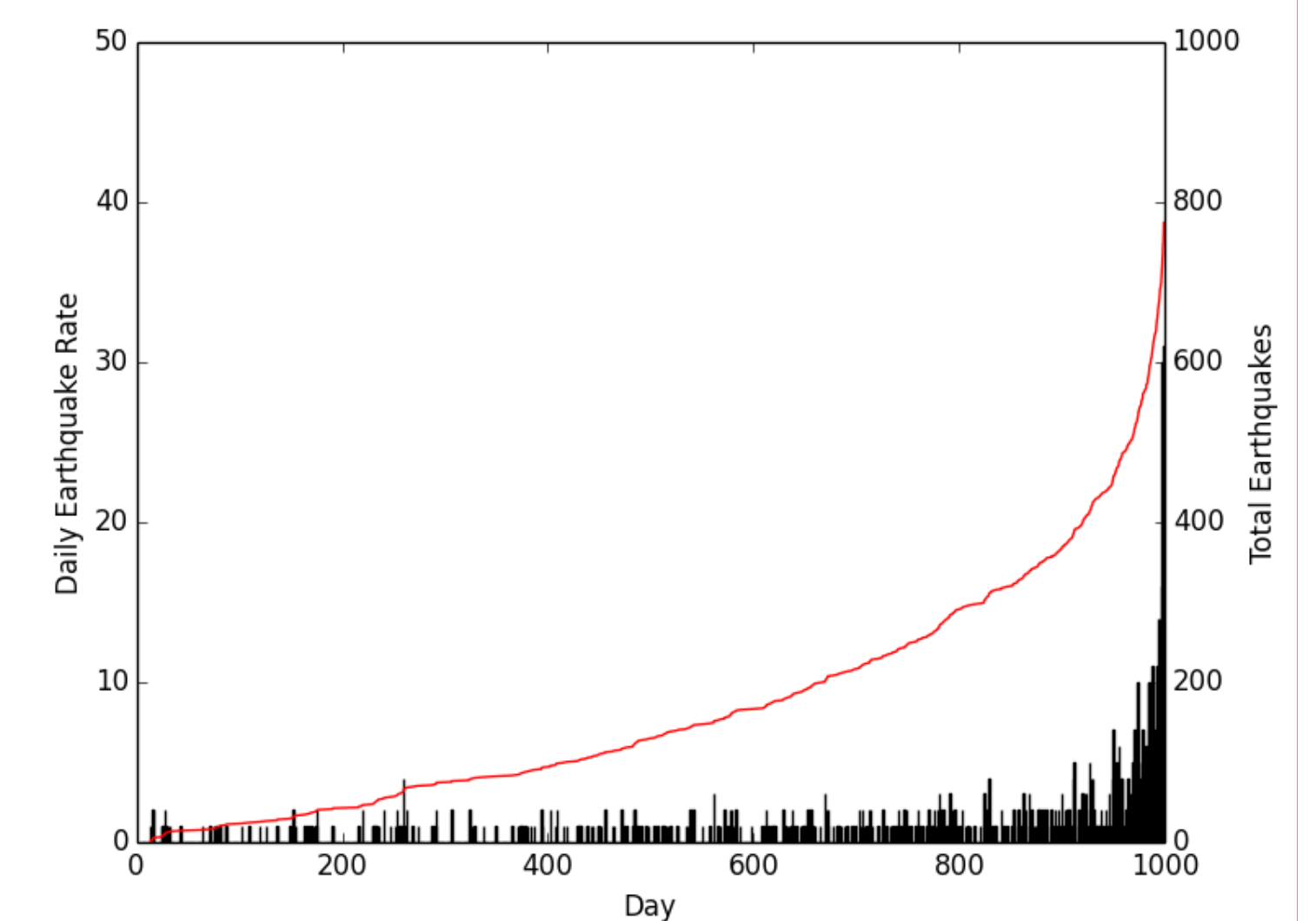


Figure 2. Synthetic earthquake data showing an acceleration in daily earthquake rate (black) and total number of earthquakes (red)

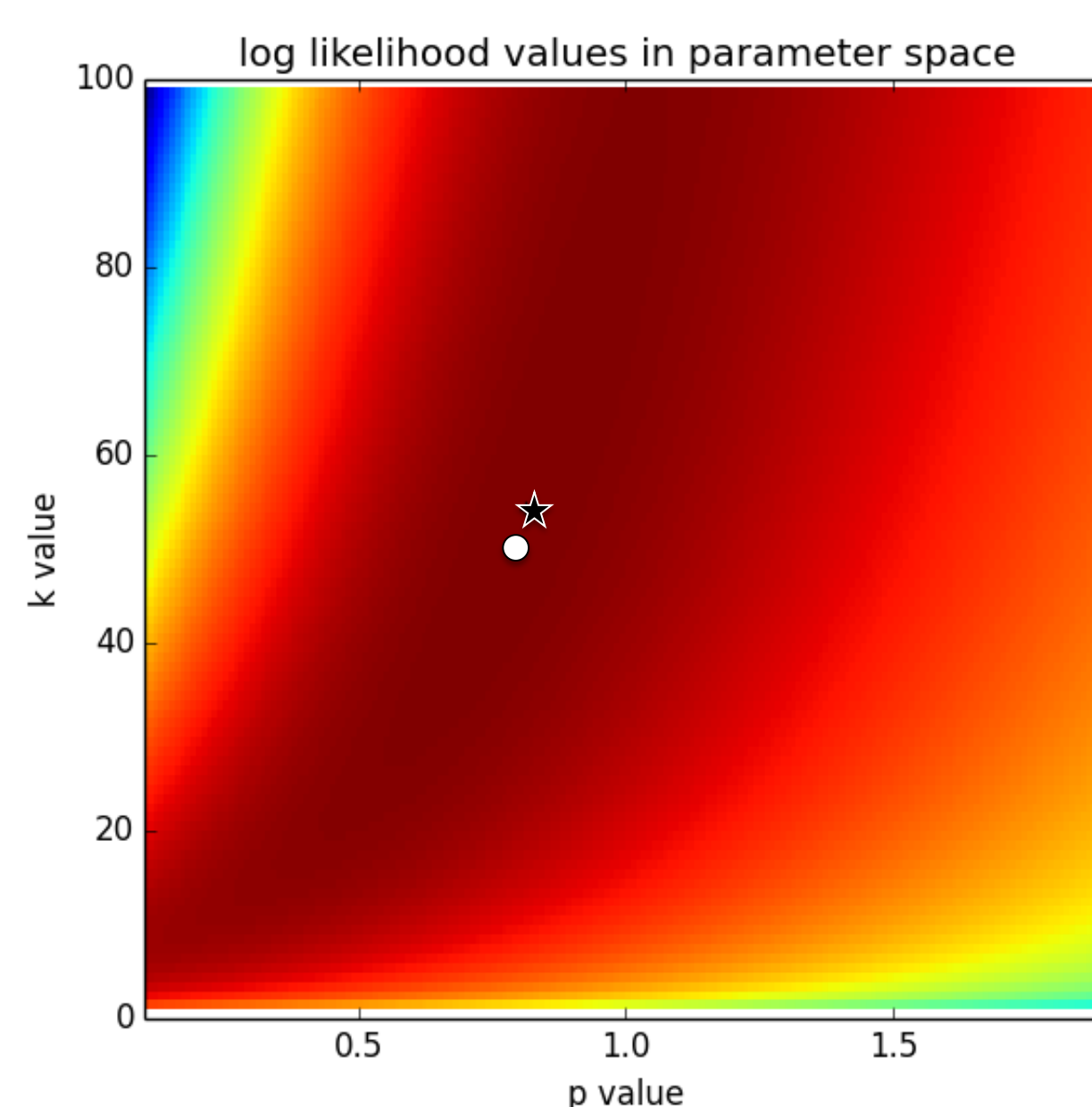


Figure 3. (Left) Log likelihood contour in parameter space displaying parameter outputs from applying our forecasting method to synthetic VT earthquake data shown in Figure 1. The parameter inputs (true values) for this case were $k=50.0$, $t_f=1000$, $p=0.80$ (white dot) and the model outputs (optimized values) were $k=51.65$, $t_f=1000$, $p=0.737$ (black star)

The Next Steps...

Error analysis as prior knowledge

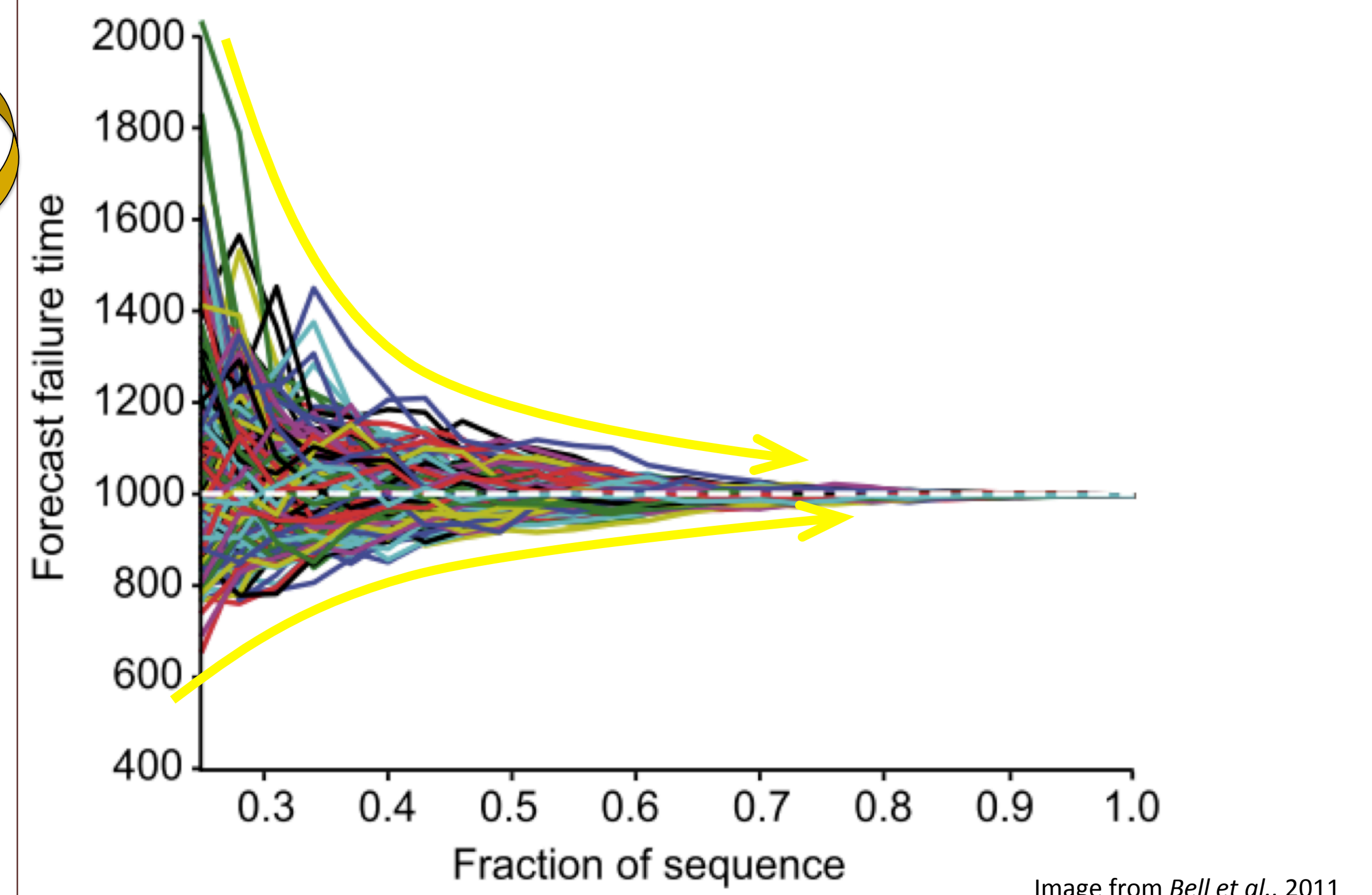


Image from Bell et al., 2011

Real-time Coda Wave Interferometry to minimize false positives?

$$P(\lambda|d) \rightarrow P(\lambda|d, \text{CWI})$$

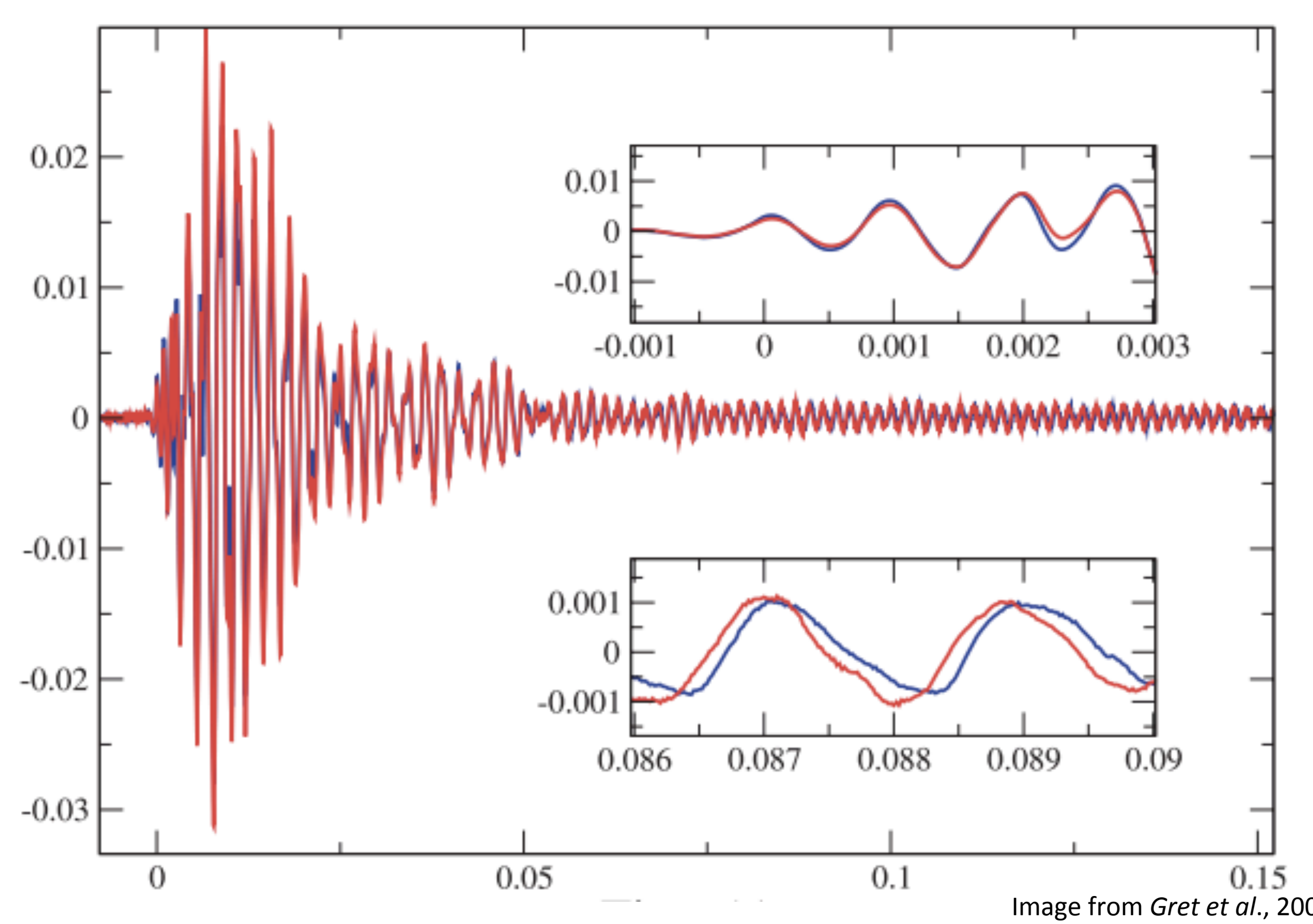


Image from Gret et al., 2005

Contact



Alyssa Crippen
WAVES Marie Curie ESR Fellow
PhD Candidate, The University of Edinburgh
Email: alyssa.crippen@ed.ac.uk

References

1. Bell, A.F., Naylor, M., Heap, M.J., and Main, I.G., 2011, Forecasting volcanic eruptions and other material failure phenomena: An evaluation of the failure forecast method: *Geophysical Research Letters*, v. 38, p. 1-5, doi: 10.1029/2011GL048155.
2. Bell, A.F., Greenough, J., Heap, M.J., and Main, I.G., 2011, Challenges for forecasting based on accelerating rates of earthquakes at volcanoes and laboratory analogues: *Geophysical Journal International*, v. 185, p. 718-723, doi: 10.1111/j.1365-246X.2011.04982.x.
3. Bouchon, M., Durand, V., Marsan, D., Karabulut, H., and Schmittbuhl, J., 2013, The long precursory phase of most large interplate earthquakes: *Nature Geoscience*, v. 6, p. 299-302, doi: 10.1038/ngeo1770.
4. Brantut, N., Heap, M.J., Meredith, P.G., and Baud, P., 2013, Time-dependent cracking and brittle creep in crustal rocks: A review: *Journal of Structural Geology*, v. 52, p.17-43, doi: 10.1016/j.jsg.2013.03.007.
5. Gret, A., Snieder, R., and Scales, J., 2005, Time-lapse monitoring of rock properties with coda wave interferometry: *Journal of Geophysical Research: Solid Earth*, v. 111, doi: 10.1029/2004JB003354.
6. Heap, M. J., Baud, P., and Meredith, P. G., 2009, Influence of temperature on brittle creep in sandstones: *Geophysical Research Letters*, v. 36, doi: 10.1029/2009GL039373.
7. Heap, M. J., Baud, P., and Meredith, P. G., 2009, Time-dependent brittle creep in Darley Dale sandstone: *Journal of Geophysical Research*, v. 114, doi: 10.1029/2008JB006212.