Can we predict seismogenic failure of single-phase magmatic liquids?

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Introduction

During ascent through the shallow crust, high viscosity magma fractures repeatedly, producing seismicity that can be used to both track magma movement and help forecast eruption times. Predictive tools have been developed in which the acceleration of the seismic signals toward failure is thought to follow a power law, such that the singularity defines the critical point at which the seismic signals run away and coincides with failure (e.g. Voight, 1988; Main, 1999). Here we use the Time-Reversed Omori Law (TROL) to describe such an increase (Bell et al., 2013; Vasseur et al., 2015):

$$\dot{\Omega}(t) = \frac{k}{(t_f - t)^p}$$

where $\dot{\Omega}$ is the event rate at time t, k is a multiplicative amplitude term and p is the power-law exponent. t_f is the predicted time of failure, which is in an ideal situation equal to the onset of an eruption or to the critical time, t_c, observed in lab experiments.

This research focuses on whether it is possible to forecast failure of single-phase viscoelastic magmatic liquids using acoustic emissions. Scaled laboratory deformation experiments are performed at volcanic temperatures and pressures in which acoustic emissions (AE) are tracked *in situ*. The TROL is used to predict the time of failure and is compared to other accelerating models to determine which model describes the acceleration of acoustic signals towards failure in single-phase magmatic liquids best.

Methods

A high-load (<300 kN), high-temperature (<1050 °C) uniaxial press (Figure 1) was used to deform both synthetic soda-lime-silica glass and natural homogeneous obsidian, obtained from the Hrafntinnuhryggur ridge at Krafla volcano, Iceland, at constant strain rate. Acoustic emissions were recorded simultaneously using two acoustic emission transducers. The acoustic events were detected from continuous streams using a standard STA/LTA (Short-Term Average over Long-Term average) detector. An amplitude threshold of 68 dB was applied to the AE data to remove noise.

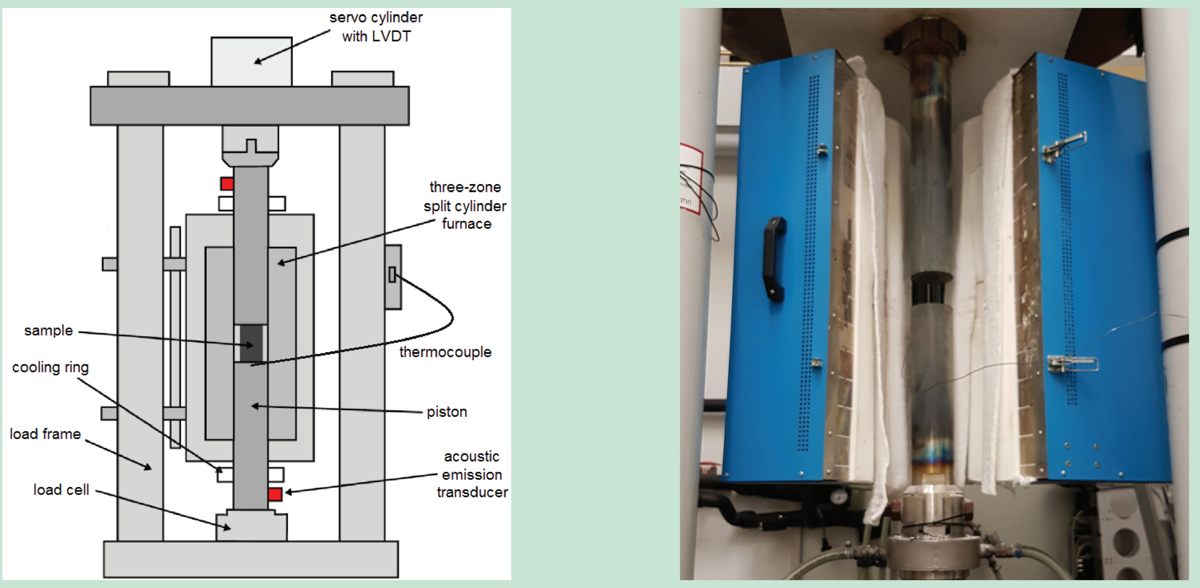


*Figure 1: **Left)** Schematic diagram of the high-load, high-temperature uniaxial press, modified after Heap et al. (2014). **Right)** Picture of the high-load, high-temperature uniaxial press.*

Three types of deformation behaviour

Three types of deformation behaviour could be distinguished, both visually when examining the samples that were recovered from the apparatus (Figure 2) and based on the mechanical and AE data (Figure 3). We refer to these three types as *viscous*, *transitional* and *brittle*.

Figure 2: The original form of synthetic soda-lime-silica glass on the left and three samples recovered from the apparatus on the right, depicting three types of deformation (viscous, transitional and brittle).

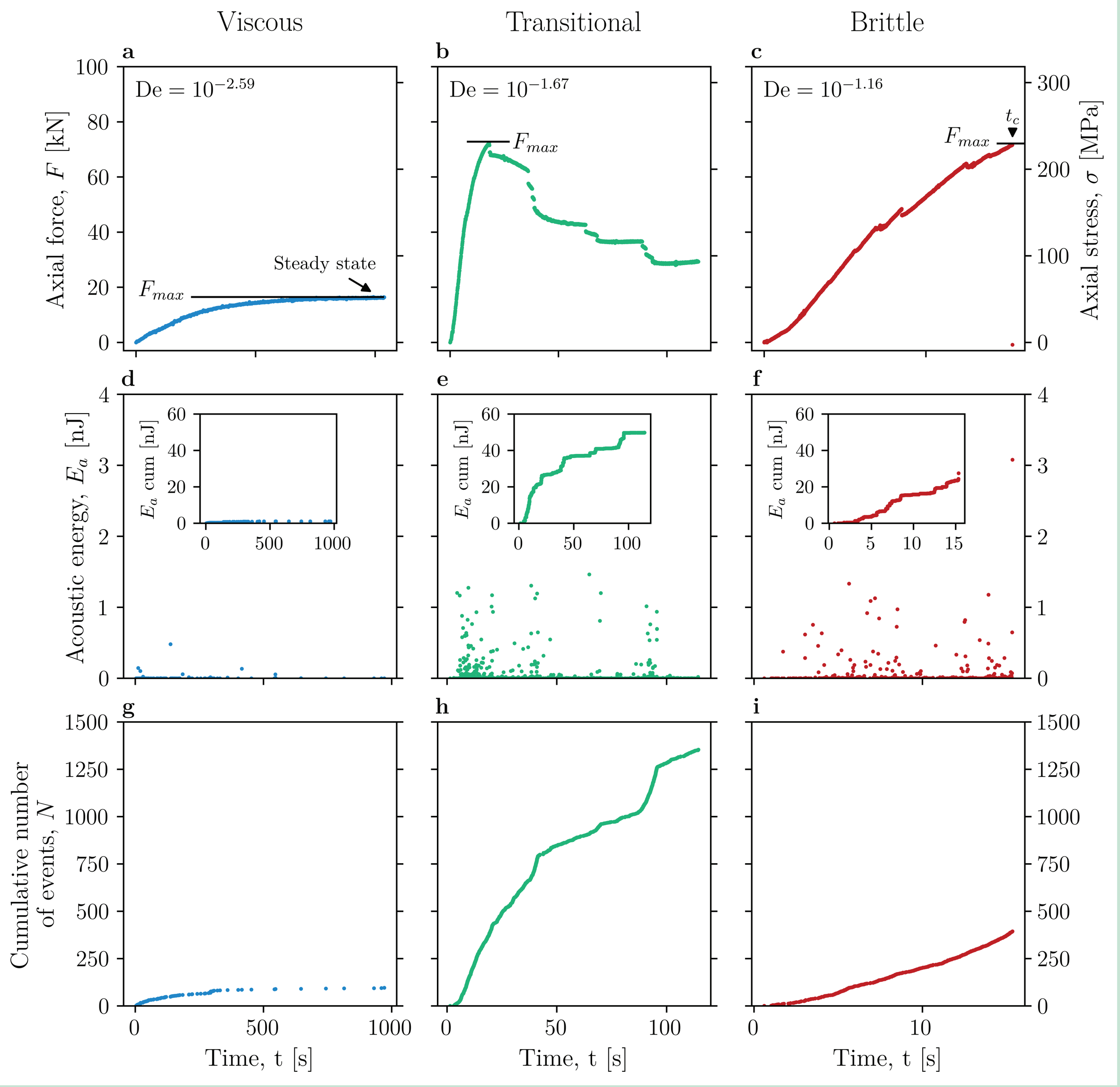


*Figure 3: **a,b,c)** Axial force and stress as a function of time. **d,e,f)** Acoustic energy as a function of time. The insets show the cumulative acoustic energy with time. **g,h,i)** Cumulative number of acoustic events as a function of time. Examples are shown for each type of acoustic behaviour (viscous, transitional and brittle). The Deborah number is given for each experiment.*

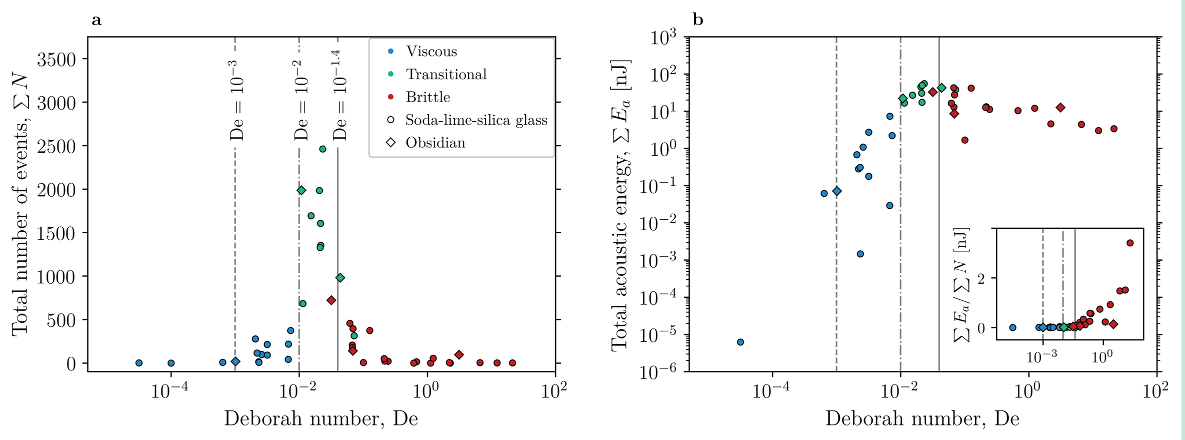


*Figure 4: **a)** Total number of events and **b)** total acoustic energy for each individual experiment as a function of Deborah number, De. The inset shows the total acoustic energy divided by the total number of events for each individual experiment as a function of De. The dashed, dashed-dotted and solid grey lines correspond to De = 0.001, De = 0.01 and De = 0.04, respectively.*

The dimensionless Deborah number (De) is used to locate the viscous-to-brittle transition. The three types of deformation behaviour seem to occur at discrete intervals of Deborah number (Figure 4), which is given by:

$$De = \frac{\lambda_r}{\lambda} = \frac{\mu\dot{\gamma}}{G_\infty}$$

where λ_r is the Maxwell relaxation time [s] and λ is the deformation time [s]. μ is the viscosity [Pa·s] and $\dot{\gamma}$ is the strain rate [s^{-1}]. According to Dingwell and Webb (1989) the infinite frequency shear modulus, G_∞, is $10^{10\pm0.5}$ Pa for all silicate compositions.

The waveforms and spectrograms of individual acoustic events for each of the deformation regimes show that the frequency content is always between 60 kHz and 1 MHz independent of De. However, the amplitude of the AE signal increases strongly with increasing De (Figure 5). This result proves that there are small amplitude events in the viscous regime, which are not associated with any visual observation that can be made after the sample is recovered from the apparatus. Our inference of these specific events is that they are related to the formation of micro-cracks that heal immediately during deformation.

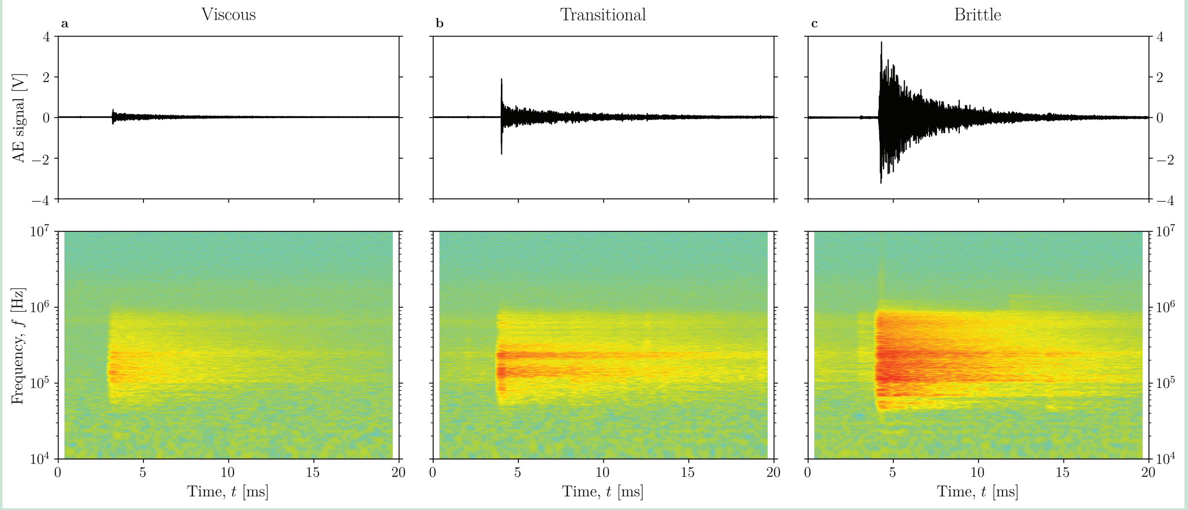


*Figure 5: A waveform of a single event (top figures) and its spectrogram (bottom figures) for the three deformation regimes: **a)** Viscous; **b)** Transitional; **c)** Brittle.*

Forecasting failure

The TROL was optimised for a large range of inital parameters to obtain the best fit and predict the time of failure. Figure 6 shows the normalised failure forecast, which is the ratio between the predicted time of failure, t_f, and the observed time of failure, t_c, as a function of Deborah number. At low De there is a cluster with a forecast error of approximately one order of magnitude. For high De, the forecast error is several orders of magnitude. Note that for those experiments the p-value is negative, which indicates a deceleration in the increase of acoustic events with time (Figure 7c). This would suggest that a power law is not the best model to predict failure of single-phase magmatic liquids.

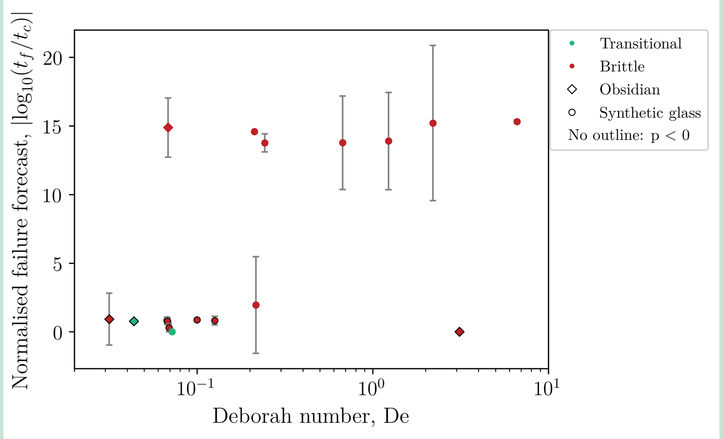


Figure 6: Normalised failure forecast as function of Deborah number, together with its standard deviation. A negative p-value (no outline) indicates a deceleration in the increase in acoustic events with time.

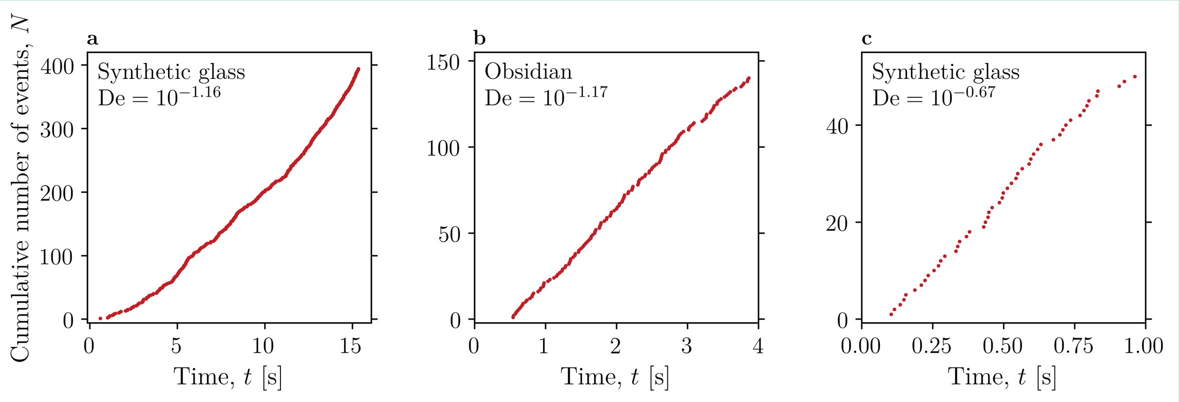


*Figure 7: Typical examples of the cumulative number of acoustic events for both synthetic glass and obsidian: **a)** Acceleration; **b)** Linear increase; **c)** Deacceleration.*

The TROL is compared to an exponential model and a linear model. The event rate for those models is given by:

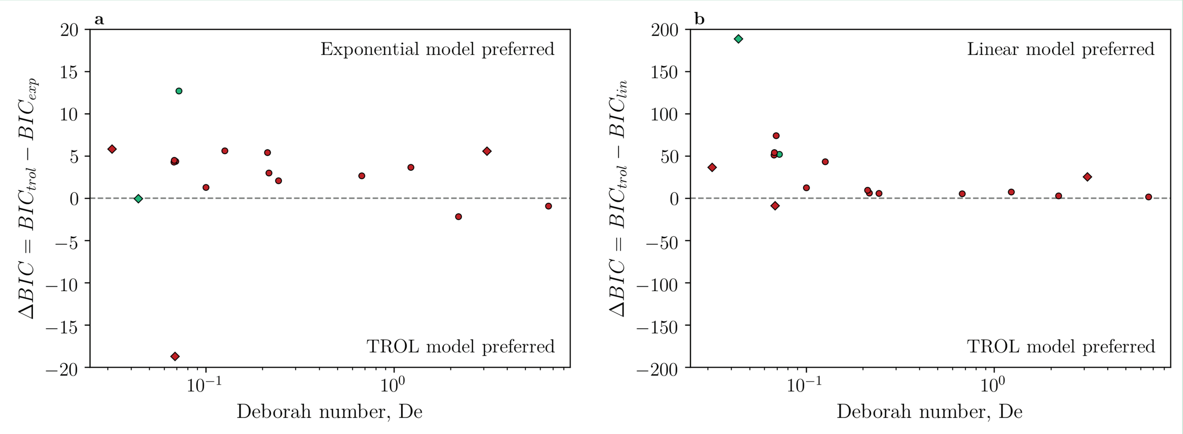
Exponential model: $\dot{\Omega}(t) = k_e \exp(qt)$ Linear model: $\dot{\Omega}(t) = k_l t$

where k_e is the pre-exponential scaling parameter, q is the exponential constant (Bell et al., 2013) and k_l is the slope of the linear trend.

The different models can be compared by assessing the difference in the Bayesian Information Criterion (BIC). The BIC depends on the likelihood of the observations given the model, L, the number of datapoints, N, and the number of free parameters, P. The latter results in a preference for the model with the fewest parameters (Bell et al., 2013). The number of data points is equal to the number of events in this case. The BIC is given by:

$$BIC = -2\ln(L) + P\ln(N)$$

The linear model is preferred over both the exponential model and the TROL for almost all experiments (Figure 8). Note that the linear model does not include a time of failure, so other metrics must be used to predict the critical time, such as a threshold for the event rate or the total number of events.



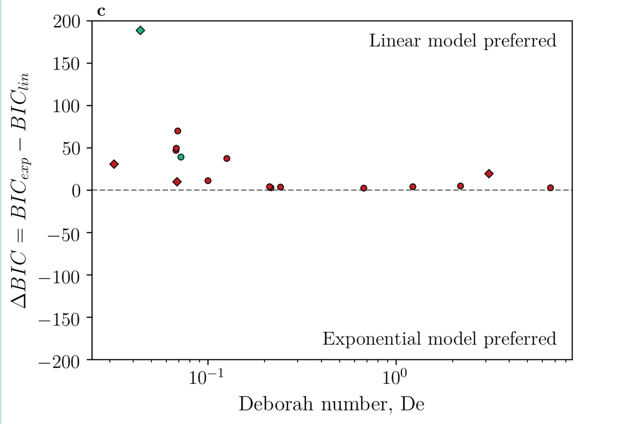


*Figure 8: The difference in BIC between: **a)** the TROL and the exponential model **b)** the TROL and the linear model; **c)** the exponential and linear model. The favoured model generally has a lower BIC value, which is expressed in either a negative or positive value of ΔBIC.*

Conclusions

- The deformation behaviour of single-phase viscoelastic magmatic liquids is viscous for De<0.01, transitional for 0.01<De<0.04 and brittle for De>0.04. For De<0.001, there are no AE due to a purely viscous response.
- The frequency content of the waveforms is always between 60 kHz and 1 MHz independent of De, but the amplitude increases with increasing De.
- At low De, the forecast error is approximately one order of magnitude. For high De, predicting failure can be several orders of magnitude off compared to the observed failure time.
- In case of single-phase magmatic liquids, a linear model is overall preferred over both the exponential model and the TROL. This may be a key reason for erroneous failure forecasts in materials including single-phase magmas and may help interpret poor predictions of eruptive behaviour at some active volcanoes. This also highlights a major shortcoming in the widely used TROL and points toward a need for novel forecasting tools.

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