Rockburst prediction—case studies using a kinematics of failure approach

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Synopsis

We present aspects of one of several ongoing case studies used in the development of prediction techniques for major seismic instabilities. The current investigation centres on accelerated coseismic deformation described by the kinematics of failure and on softening, as well as the characterization of areas of interest by measures of the seismic response at such sites.

Introduction

The first obstacle in any investigation of a problem is the starting point or, equivalently, the first question one asks. This first question usually revolves around:

- how much information is available and
- are there patterns in the information that show the way to the nature of the system? In attempting to predict the evolution of a system towards failure, it is natural to focus on patterns in the system's behaviour prior to previous failures.

One question begets more: What is meant by failure? What is meant by 'the system'? What constitutes a pattern? What does 'prior' to failure mean?

What is failure?

For the purposes of this discussion failure will be defined as the infinite rate of deformation of a rock mass of interest.

Comparative studies of phenomenological models describing kinematics of failure

The starting point for inverting for the 'time to failure' in a given volume of rock is to search for a variable that has the following behaviour with time as instability approaches.

In the equation

$$\dot{\Omega} = \frac{C}{\left(t_f \pm t\right)^{\alpha}} \qquad [1]$$

$\dot{\Omega}$ is the instantaneous rate of change (time derivative) of a variable at time t. The variable Ω is derived from a given physical model of the process leading to instability and C, α and t_f (the time at failure) are constants, unique, to Ω, to be determined. An abbreviated history and physical background to Equation [1] and its application to seismicity is given here. Ω represents a model that describes the kinematics of failure, while the right-hand side of Equation [1] is essentially a translation of the behaviour of the model into a time evolution which contains the time of failure. Note that Equation [1] indeed describes a catastrophe such as failure: at the time of failure, $t = t_f$, and Ω changes infinitely quickly with time.

Saleur *et al* (1996) postulated to replace a power law exponent in Equation [1] with a complex exponent $\alpha = \alpha' + i\alpha''$, $i = \sqrt{-1}$, which results in log-periodic corrections to the creep to failure curve (Figure 2).

Deformation kinetics

Varnes (1987) gives a short potted history of the origins of Equation [1] from the viewpoint of three different phenomena, and a summary follows.

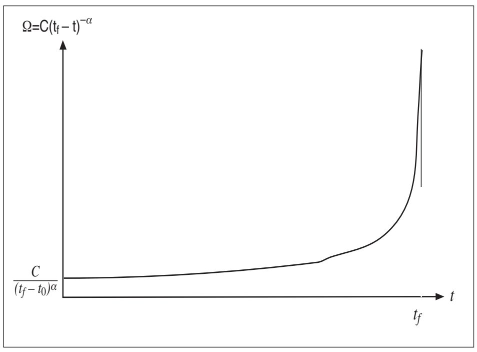

Figure 1—Characteristic behaviour with time of a parameter describing the approach to failure (generated with simulation algorithm)

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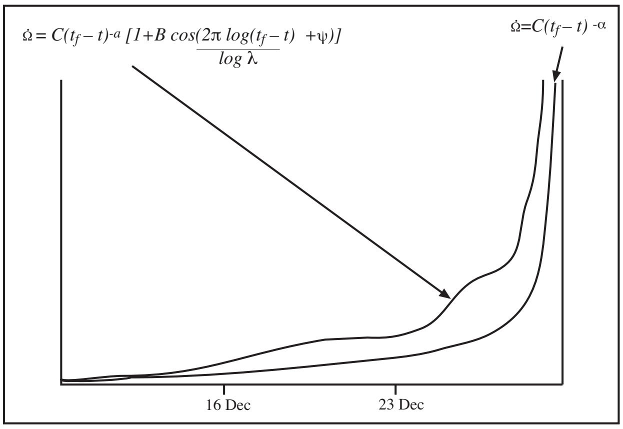

Figure 2—Log-period corrections to the usual power law

Rate process theory

Glasstone *et al* (1941) related viscosity and plasticity mathematically to thermal activation and forces and rates of shear at atomic and molecular levels. The theory is stated mathematically as

$$\dot\Omega = \pm\frac{dN}{dt} = N\frac{kT}{h}e^{\pm\frac{\Delta F}{kT}}2\sinh\left(\frac{\lambda f}{NkT}\right) \qquad [2]$$

which is an expression for the net rate at which bonds are broken (bond repair is also possible) with N the number of bonds per unit area, f an assumed constant force due to applied exterior force, acting on N bonds through an average distance λ, during bond breaking. ΔF is the free energy of activation for the process, k is Boltzmann's constant and h is Planck's constant. T is absolute temperature.

The hyperbolic sine term comes from the difference in probabilities between bond breaking and bond healing. The force f biases the process towards bond breaking ('rupture'). If the force is large enough, it outweighs thermal oscillation ($\lambda f \gg NkT$) and healing can be neglected, so that $2\sinh((\lambda f)/(NkT)) \approx \exp((\lambda f)/(NkT))$. The $(\lambda f)/(NkT)$ defines local stress, so it can be written as $\chi\sigma_0$, that is, proportional to the constant applied stress. In a process of rupture, the number of bonds, N, are used up and goes to zero, so that at the time of total failure, t_f, $\chi\to\infty$. Of course, at t=0, χ=1. With some tedious but straightforward algebra, Equation [2] can then be shown to reduce to

$$\frac{d\chi^{\sigma_0}}{dt} = \frac{1}{t_f \pm t} \qquad [3]$$

Remarkably, this equation, developed to explain viscosity at molecular level, has been applied to larger masses in thermally activated creep processes and fracture of brittle materials as well as stress corrosion and crack propagation in the solid earth (see references in Varnes (1987)).

Equation [3] gives a relation between the rate of stress increase and remaining time in a progressively failing system. There are two problems with it as it stands:

- It needs to relate (t_f–t) to a more readily observable quantity and
- the derivation of [3] assumes large stress—just how large 'large' is, is not easy to decide in the real world.

Tertiary creep

Many materials, when subjected to sustained differential stress which ultimately leads to failure, follow creep curves like the one in Figure [3]. Servi and Grant (1951), after a series of tests to failure on the same material, but at different stress levels, showed that the minimum creep rate, $\dot\varepsilon$, occurring at the point of inflection on a strain–time curve, obeys the relation

$$\dot\varepsilon_{\min}\left(t_f \pm t\right) = constant \qquad [4]$$

where the dot indicates differentiation with respect to time, which was eventually generalized by Saito (1969) after an analysis of slope failures to

$$\frac{d\varepsilon}{dt} = \frac{C}{\left(t_f \pm t\right)^{\alpha}} \qquad [5]$$

that is, the creep rate is proportional to a power of the remaining time during tertiary creep to failure.

Continuum damage mechanics

Kachakov and Rabotnov first postulated relations between stress, strain, time and an internal state variable called 'damage' in metals in the 1960s in the Russian literature. Leckie and Hayhurst (1977) generalized these relations to multiaxial stress states and Ashby and Dyson (1986) included creep damage:

$$\frac{\dot\varepsilon}{\dot\varepsilon_0} = \left(\frac{\sigma}{\sigma_0}\right)^{j}\frac{1}{(1 \pm \omega)^{k}} \qquad [6]$$

$$\frac{\dot\omega}{\dot\omega_0} = \left(\frac{\sigma}{\sigma_0}\right)^{p}\frac{1}{(1 \pm \omega)^{g}} \qquad [7]$$

where ω is the damage variable (ω = 0 when the material is undamaged and ω = 1 at rupture). Assuming that the load (and thus σ/σ_0) remain constant and that t = 0 when ω = 0, and $t = t_f$ when ω = 1, Equation [7] can be integrated:

$$1 \pm \omega = \left(\frac{t_{f\pm t}}{t_f}\right)^{\frac{1}{g+1}}. \qquad [8]$$

Combined with Equation [6] this gives Equation [5] with

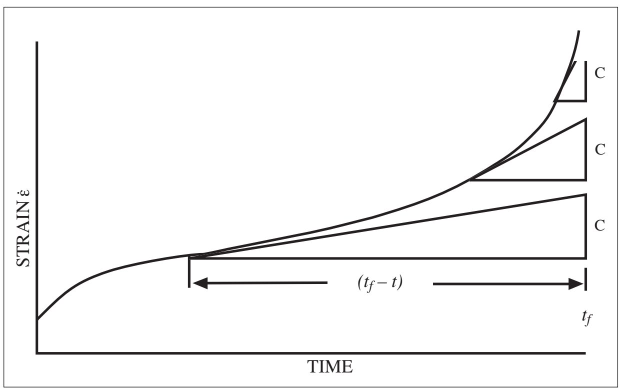

Figure 3—Strain versus time creep curve with a decelerating primary part and accelerating tertiary part (modified from Varnes, 1989)

$$C = \varepsilon_0 \left(\frac{\sigma}{\sigma_0}\right)^j t_f^{\frac{k}{g+1}}, \quad \alpha = \frac{k}{g+1} \cdot \qquad [9]$$

Thus the same expression as that for tertiary creep is recovered.

Power law behaviour—a few comments

The behaviour exemplified by Equations [9] and [1], commonly called power–law behaviour, since one variable depends on a power of another (say, strain on a power of the remaining time to failure) has in recent years generated interest far beyond materials science. Power law behaviour has an intimate connection with (some would say is equivalent to) scaling laws found in renormalization group theories and complex systems.

To clarify: Equations [9] and [1] say that the rate of change of a variable at a time t is dependent on the future time of failure t_f. This being so, it should then be possible to invert for the time of failure if the variable Ω or its rate of change at t is known. In recent years, with the further expansion of chaos theory and nonlinear dynamics, this type of dependency has increasingly been shown to be a fundamental property of nature, encoded in scaling laws. If a variable f depends on, say, the length of a distance L through a power law,

$$f_L = L^\gamma$$

then, for another distance, KL, where K is some number,

$$f_K = (KL)^\gamma = K^\gamma L^\gamma = K^\gamma f_L$$

and the new f is thus K^γ times bigger or smaller than the original. The variable scales: it is still the same variable, just bigger or smaller. This is the same as the argument which states that there is no qualitative difference between large and small seismic events: they are scaled versions of each other. In terms of a time to failure analysis, smaller events are seen as precursors to bigger ones, so that each successive event is in some fashion the sum total of the preceding ones. Said the other way around: each event to some extent is the predictor of following events. Fractal phenomena exhibit scaling, or more strongly, scale invariance. There is increasing evidence that seismicity is such a scale invariant process (Saleur *et al*, 1996, Newman *et al*, 1994). This means that small scale seismicity is a scaled-down version of larger processes. In this sense, the dependence of Ω at time t on a future time t_f should not be seen as a crystal ball effect, but rather as a manifestation of the scale invariance of the process in time. Physically, nothing prevents scaling in time as well as in space.

Power law behaviour in seismicity

Kostrov and Das (1988:158) present a concise explanation of the treatment of the earth's interior as a continuous medium, extended to seismicity as a continuum process. To paraphrase: in order to describe seismicity, the appropriate level of description is one in which whole regions which contain seismic events are considered as particles in a continuous medium. The elementary time unit is also scaled to one which is larger than the average recurrence time of seismic events. On this level, sequences of events merge on the whole into a process of quasi-plastic deformation. The essential point is then that larger events at some fixed level of description are viewed as fractures or failures of a material, while smaller events are 'smeared out' and appear as deformation, not failure.

In the light of the above statements about power law behaviour in seismicity, parameters are sought which, during the nucleation period leading to instability, have the characteristic behaviour exhibited in Figure 1. Three candidate parameters are currently under investigation.

Seismic strain rate

The seismic strain rate during time $\Delta t = t_2 - t_1$ in a volume ΔV is given by

$$\frac{\Delta \varepsilon_S}{\Delta t} = \frac{\sum_{t=t_1}^{t_2} M_{(t)}}{2\mu \Delta V (t_2 \pm t_1)} \qquad [10]$$

where $M_{(t)}$ is the scalar seismic moment of the event that takes place at time t and μ is the rigidity of the rock. The argument for using seismic strain rate depends, of course, on the validity of tertiary creep as a short-term precursor.

Accelerating coseismic deformation and softening

Before failure can occur, there must be softening in a critical volume of rock. Note that this volume is also referred to as the 'volume of interest'. Stresses are transferred to outside the critical volume during nucleation so that low stress drop events can be expected in the volume, while events with larger apparent volumes should become more common producing accelerated deformation. This implies a drop in average energy index within this volume (Mendecki, 1997). A parameter to attempt to fit to the power law could therefore be

$$\frac{\Delta \Omega}{\Delta t} = \frac{\sum_{t=t_1}^{t_2} V_{a(t)}}{\Delta V \overline{EI} (t_2 \pm t_1)} \cdot \qquad [11]$$

Here, $V_{a(t)}$ is the apparent volume of an event occurring at time t, ΔV is the volume of interest and $\overline{EI}$ the average energy index during Δt.

Seismic Schmidt number

Increasing strain rate and dropping seismic stress in the nucleation volume (Mendecki, 1997) implies a decrease in seismic viscosity,

$$\eta_s = \frac{\sigma_s}{\dot{\varepsilon}_s} \cdot$$

The volume is, however, trying to diffuse, so that the average distance $\bar{X}$ between events can be expected to increase. At the same time, an increase in micro seismicity should lead to a decrease in the average time $\bar{t}$ between events. In other words, the seismic diffusion,

$$d_s = \frac{(\bar{X})^2}{\bar{t}}$$

should increase.

Given these two, a parameter to test is the seismic Schmidt number,

$$\frac{1}{Sc} = \rho \frac{d_s}{\eta_s} = \frac{\rho (\bar{X})^2 \left(\sum_{t=t_1}^{t_2} M_{(t)}\right)^2}{\bar{t}\, 4\mu^2 \Delta V (t_2 \pm t_1) \sum_{t=t_1}^{t_2} E_{(t)}} \cdot \qquad [12]$$

Note that this parameter is already a rate.

What is 'the system'?

The case studies presented here were selected from two regions which differ, both geologically and in mining practice. Since the three computer programs used to analyse the data (and fit it to a failure curve) are only at the level of research tools, the results so far are *speculative* and the data sets are kept anonymous. A summary of the cases under study here, follows.

- Area 1 represents relatively deep mining in a region where the infrequency of faults and dykes and the relatively small throws of these structures allow longwall mining.
  Here, events of a given critical local magnitude or higher, in a period of about a year, at several sites, are considered. A metaset of data sets were selected by a mine seismologist by contouring the inverse Deborah number. This is an attempt to delineate a volume of interest (a system) by considering the decreasing usefulness of past data as a major instability is approached, both in time and in space. Recall that

  $$\frac{1}{De_s} = \mu \frac{\Delta t}{\eta_s}$$

  where Δt is the flow time or observation period and η_s is the seismic viscosity. In an alternate hierarchy of description η_s really references the 'stiffness' of a flow of information, or how much information from one event affects another. Thus the smaller η_s, the more 'fluid' the communication between events. Contouring $(De_s)^{-1}$ often leads to clear hills of instability in time and space. Such hills possibly demarcate areas and times of nucleating instability. Another metaset of the same sites is being selected using 'conventional' methods, such as delineating a longwall or pillar.
- Area 2 represents intermediate depth mining of an orebody disrupted by numerous faults and dykes, resulting in scattered mining methods. Generally, faults in this region have a relatively 'soft' character and the orebody is overlain by a shale band. This combination can be considered to allow generally 'soft' rockmass response to mining.

Events of a given critical local magnitude or higher over a period of ten months are being studied in this region (this catalogue, as with the previous region, is continually updated). The cases come from several small sites which are under continuous monitoring. Some monitoring sites have been chosen by mine seismologists on the basis of experience and knowledge of the area; some were delineated by contouring the inverse Deborah number.

What constitutes a pattern?

One of the problems with developing an algorithm for the prediction of instabilities in the South African mining environment is that indicators of preparation behave differently in different regions. Sometimes they behave differently from mine to mine in the same region, or from workplace to workplace. A seismologist over the years develops an intuition about a given area, and uses this intuition in such matters as choosing the time lengths of sampling windows for different parameters, threshold values for those parameters, as well as threshold values for the rates of change of these parameters. Even the question of which parameters are the most indicative in a given area (or at a given time, since rates of production and work areas change) is a matter of experience and learned intuition.

The algorithm INDICATOR is an attempt to start to quantify this 'gut feel' knowledge. The idea for it is rooted in the work of Gelfand *et al* (1976), Knopoff (1997) and Keilis-Borok and Lichtman (1993), who attempted to use nonparametric statistics to determine the probability that a given factor is a precursor to, or a harbinger of, a major seismic event.

Essentially, a questionnaire is constructed which asks questions, the answers to which are either 'Yes' or 'No'. A 'Yes' answer results in '1' being assigned to an event for a given factor, while a 'No' results in a '-1'. In this fashion, a bi-polar cipher can be built up which characterizes an event. With enough events from a given area or, if one is allowed to dream a little, a workplace, it may be possible to construct a cipher characterizing the seismic rockmass response at a *given locality*. Examples from INDICATOR should make the idea clearer.

Tables I and II present output from INDICATOR when used on some catalogues from the two regions. Twenty questions, appearing across the top rows of the tables, are posed. Thus, for example in Table I, the questions were:

- Did any $M_L \geq M_{thres}$ occur 150 hours before an event with at least given critical M_L?
- Did the cumulative apparent volume increase by at least 0.003 km^3 60 hours during such an event, given a background cumulative apparent volume of 0.003 km^3 already *in situ*?
- Did the energy index of an event, immediately prior to the main event, differ from that of one 36 hours previously, by at least a quarter of an order of magnitude?

And so on. Question 4 asks whether there was a drop in energy index, and 5 and 6 asks the same as 3 and 4, but of the median energy index, in a time window of 30 hours or 5 events. Questions 7, 8, 9 and 10 look for fluctuations in the energy index and median energy index, and 11 and 12 consider overall changes and fluctuations in seismic Schmidt number over 24 hours before an event. In the rest of the questions, ε_S, σ_S, $\overline{X}$ and $\overline{t}$ seismic strain, stress, average inter-event distance and time, respectively.

What does 'prior to failure' mean?

The time windows in Tables I and II were chosen by the simple expedient of running a rudimentary program testing every combination of time windows (and filters, for median energy index) between one day and seven days. Longer windows than seven days are problematic in that the time series of the parameters often acquire a 7-day 'tide' induced by the production cycle.

Of note in the tables are the threshold values (number of 'No' answers for an event) which are needed to establish the suitability of a question as a diagnostic question and the subsequent splitting of datasets for pattern recognition purposes. This is not of particular consequence to the current discussion. What should be noted, though, is the different patterns of answers for Tables I and II.

Table I

INDICATOR output for Region A

Indicator	$M_L \geq$ thres	$\Delta V_A \geq 0.003$	$\lvert\Delta \log EI\rvert \geq 0.25$	$\Delta \log EI \leq -0.25$	$\lvert\Delta \log EI_M\rvert \geq 0.25$	$\Delta \log EI_M \leq -0.25$	Any $\lvert\Delta \log EI\rvert \geq 0.25$	Any $\Delta \log EI \leq -0.225$	Any $\lvert\Delta \log EI_M\rvert \geq 0.25$	Any $\Delta \log EI_M \leq -0.25$	$\Delta \log Sc_s \leq -1$	Any $\Delta \log Sc_s \leq -1$	$\Delta\varepsilon_s > 0$	$\Delta\sigma_s < 0$	$\Delta X > 0$	$\Delta\bar{t} < 0$	Any $\Delta\varepsilon_s > 0$	Any $\Delta\sigma_s < 0$	Any $\Delta \dot{X}$ U	Any $\Delta\bar{t} < 0$	Threshold
Time before event	150h	60h	36h	36h	36h	36h	36h	36h	36h	36h	42h	42h	42h	42h	42h	42h	42h	42h	42h	42h	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Data Sets 1	-1	-1	1	1	1	1	1	1	1	1	-1	1	1	-1	1	1	1	1	1	1	4
1	1	1	1	1	1	1	1	1	1	1	-1	1	1	1	1	1	1	1	1	1	1
2	1	-1	1	1	1	-1	1	1	1	-1	1	1	-1	-1	1	-1	1	1	1	-1	7
3	1	-1	-1	-1	-1	-1	1	1	-1	-1	-1	1	-1	-1	1	1	1	1	1	1	10
4	-1	-1	1	1	1	1	1	1	1	1	-1	-1	1	1	1	1	1	1	1	1	4
5	-1	-1	-1	-1	-1	-1	1	1	-1	-1	-1	-1	1	1	-1	1	1	1	-1	1	12
5	-1	-1	1	1	-1	-1	1	1	-1	-1	-1	-1	1	-1	-1	1	1	1	-1	1	11
5	-1	-1	1	-1	1	1	1	1	1	1	-1	1	1	-1	-1	1	1	1	-1	1	7
6	-1	-1	1	-1	-1	-1	1	1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	9
7	-1	-1	-1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1	1	1	1	1	1	10
8	-1	0	1	-1	1	1	1	1	1	1	-1	-1	1	1	1	1	1	1	1	1	4
	3	1	8	5	6	5	11	11	6	5	1	6	9	5	8	10	11	11	8	10	
Percentage yes	27.2	9.0	72.2	45.4	54.5	45.4	100	100	54.5	45.4	9.0	54.5	81.8	45.4	72.2	90.9	100	100	72.2	90.9	

Number of events of local magnitude M_{crit} : 11
Median Energy Index filter = 30h, 5 events

Table II

INDICATOR output for Region B1

Indicator	$M_L \geq$ thres	$\Delta V_A \geq 0.003$	$\lvert\Delta \log EI\rvert \geq 0.25$	$\Delta \log EI \leq -0.25$	$\lvert\Delta \log EI_M\rvert \geq 0.25$	$\Delta \log EI_M \leq -0.25$	Any $\lvert\Delta \log EI\rvert \geq 0.25$	Any $\Delta \log EI \leq -0.225$	Any $\lvert\Delta \log EI_M\rvert \geq 0.25$	Any $\Delta \log EI_M \leq -0.25$	$\Delta \log Sc_s \leq -1$	Any $\Delta \log Sc_s \leq -1$	$\Delta\varepsilon_s > 0$	$\Delta\sigma_s < 0$	$\Delta X > 0$	$\Delta\bar{t} < 0$	Any $\Delta\varepsilon_s > 0$	Any $\Delta\sigma_s < 0$	Any $\Delta X > 0$	Any $\Delta\bar{t} < 0$	Threshold
Time before event	48h	48h	66h	66h	66h	66h	66h	66h	66h	66h	48h	48h	48h	48h	48h	48h	48h	48h	48h	48h	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Data Sets 2	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	1	-1	1	1	1	1	1	1	7
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3	-1	1	1	1	-1	-1	1	1	-1	-1	1	1	-1	1	1	-1	1	1	1	-1	8
3	-1	1	-1	-1	-1	-1	1	1	-1	-1	-1	-1	-1	1	1	-1	1	1	1	-1	12
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3	-1	1	1	1	-1	-1	1	1	-1	-1	-1	-1	1	-1	-1	1	1	1	-1	1	10
3	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	-1	1	1	-1	1	1	1	-1	1	10
5	-1	1	-1	-1	-1	-1	1	1	-1	-1	-1	1	-1	1	1	-1	1	1	1	-1	11
5	1	1	1	1	-1	-1	1	1	-1	-1	-1	1	1	-1	1	-1	1	1	1	-1	8
5	-1	-1	-1	-1	-1	-1	1	1	-1	-1	-1	-1	1	-1	1	1	1	1	1	1	11
5	-1	1	1	1	1	1	1	1	1	1	-1	1	1	-1	-1	1	1	1	-1	1	5
	4	11	7	5	3	3	13	13	3	3	1	4	9	5	7	6	13	13	7	6	
Percentage yes	30.8	84.6	53.8	38.5	23.1	23.1	100	100	23.1	23.1	7.7	30.8	69.2	38.5	53.8	46.2	100	100	53.8	46.2	

Number of events of local magnitude M_{crit} : 13
Median Energy Index (EI_M) filter = 138h, 5 events

Case studies

The rest of this discussion will focus on Table I, a metaset chosen by contouring the inverse Deborah number. On the basis of the relatively high frequency of 'Yes' answers for the energy index batch of questions, it was decided to test the time to failure algorithm by using the parameter

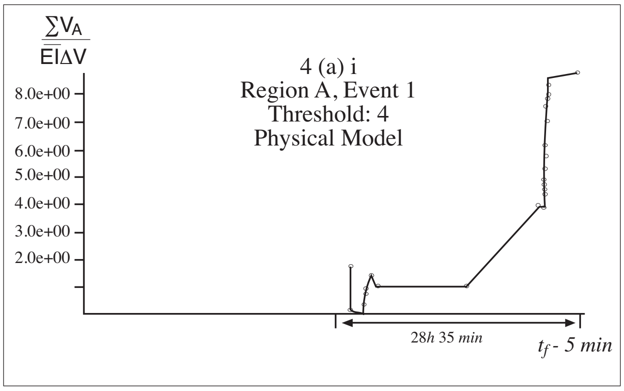
$$\frac{\sum_{t=t_1}^{t_2} V_{A_{(t)}}}{\Delta V \bar{E} I\left(t_2 \pm t_1\right)}$$

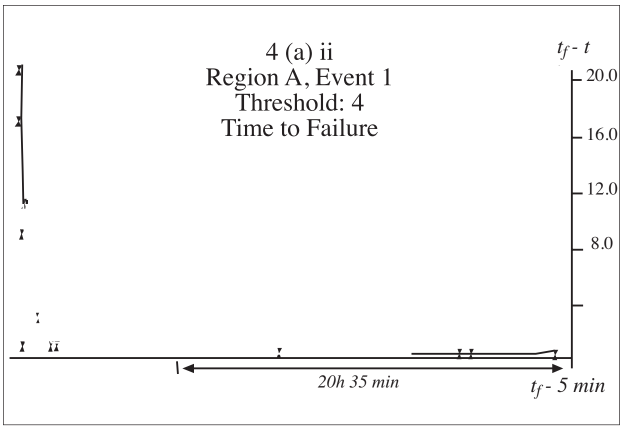
Figures 4 to 6 summarize the result. These speculative results separate into three groups:

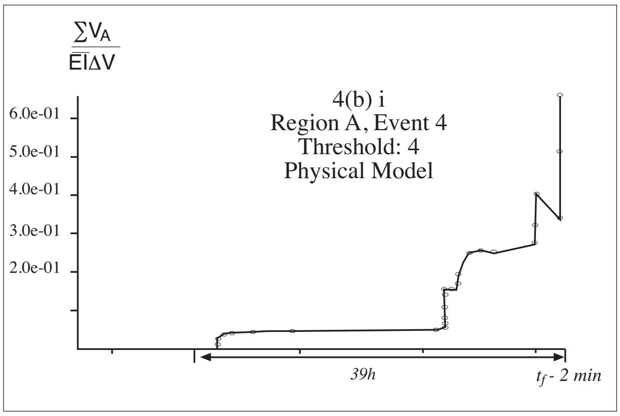
Figure 4: Four events for which the current algorithm performed well, in the sense that the time to failure (t_f - t) dropped close to zero a considerable time before a large event. Noteworthy are the facts that:

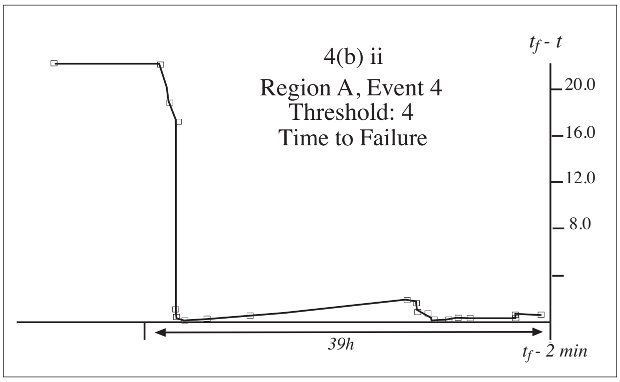
- ➤ The measure of deformation exhibits an accelerating, *oscillatory*, behaviour at about the same time as the time to failure drops to zero (remember Figure 3!).
- ➤ In contrast to the few cases in the catalogue in which (t_f - t) became zero and no major event followed, the time to failure becomes zero and stays that way for a considerable period (in the few mispredictions, (t_f - t) is zero for only a single time step).
- ➤ The average threshold for these cases is 6.25, the median 5.5.

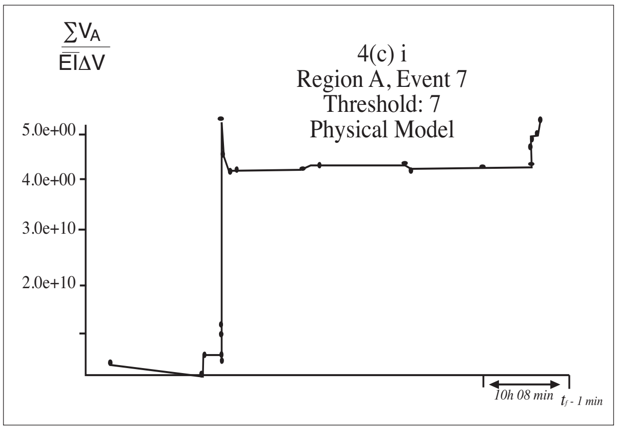
Figure 4—Four exemplary cases of premonitory accelerated seismic deformation. The t_f - t axis runs from 0 to 20 days, in 4-day intervals

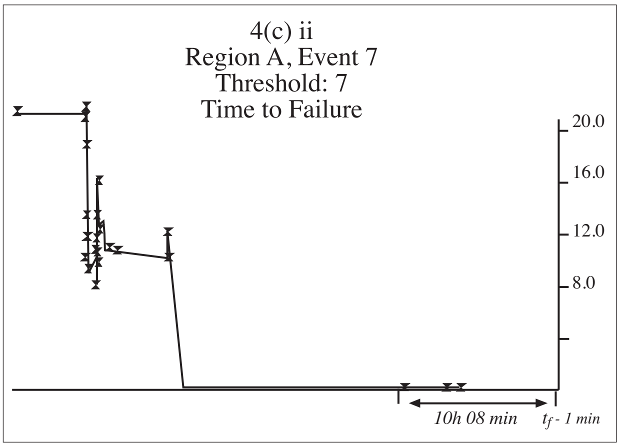


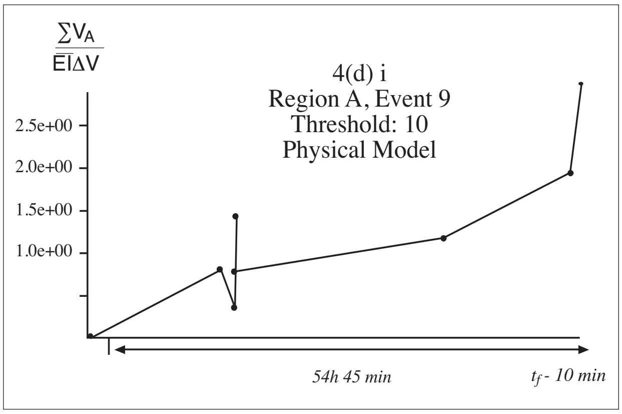












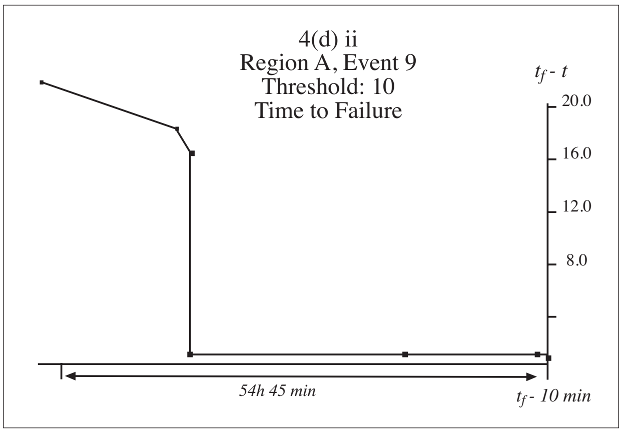
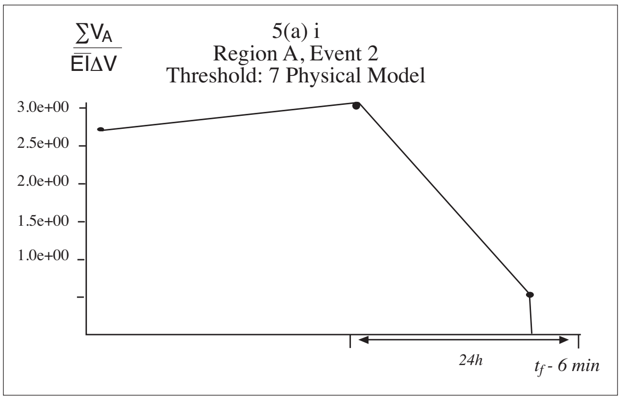


Figure 5—Really bad behaviour of the time to failure algorithm. The common feature in Figures 5 is a scarcity of events prior to the main event



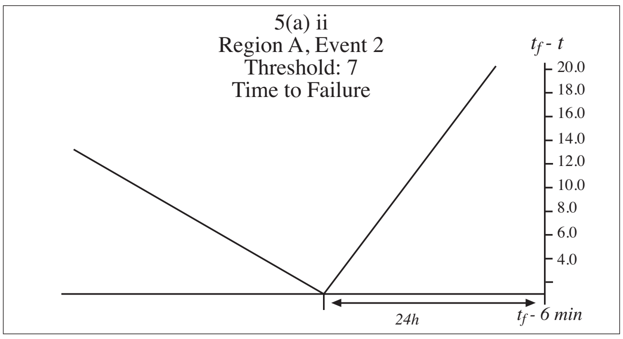
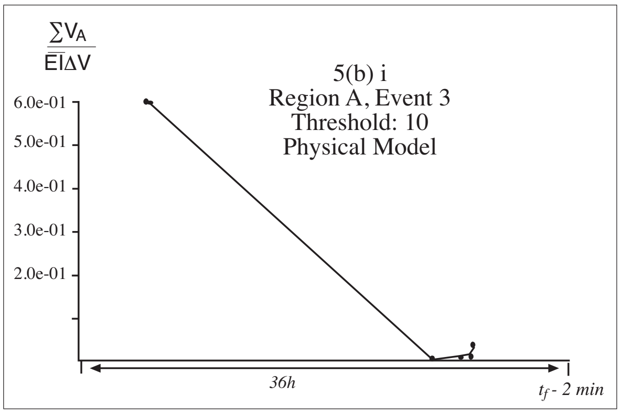
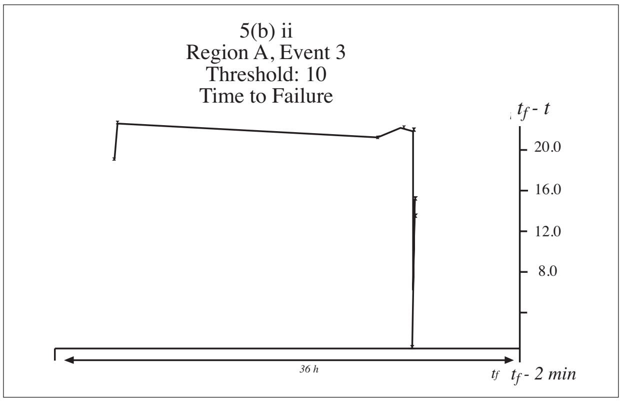


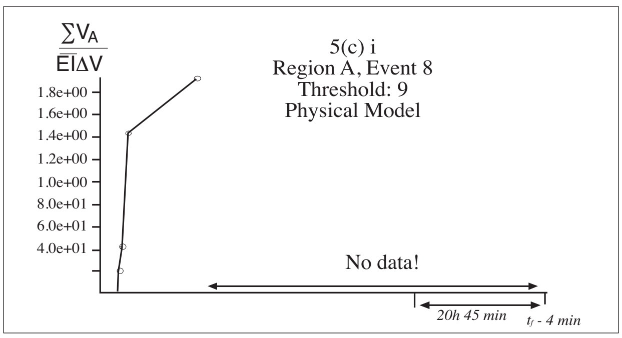
Figure 5: Four events for which the performance was not so great. The explanation lies in the selection of the volume of interest and then the application of a measure of coseismic deformation as a predictor: recall that the data sets in this region were delineated using contours of the seismic viscosity,

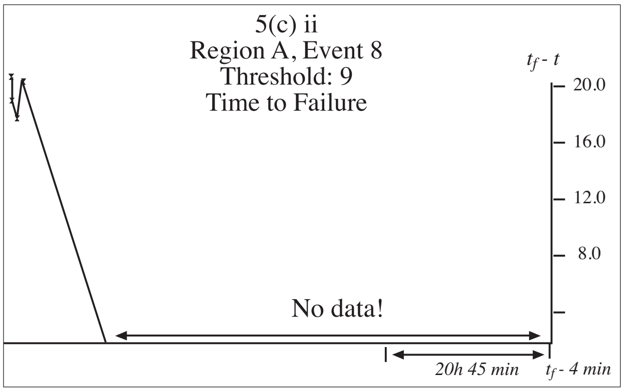
$$\eta_s = \frac{2\mu^2 \Delta V \Delta t \Sigma E}{(\Sigma M)^2}$$

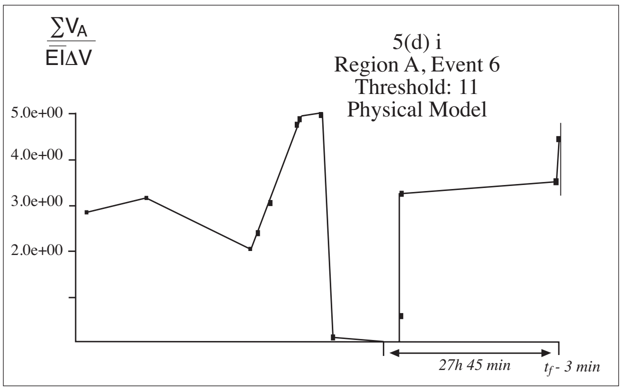
Thus, even with a scarcity of events (quiescence) η_s can increase since the time period Δt grows, and/or the few next events are of higher energy to moment ratio. These four cases are a reminder that there is not one unique way, even in the same region, of choosing a volume of interest from which to select a time series characterizing seismic activity at a given site. The average threshold for these events is 9.25, the median 9.5. Naïve use of the inverse Deborah number can exacerbate the issue. A very few events of large moment (soft events) can distort the statistical picture drastically.











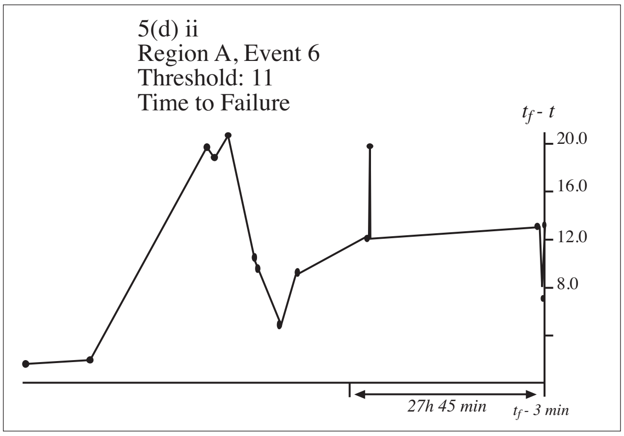
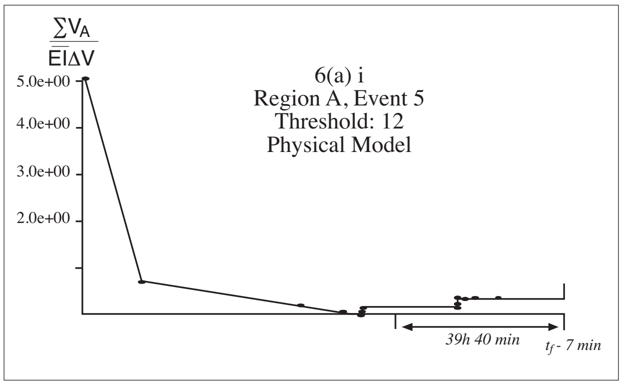
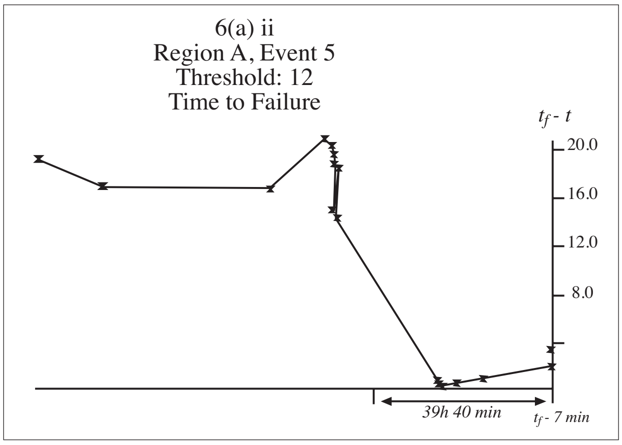


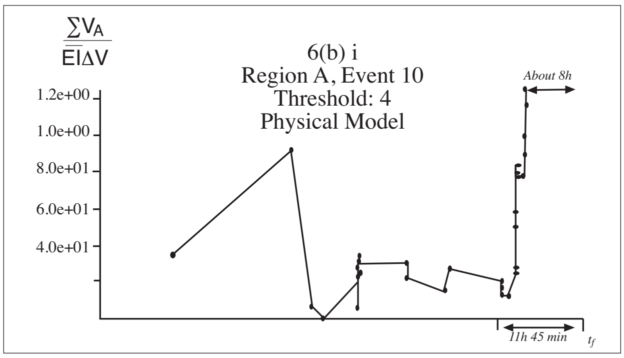
Figure 6: The two events here represent prediction disaster as far as the variable used and current algorithm is concerned. They also remind one that the list of diagnostic questions needs fine-tuning and expansion. One can speculate that Figure 6(a) probably shows the onset of accelerating deformation, but that *perhaps* an asperity on a structure was triggered 'prematurely' (compare the behaviour at around t_f with the onset of accelerated deformation in Figures 4). In fact the event in Figure 6(a) was indeed plotted on a geological structure, at some distance away from the events prior to failure. It may even be that this event had very little to do with the activity in the rest of the data set.

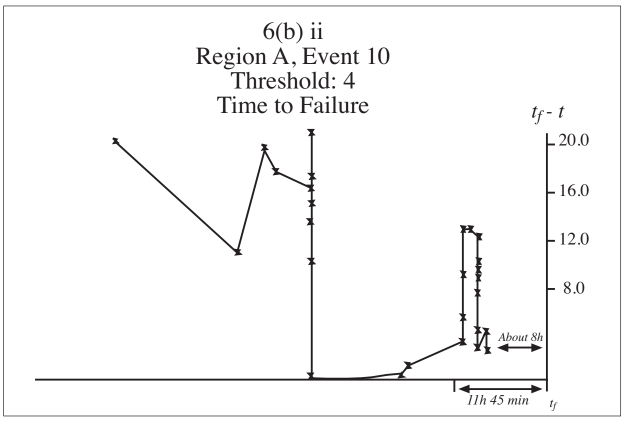
Figure 6(b) is interesting from the viewpoint of back-analysis, as well as physics. The gap of eight hours suggests either a sudden stiffening of the system during the preceding rapid deformation, or that the event was part of a larger developing process, temporarily defused at t_f.

Figure 6—Possibly interrupted or ongoing but defused processes of coseismic deformation









Discussion

Using the kinematics of failure to study the prediction of major seismic instabilities is showing promise. In those cases where it does not work at all, one can usually find the reasons why. Sufficient data is an imperative, unless the evolution of mining-initiated processes at a site are clearly controlled by geological structures. One of the priorities is to bring order to the list of possible approaches to the problem. These approaches have to take cognisance of different methods of data selection (delineation of critical volumes and times), site and process characterization. As far as actual computation is concerned, there are possibly more efficient inversion methods, the investigation of which have only just begun.

The research tools we have developed in this first year of the project are giving us tantalising glimpses of the possibility that, 'hey, it might work after all!'

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