Experiences in rockburst prediction

Gerrie van Aswegen
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Rockbursts can be traumatic phenomena

Objectives of seismic monitoring in rockburst prone mines

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- **Potential rockburst detection**
- **Long term hazard assessment**
  - **Back analysis**
  - **Calibrated models**
- **Medium term hazard assessment**
  - **Spatial detection of potential instabilities**
    - **Essentially using the asperity model for spatial prediction**
  - **Monthly hazard ratings**
- **Short term hazard assessment**
  - **Time history analyses for the detection of unstable processes**

Definitions

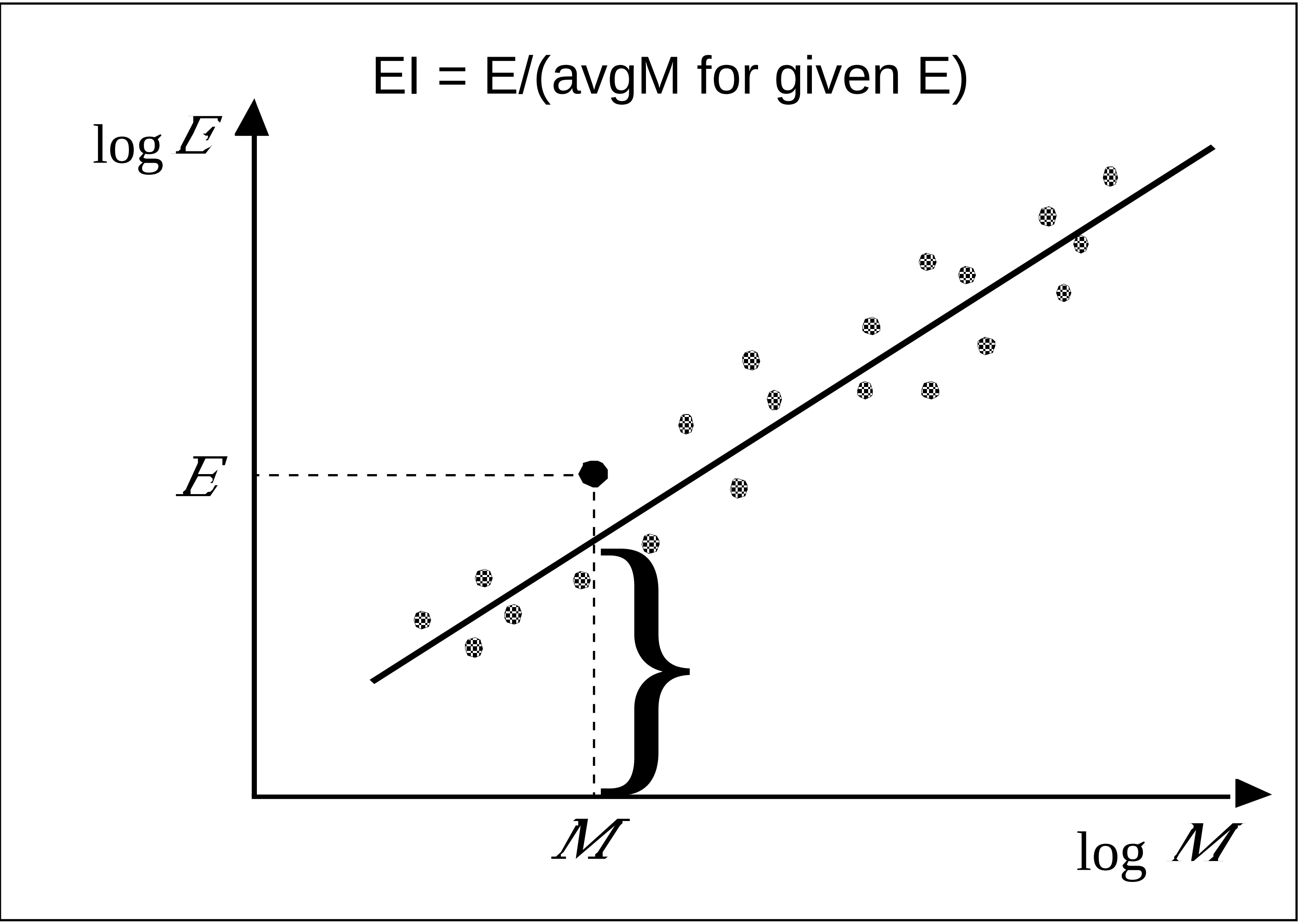
- Basic seismic source parameters
- Derived parameters

Definitions

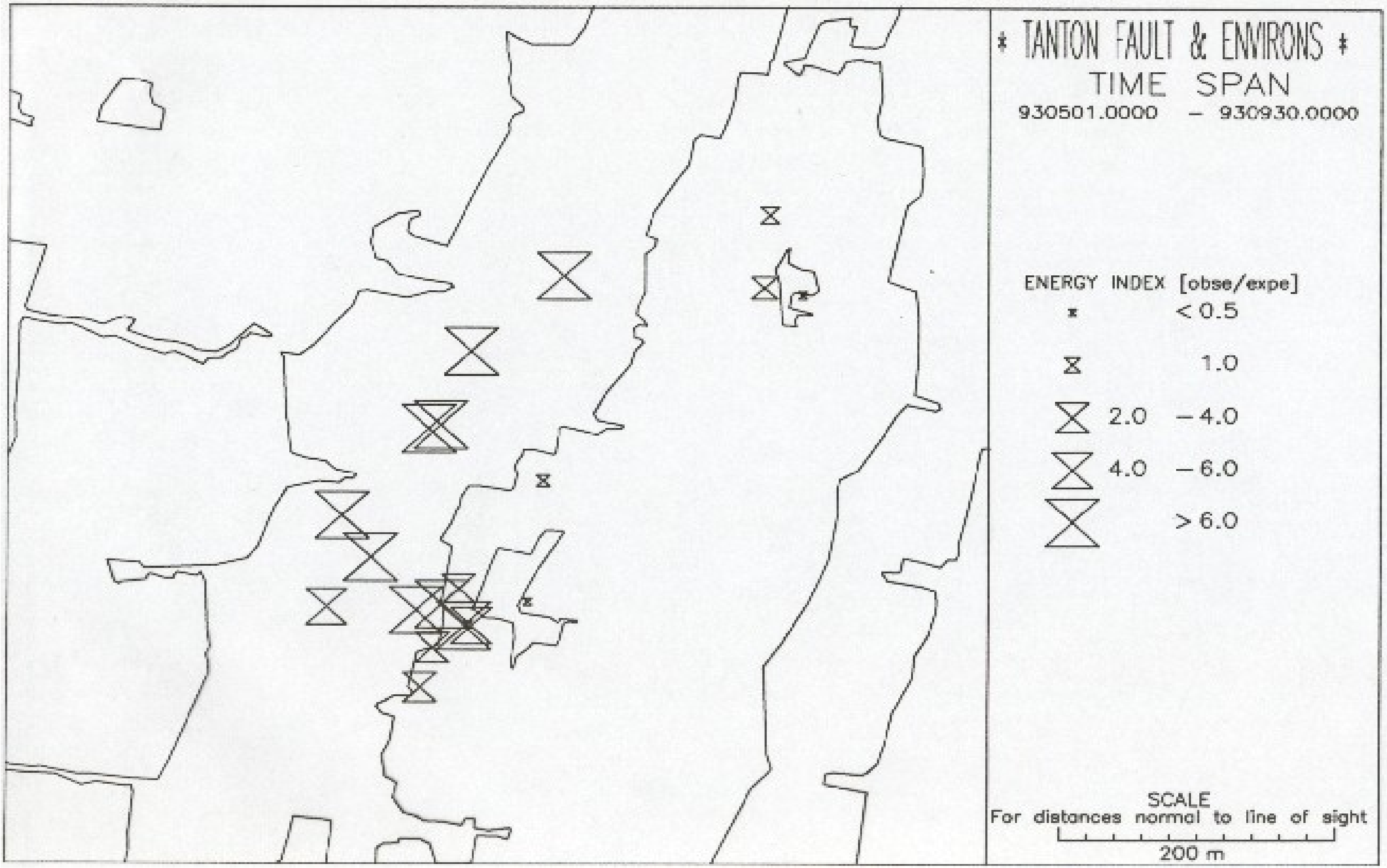
- Basic seismic source parameters
  - Time (t0)
  - Space (x,y,z)
  - Seismic potency – i.e. moment/G
  - Radiated seismic energy

- Derived parameters
  - Energy Index
  - Apparent volume
  - Seismic Schmidt number

The E-M relation
$\log(E) = c + d \cdot \log(M)$



The E-M relation:
EI at work



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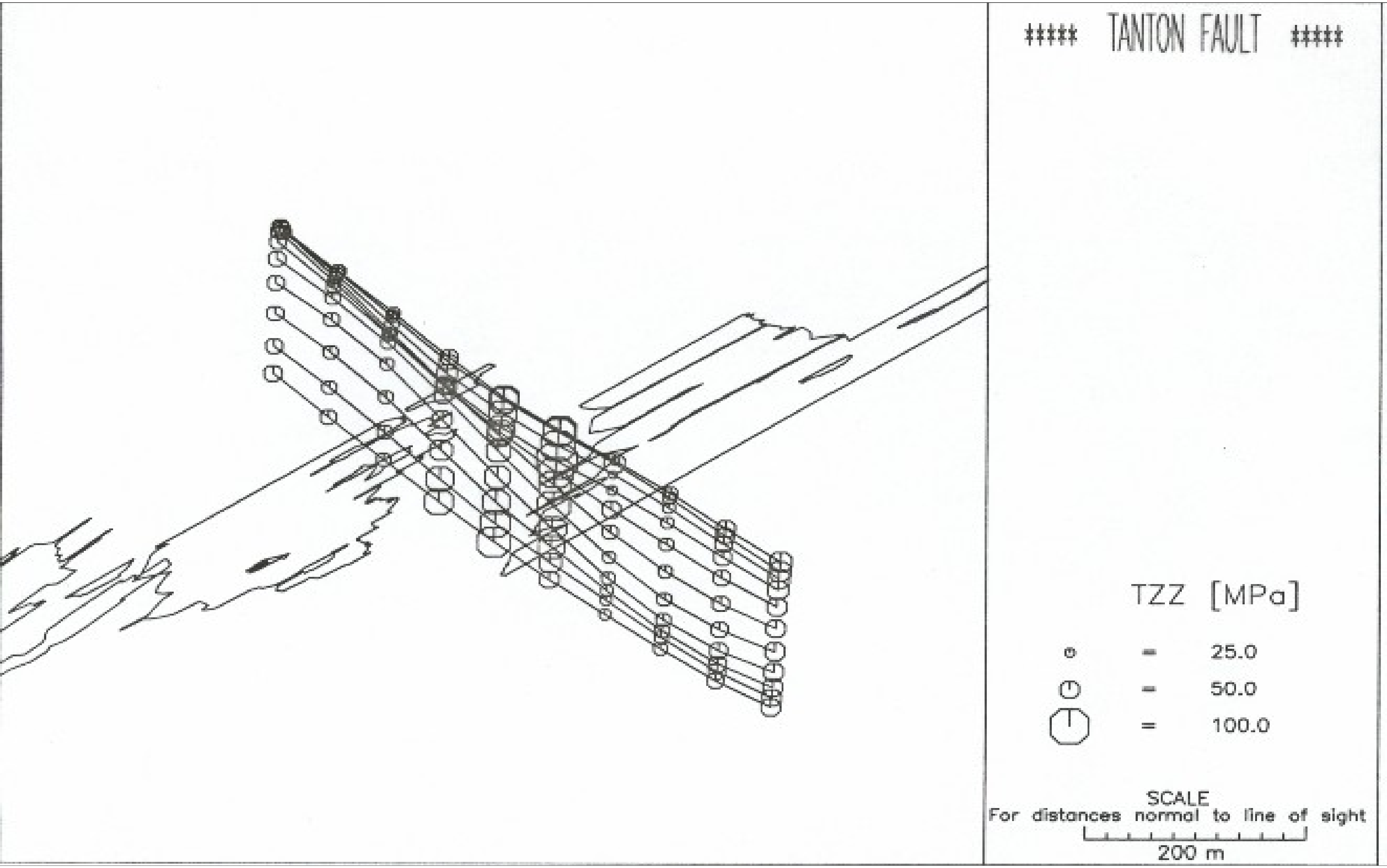

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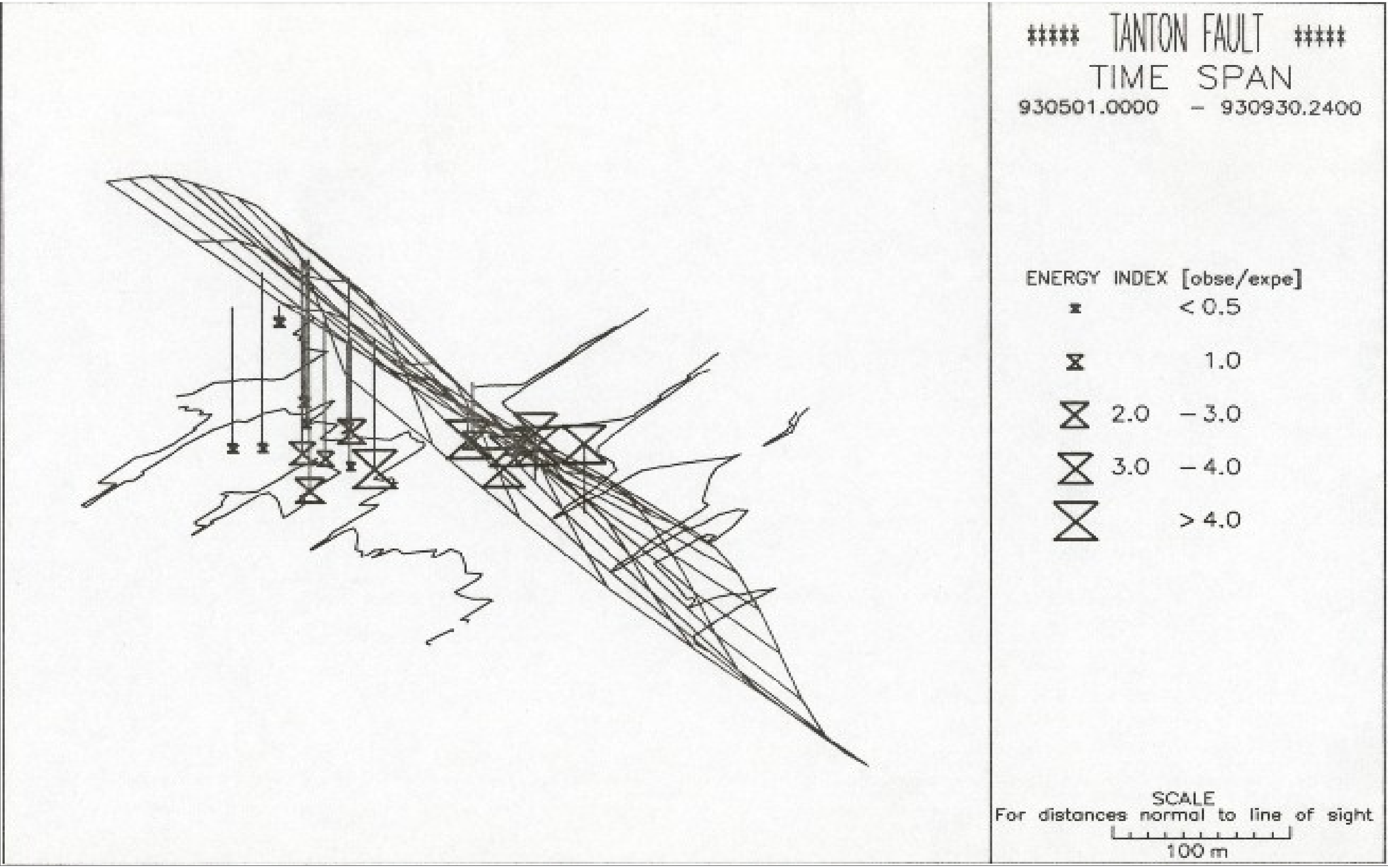


Apparent volume

Seismic source volume scales with

moment/stress drop

Replacing stress drop with apparent stress:

moment/(E*G/M)

Apparent volume

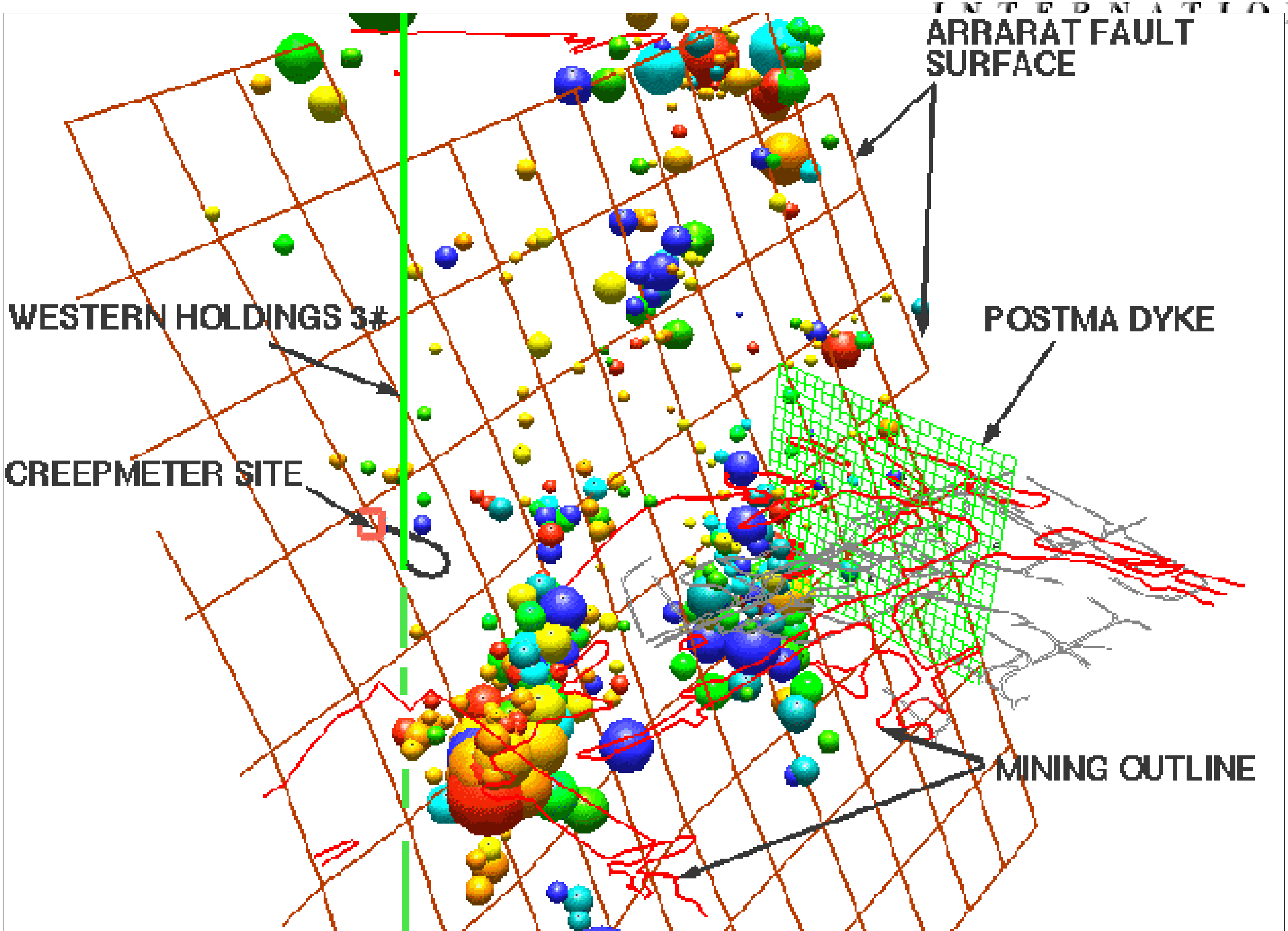
$$V_A = M(c_3\sigma_A) = M^2/(c_3GE)$$

Apparent volume, [m3]

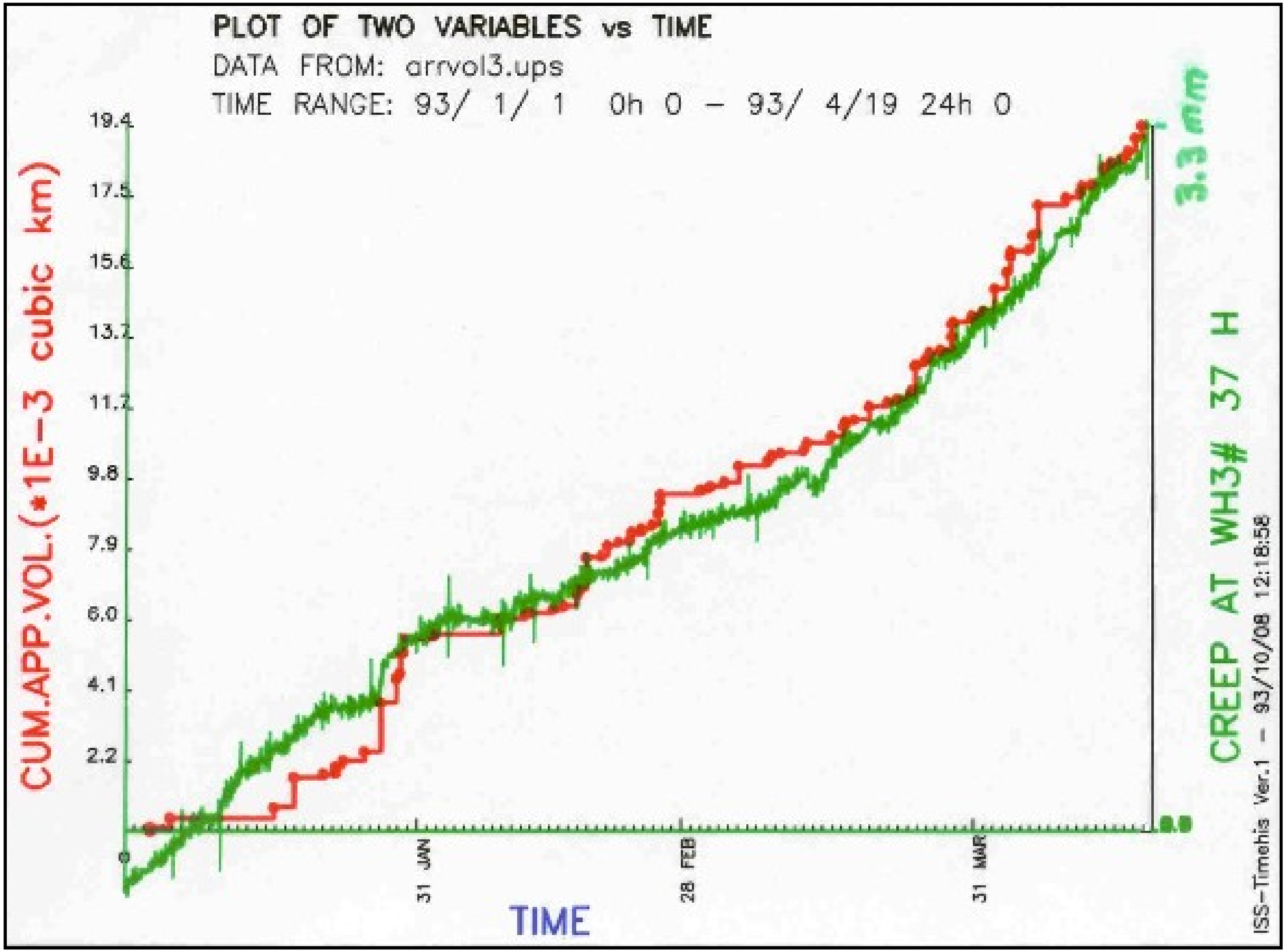
c3 – scaling factor ~2.

The apparent volume scales the volume of rock with co-seismic inelastic strain of an order of apparent stress over rigidity. The apparent volume V_A is less model dependent than the source volume *V*.

A creepy fault



Subsequent fault creep and $\Sigma\ V_A$



More derived parameters

Seismic strain, $\epsilon_S\ (\Delta V, \Delta t) = \Sigma M / (2G\Delta V)$ and **Seismic strain rate, [s^{-1}]** $\dot{\epsilon}\ (\Delta V, \Delta t) = \epsilon_S\ / \Delta t$	Seismic strain measures strain due to cumulative coseismic deformations within the volume ΔV over the period Δt. Its rate is measured by $\dot{\epsilon}_S$.
Seismic stress, σ_S[Pa] $\sigma_S(\Delta V, \Delta t) = 2G\Sigma E / \Sigma M$	Seismic stress measures stress changes due to seismicity.
Seismic stiffness modulus, K_s [Pa] $K_S(\Delta V, \Delta t) = \sigma_S / \dot{\epsilon}_S = 4G^2\Delta V\Sigma E / (EM)^2$	Seismic stiffness measures the ability of the system to resist seismic deformation with increasing stress. The stiffer systems limit both the frequency and the magnitude of intermediate and large events but have time-of-day distribution with larger statistical dispersion, thus are less time predictable.
Seismic viscosity, [Pa · s] $\eta_S(\Delta V, \Delta t) = \sigma_S / \dot{\epsilon}_S$	Seismic viscosity characterises the statistical properties of the seismic deformation process. Lower seismic viscosity implies easier flow of seismic inelastic deformation or greater stress transfer due to seismicity.

More derived parameters

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Seismic diffusivity, [m²/s] $D_S(\Delta V, \Delta t) = (\Delta V)^{\frac{2}{3}} / \tau_S$, or in a statistical sense $d_S = (\bar{X})^2 / \bar{t}$.	Seismic diffusivity can be used to quantify the magnitude, direction, velocity and acceleration of the migration of seismic activity and associated transfer of stresses in space and time. There is an inverse relationship between the diffusivity D_s and the friction parameters.
Seismic Deborah number $De_S(\Delta V, \Delta t) = \tau_S / flowtime$, where *flowtime* is a design parameter not necessarily equal to Δt.	Seismic Deborah number measures the ratio of elastic to viscous forces in the process of seismic deformation and has successfully been used as a criterion to delineate volumes of rockmass softened by seismic activity (soft clusters). The lower the Deborah number the less stable is the process or the structure over the design *flowtime* - what may be stable over a short period of time (large De_s) may not be stable over a longer time (lower De_s).
Seismic Schmidt number $Sc_{sD}(\Delta V, \Delta t) = \eta_S / (\rho D_S)$ or $Sc_{sd} = \eta_S / (\rho d_S)$ where ρ is rock density.	Seismic Schmidt number measures the degree of complexity in space and time (the degree of turbulence) of the seismic flow of rock. Note that seismic Schmidt number Sc_{sd}, encompasses all four independent parameters describing seismicity: $\bar{t}, \bar{X}, \sum M, \sum E$

Seismic Schmidt number

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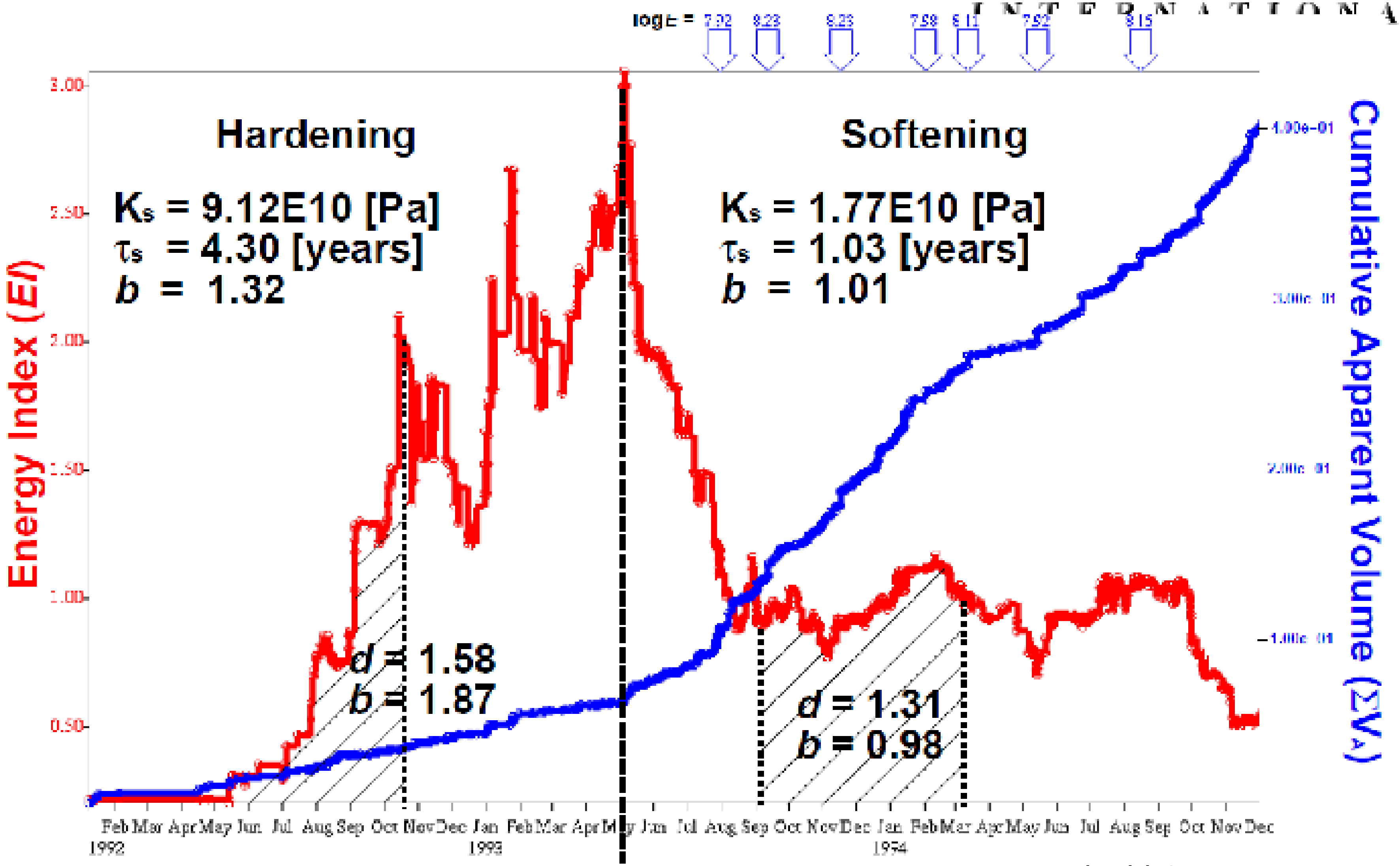
$$\bar{t}, \bar{X}, \sum M, \sum E$$

EI, Apparent Volume

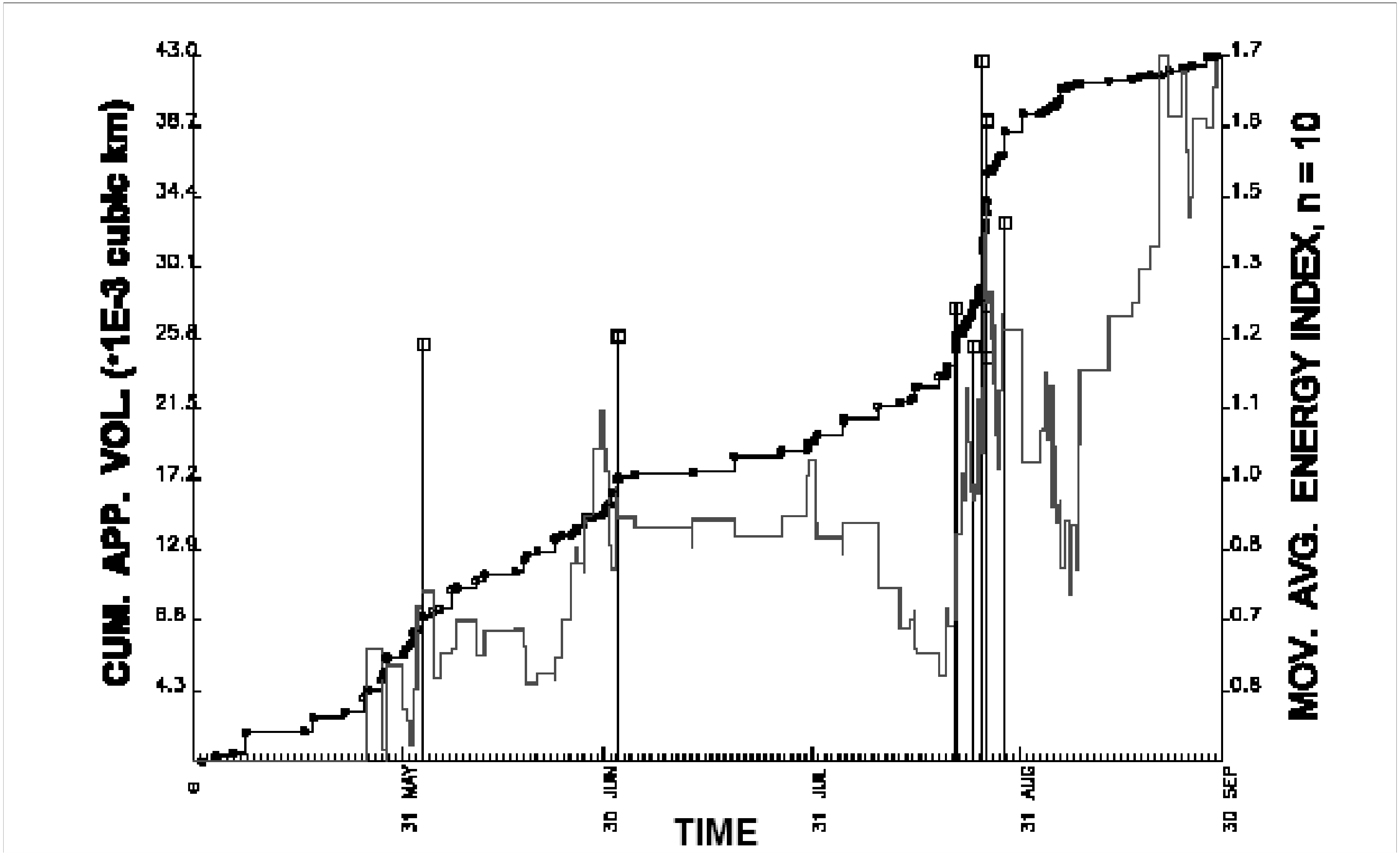


Mendecki & van Aswegen, 1997

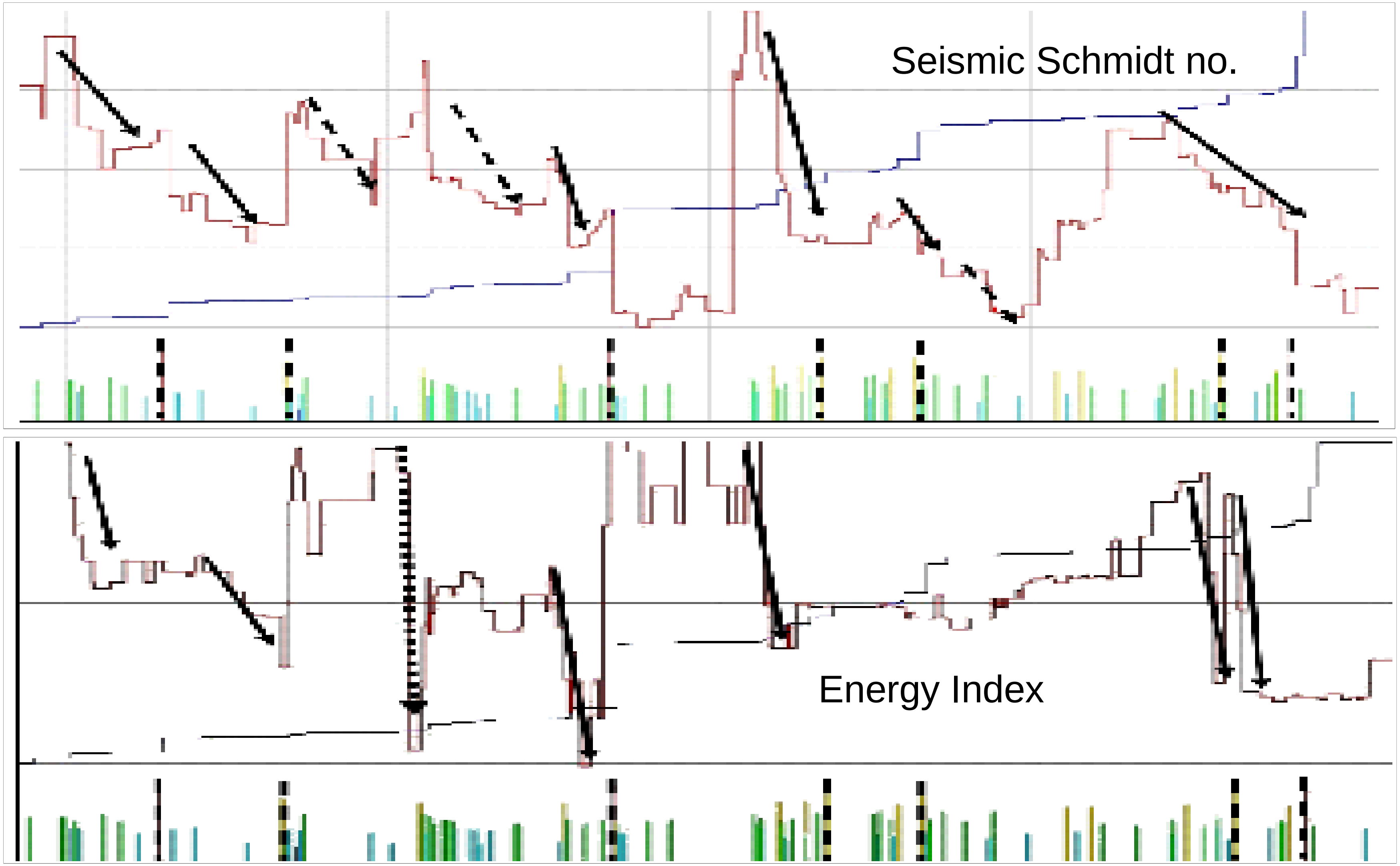
Short term seismic hazard assessment

Through time history analysis

Time history analyses



Simplistic time history analyses



Vertical broken lines depict events ≥ mag 1.8

Useful parameters for short term stability assessment

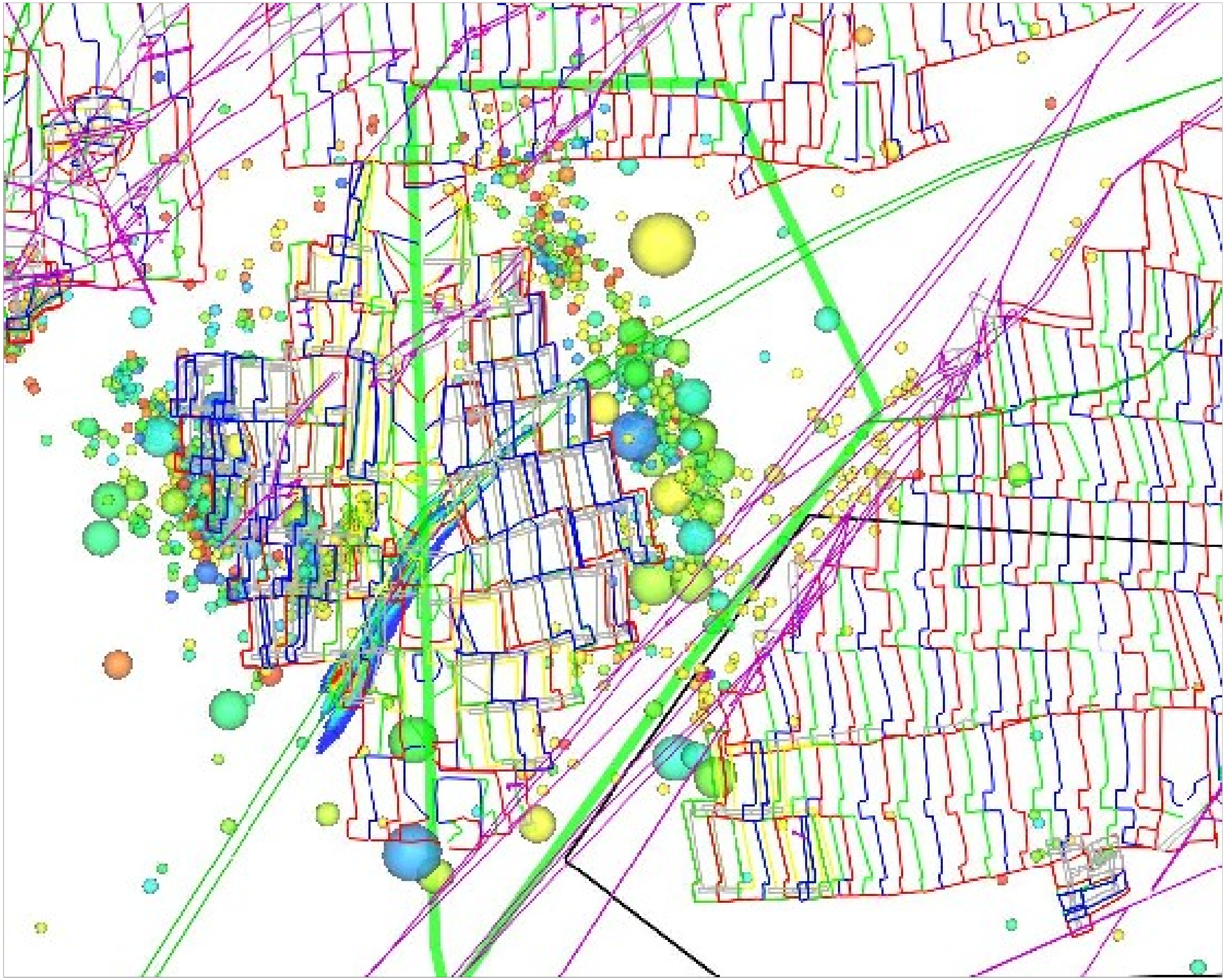
Parameter	Measures
Energy Index	Stress
Apparent volume – the slope of the cumulative curve	Strain rate
Seismic Schmidt number	Turbulence of seismic deformation
Seismic activity rate	Number of seismic events per time

RRoSH - rules

Parameter \Rating	0	1	2
Cum. Apparent volume	No tendency towards power law behaviour	Weak tendency to power law behaviour	Strong tendency to power law behaviour
Log(Energy Index)	Absolute value of change < .25	0.25 ≥ absolute value of change ≤ 0.25	absolute value of change ≥ 0.5
Log(seismic Schmidt no.)	Absolute value of change < 0.5	drop in value ≥ 0.5 ≤ 1.0; increase in value ≥ 0.5	drop value ≥ 1.0
Activity rate	Average	Above average, < 75% of 100 day peak	> 75 % of 100 day peak

In addition, anomalous spatial patterns judged (qualitatively) and rating the increased by 1 or 2

Example: 120-55-E



The E-M relation

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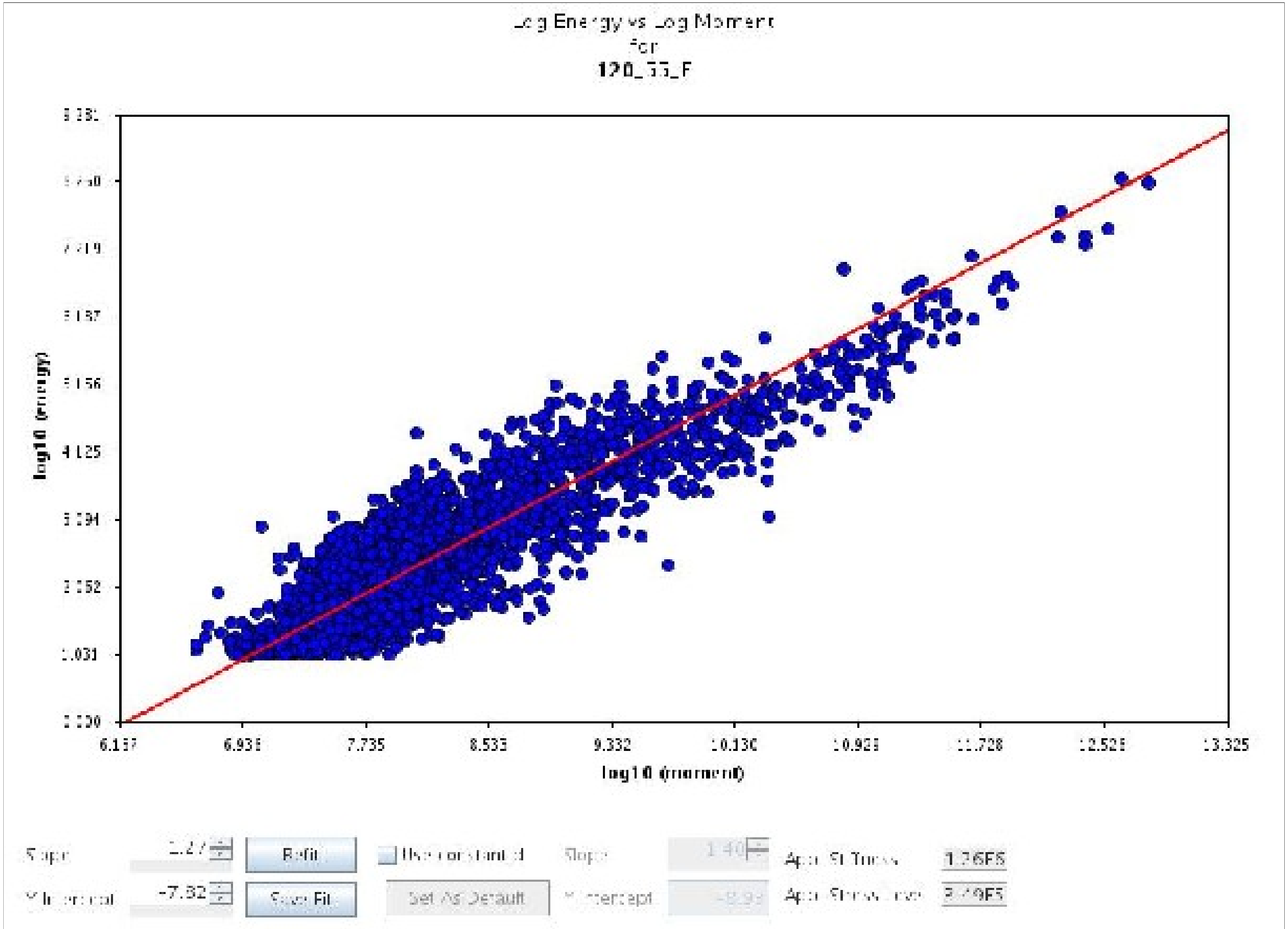
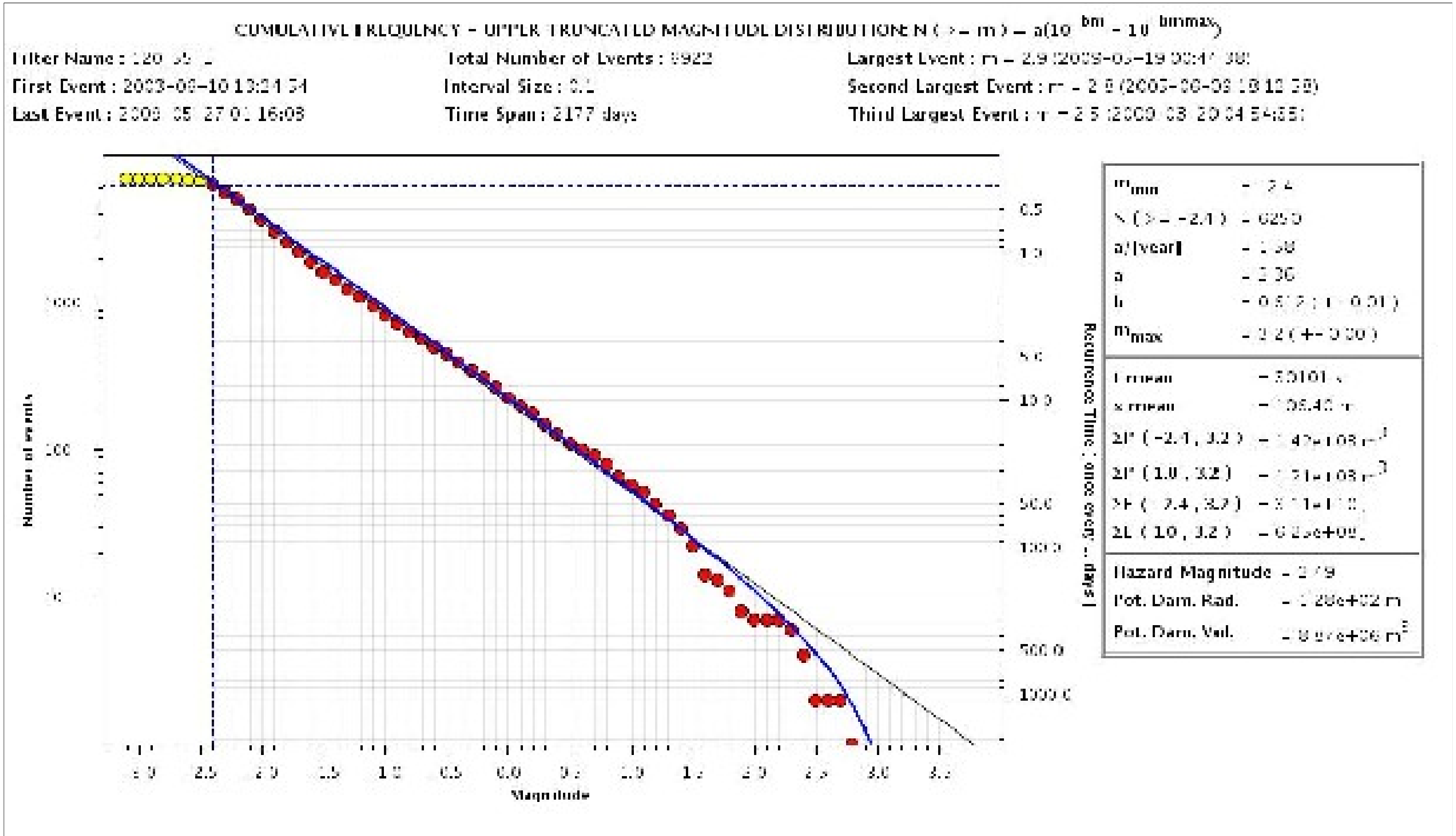


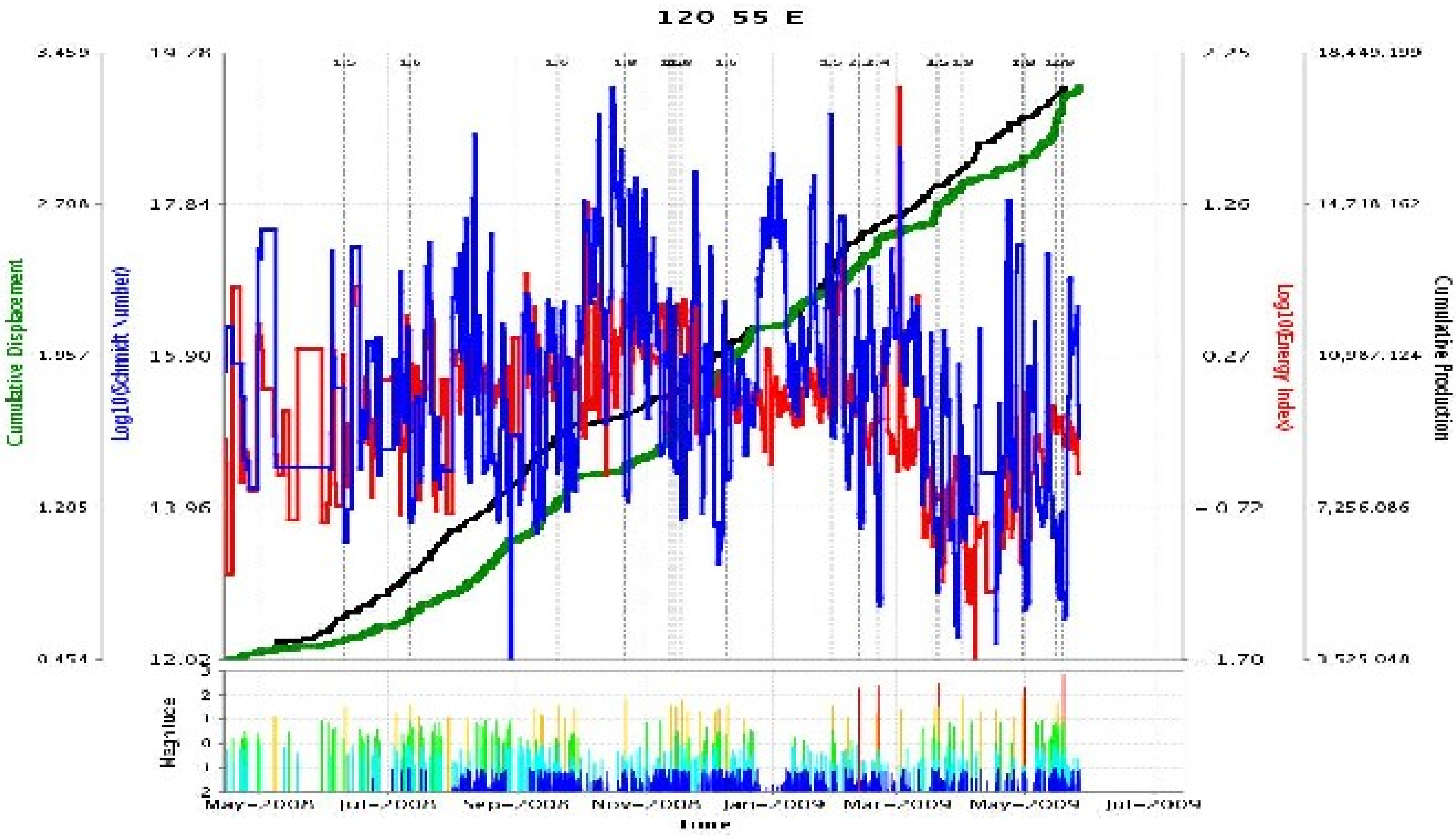
Upper Truncated GR



Probability Table and Recurrence Times

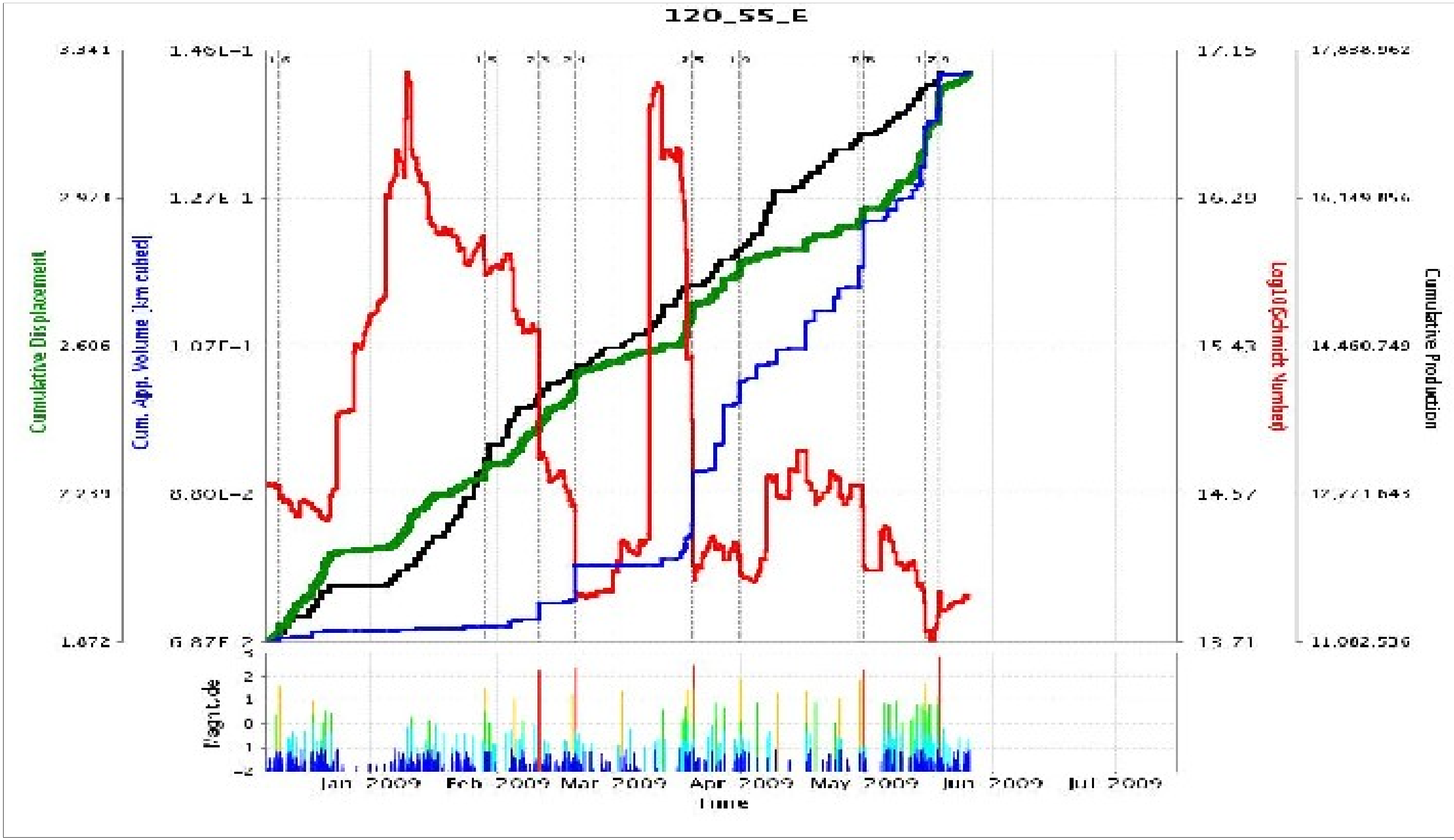
	m ≥ 1.7	m ≥ 1.9	m ≥ [illegible]	m ≥ 2.3	m ≥ 2.5	m ≥ 2.7	m ≥ 2.9	m ≥ 3.1
mean recurrence days	[illegible]	155	[illegible]	144	526	876	1751	7,196
Pr(2 weeks)	0.123	0.075	0.054	0.037	0.021	0.015	0.007	0.002
Pr(1 month)	0.238	0.133	0.112	0.078	0.052	0.031	0.015	0.004
Pr(3 months)	0.500	0.195	0.299	0.216	0.147	0.091	0.045	0.011
Pr(6 months)	0.755	0.547	0.514	0.391	0.277	0.177	0.097	0.071
Pr(1 year)	0.942	0.870	0.763	0.628	0.479	0.321	0.173	0.013

120-55-E TH



120 55 E
Cumulative Displacement
Log10(Schmidt Number)
Log10(Energy Index)
Cumulative Production
17.84
15.90
13.96
12.02
1.26
0.27
10,987,124
7,256,086
1.205
Magnitude
May-2008
Jul-2008
Sep-2008
Nov-2008
Jan-2009
Mar-2009
May-2009
Jul-2009
Time

120-55-E TH

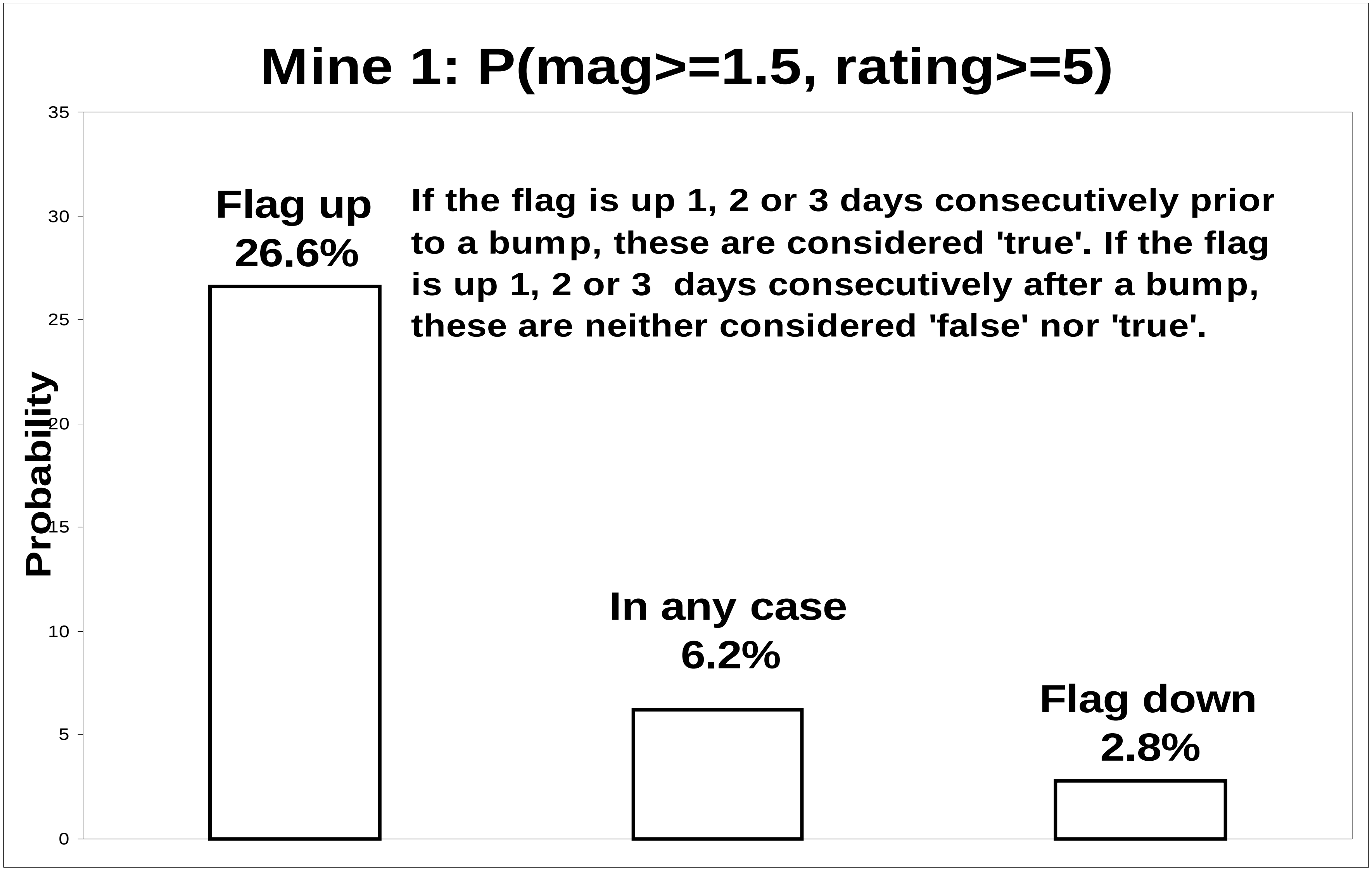

120_55_E
Cumulative Displacement
Cum. App. Volume [km cubed]
Log10(Schmidt Number)
Cumulative Production
Magnitude
Jan 2009
Feb 2009
Mar 2009
Apr 2009
May 2009
Jun 2009
Jul 2009
Time

Night shift report

(after blasting, before night shift):

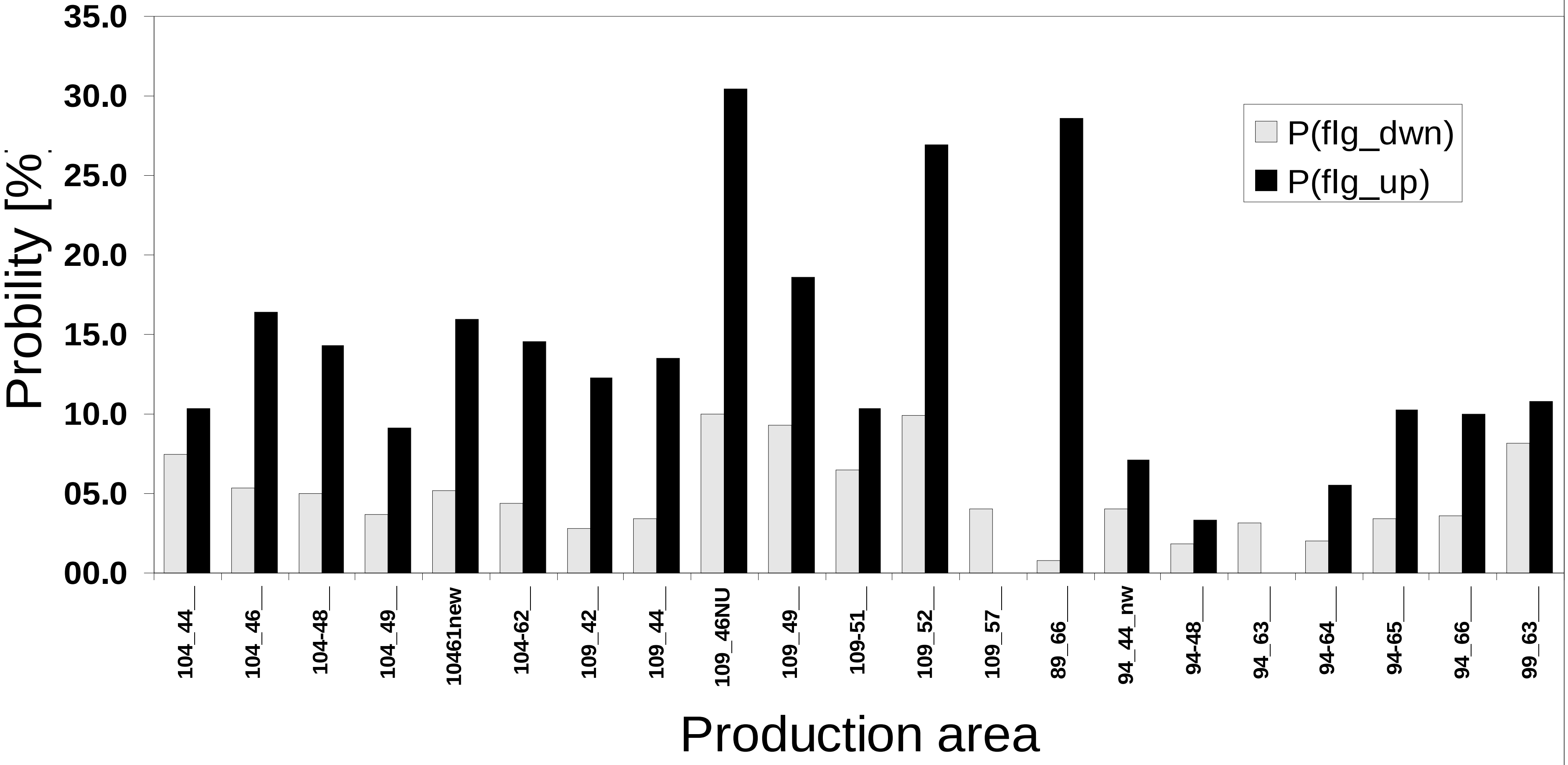
robot system (18h30 – 21h00)

Poly	Last Event Date	Last Event Time	New Events	Va	Log10Ei	Schmidt	Act	Large Events	Current Rating	Comments / Observations
101_102	20030226	180515	3	1.0	1.0	2.0	1.0	M0.7@26/02,18h00 .	6.000000	remain in RED status
101pillr	20030223	160553	0	0.0	1.0	1.0	0.0	0	2.000000	. nn
104_106_	20030226	180145	4	0.0	1.0	2.0	1.0	M1.1@26/02,16h01 . M0.9@26/02,18h01 . M0.7@26/02,18h01	4.000000	. Schmidt is falling and act. up.
306_ger_	20030226	180515	7	1.0	1.0	2.0	2.0	M1.1@26/02,16h01.. M0.7@26/02,18h00 . M0.9@26/02,18h01.. M0.7@26/02,18h01 .	6.000000	. Activity rate up.
107_109_	20030226	180055	1	0.0	2.0	1.0	0.0	M1.4@26/02,18h00	2.370000	. At last some activity
111_112_	20030223	51559	0	0.0	1.0	1.0	0.0	0	1.800000	. nn
114_115_	20030223	182640	0	0.0	1.0	1.0	0.0	0	1.800000	. nn
114_116W	20030226	175302	1	0.0	2.0	1.0	0.0	M0.6@26/02,17h53 .	3.000000	.
33 112st	20030219	53209	0	0.0	0.0	0.0	0.0	0	0.000000	. Still mining here ?? last event 6 days back
118_120	20030226	174612	1	0.0	2.0	2.0	0.0	0	4.000000	. Long term Schmidt and EI dropping strongly
120W___	20030221	175722	0	0.0	0.0	0.0	0.0	0	0.000000	Rating dropped old event
83_90___	20030226	182418	2	1.0	1.0	1.0	1.0	M1.7@26/02,18h23.. M1.4@26/02,18h24 ..	4.000000	. Activity rate up
94Wpillr	20030224	200354	0	1.0	2.0	2.0	0.0	0	5.500000	. nn
97_100__	20030226	62004	0	0.0	1.0	1.0	0.0	0	1.800000	
declE	20030226	135710	1	0.0	2.0	1.0	1.0	0	4.000000	.



Mine 1: P(mag>=1.5, rating>=5)
Probability
0
5
10
15
20
25
30
35
Flag up
26.6%
If the flag is up 1, 2 or 3 days consecutively prior to a bump, these are considered 'true'. If the flag is up 1, 2 or 3 days consecutively after a bump, these are neither considered 'false' nor 'true'.
In any case
6.2%
Flag down
2.8%

P[mag. >=1 ON SHIFT within 2 days of rating >= 5
Mponeng 2003 - 2004



Hazard assessment success rate: example case 1 - 2002

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Phenomenon	Probability
The occurrence of a mag.≥ 1 event on-shift	**05.28%**
The occurrence of a mag. ≥1 event on-shift if the RRoSH ≥ 3 during the 60 hours before, i.e. **FLAG UP**	**14.18%**
The occurrence of a mag. ≥ 1 event on-shift if the RRoSH < 3 during the 60 hours before, i.e. **FLAG DOWN**	**00.23%**

Hazard assessment success rate: example case 2 - 2002

Phenomenon	Probability
The occurrence of a seismic event ≥ 1.0 on-shift	**10.30**
The occurrence of a seismic event ≥ 1.0 on-shift if the RRoSH ≥ 4 during the two days prior – **FLAG UP**	**36.97**
The occurrence of a seismic event ≥ 1.0 on-shift if the RRoSH < 4 during the two days prior - **FLAG DOWN**	**02.52**

Australian mine: *m*2.3 fault-slip event

Australian mine: EI, cum. apparent volume

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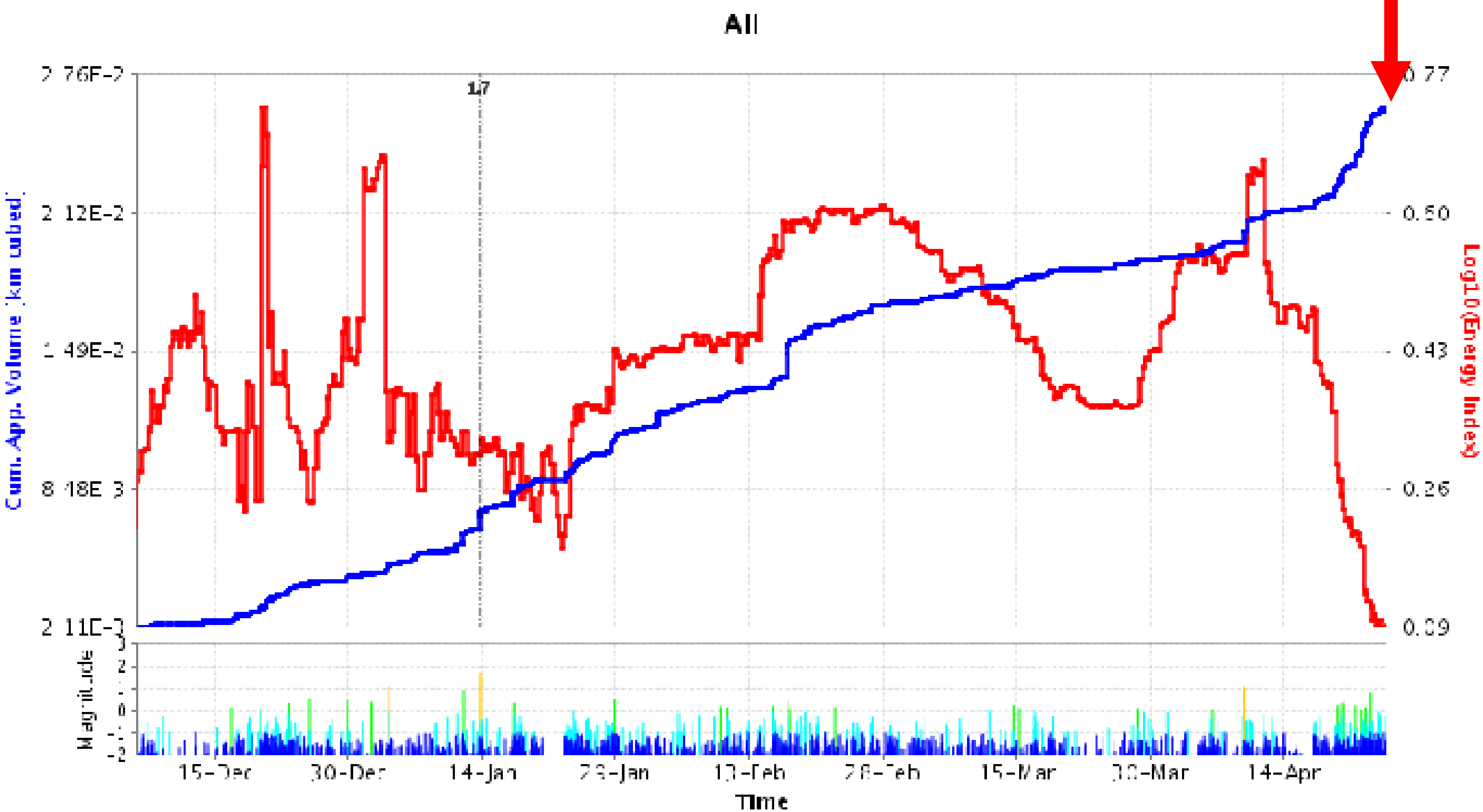
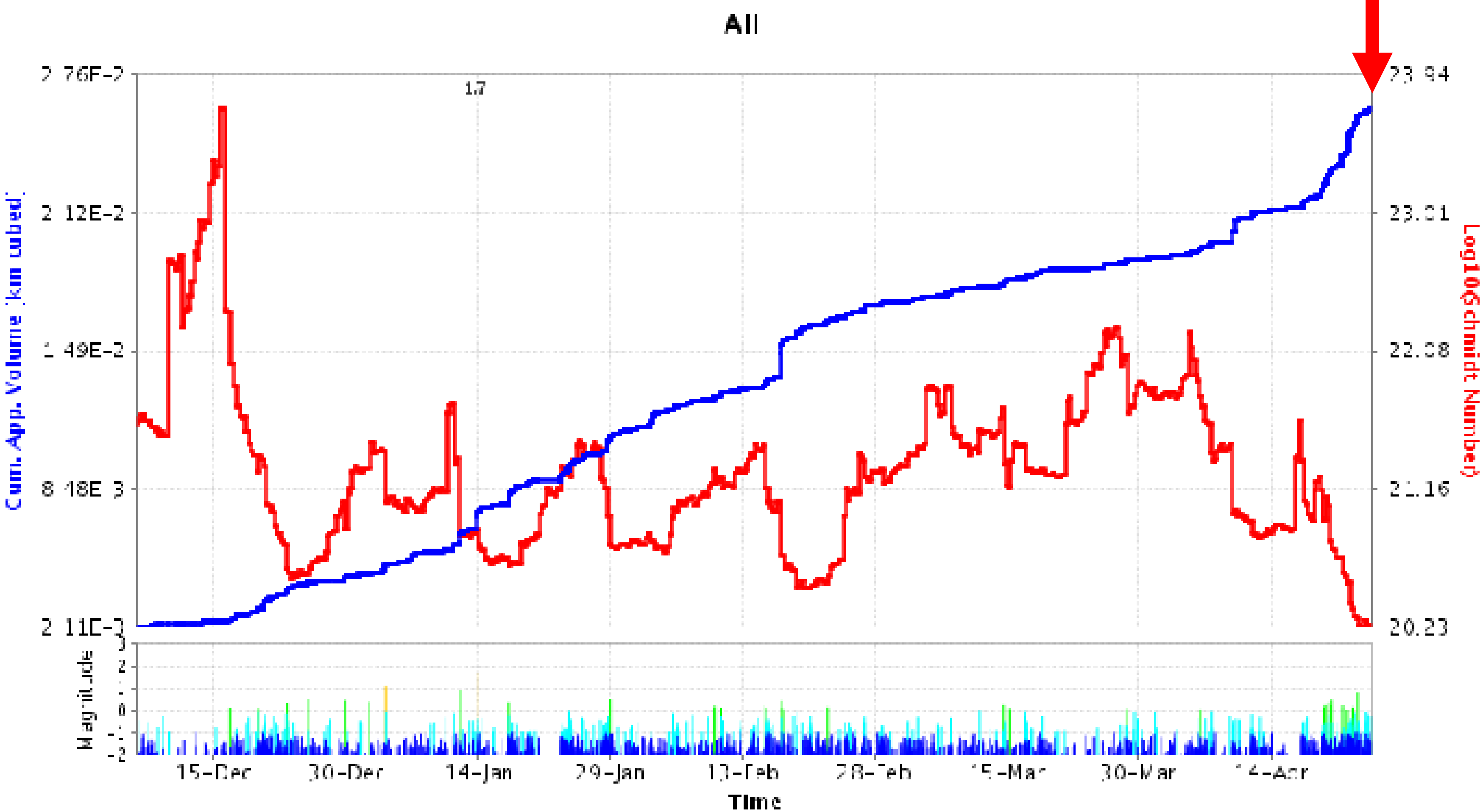
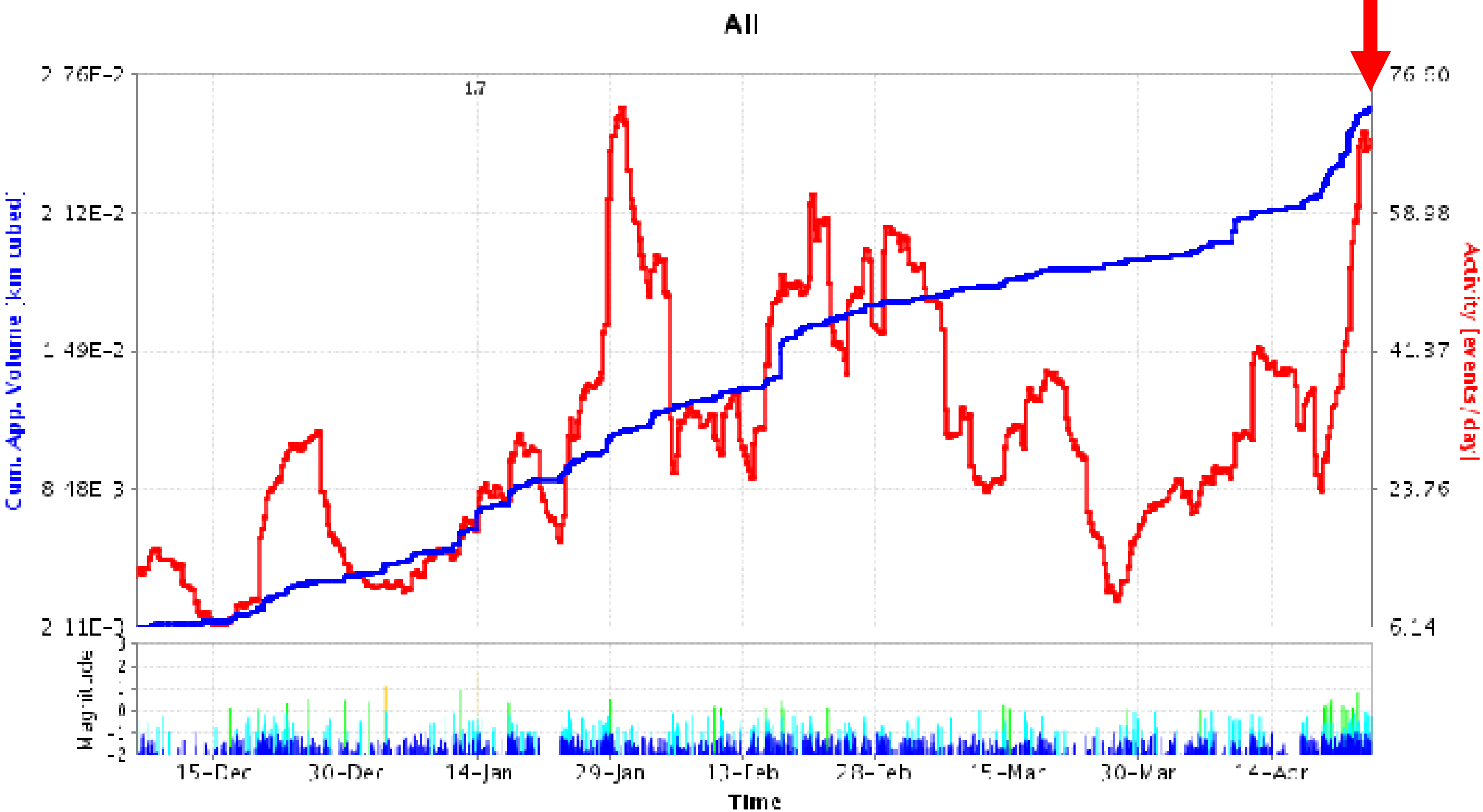


Australian mine: Sc, cum. apparent volume



Australian mine: seismic activity



Conclusions

- We get more information from the seismic data ..
- Translate data into rock mechanics language
- Consider stability in term of stress, strain rate, turbulence, spatial patterns
- Last step is to integrate all this with on-line numerical modeling