Sellers, E. J., Kataka, M. O., and Linzer, L. M., Source parameters of acoustic emission events and scaling with mining-induced seismicity, JGR 108, B9, 10.1029/2001JB000670

廣瀬仁
2004年5月31日

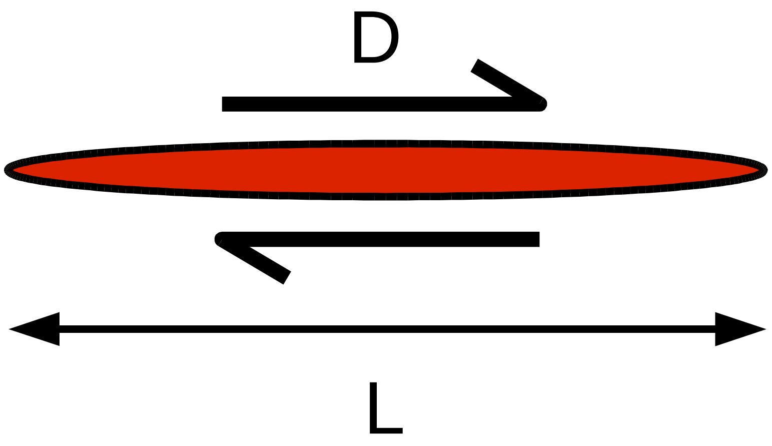
背景 1

- 大きな地震 (破壊) と小さな地震 (破壊) では働く物理プロセスは同じか? 異なるか?
  - 同じなら、実験や微小地震の研究で大地震のことも分かる (小さい研究室にはありがたい)
  - 異なるなら、大地震を経験しない限り大地震のことは分からない (E-defense的?)
- 大小地震でスケーリング則が成り立つとして
  - 上限: 地震発生層の深さ・幅
  - 下限: 原子間隔・粒子サイズ; 測定装置の限界

背景 2

- 応力降下量
  - 地震の規模によらず一定 [断層は自己相似的]
  - 規模に依存する [あるユニバーサルパラメタで記述可能?]

$$\Delta\sigma \propto D/L$$



- Gutenberg-Richter の関係
  - 自己相似的な断層

$$\log N = a - bm$$

この研究の目的

- 金鉱山で発生する、掘削に誘発される微小地震の予測アルゴリズムの改良
- 鉱山地震の応力状態 (高垂直応力・低水平応力)を模した最も簡単な系である一軸圧縮実験で発生するAEを調べる
- 地震学的なパラメタを推定して、自然地震や鉱山地震と比較
- スケーリング則の検証

実験方法

- サンプル: Elsburg珪岩 (石英 70-84%)
- 一軸圧縮強度: 120-180MPa
- 粒径: 0.24-1.52mm
- 密度: ~2700kg/m3
- Vp: 5200m/s
- Vs: 3200m/s

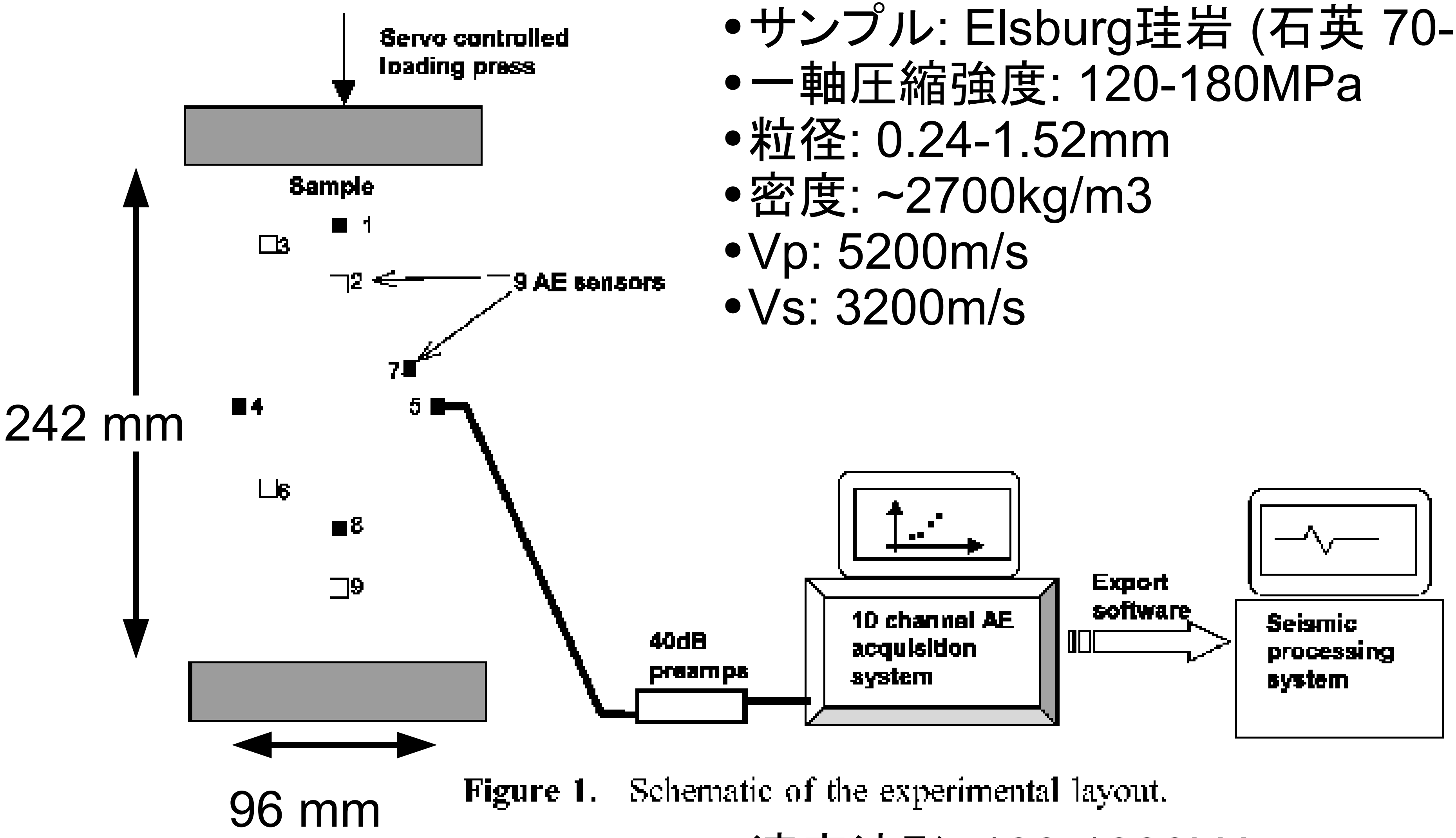


Figure 1. Schematic of the experimental layout.

- 速度波形; 100-1000kHz
- サンプリングレート: 4MHz

震源パラメタの推定

Brune (1970) のモデルに基づく

- 地震モーメント

$$M_0 = 4\pi\rho\beta^3 R\Omega_0 / f_{\theta\phi}^{\beta}$$

- 応力降下量

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r^3}$$

$$r = \frac{2.34}{\pi}\frac{\beta}{f_0}$$

$$\Omega(f) = \frac{\Omega_0 \exp(-\kappa f)}{1+(f/f_0)^2}, \qquad \kappa = \frac{\pi R}{Q\beta}$$

波形例

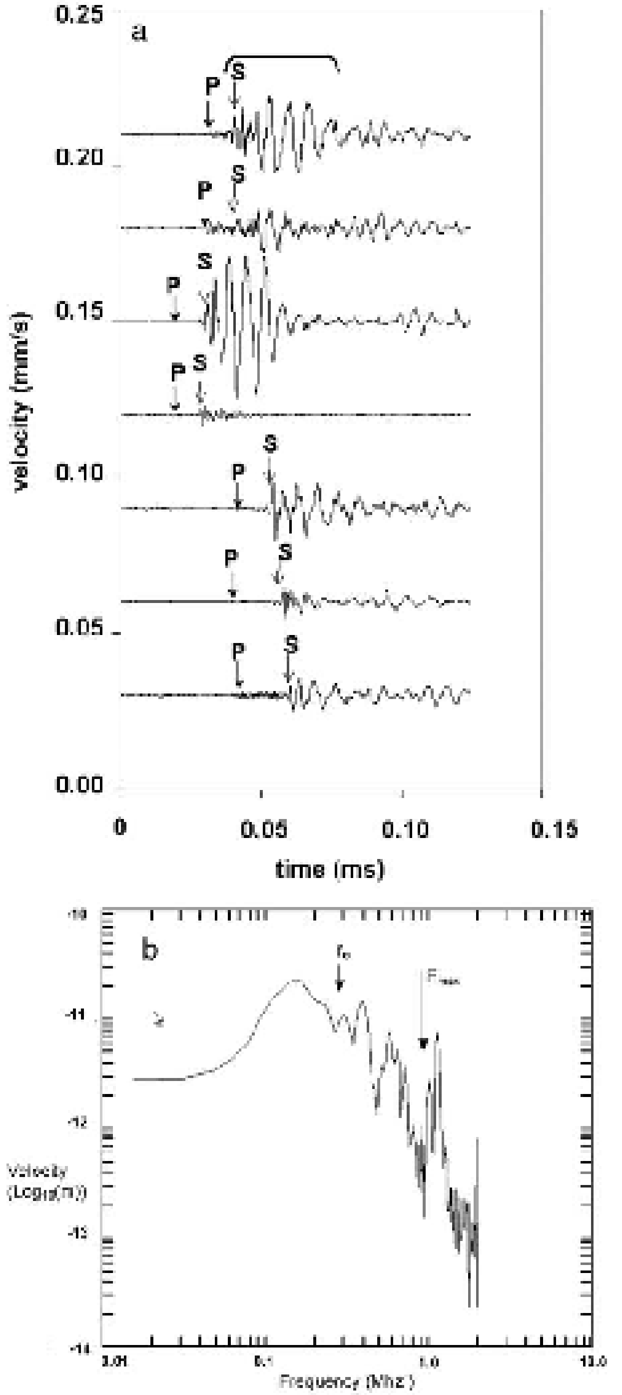


Figure 2. (a) Velocity waveforms (with offset axes) for event 41 showing the P wave and S wave picks and the window used for the (b) S wave velocity spectra for

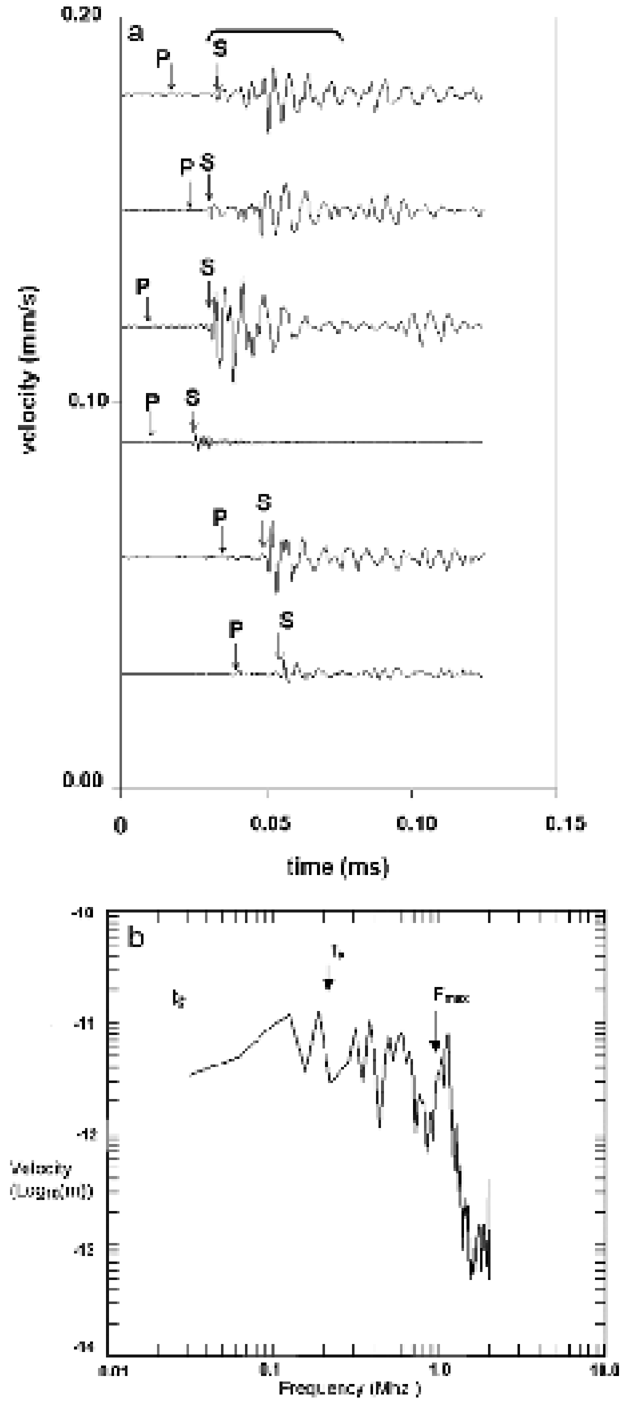


Figure 3. (a) Velocity waveforms (with offset axes) for event 10149 showing the P wave and S wave picks and the window used for the (b) S wave velocity spectra for

モーメントテンソルの推定

- 絶対法
  - 理論的Green関数
  - 通常は Ray path を単純化
  - 震源位置・波形の振幅に敏感に依存
- 相対法
  - 単独基準イベント
    - 基準イベントのGreen関数を別の方法で推定
    - クラスタ内の地震は共通のRay pathと仮定
  - 複数基準イベント
    - 3つ以上のメカニズムの異なる地震 [Daum et al., 1997]
    - 基準イベントが似たメカニズムなら分解が困難

Hybrid moment tensor inversion (1)

- イタレーション法
- 重み付けに工夫
  - センサー付近の影響での増幅/減衰を考慮
  - 波線の focusing / defocusing を補正

Andersen (2001)

Hybrid MT inversion (2)

- インバージョンの定式

$$u_j(x,t)=G_{jp,q}(x,t;\xi,t')M_{pq}(\xi,t')$$

全成分で同じ時間依存
震源時間関数はdelta関数

$$u_j=G_{jp,q}M_{pq}$$

$$\mathbf{u}=\mathbf{G}\,\mathbf{m}$$

Hybrid MT inversion (3)

$$u_{ijkl}^{\text{new}} = u_{ijkl}^{\text{old}} + w_{\text{IterNo}} \left(\bar{r}_{jkl} - 1 \right) u_{ijkl}^{\text{old}}$$

$$\bar{r}_{jkl} = \text{median} \left(\frac{u_{ijkl}^{\text{th}}}{u_{ijkl}^{\text{obs}}} \right)_{i=1,\ldots,N_{eq}}$$

i : イベント
j : 観測点
k : 震動成分 (1, 2, 3)
l : P波 (1), S波 (2)

$$w_{\text{IterNo}} = \frac{10^{(\text{IterNo}-1)/10}}{10}$$

(繰り返し回数で単調増加)

$$\mathbf{u}_i = \mathbf{G}_i \mathbf{m}_i$$

結果 (1) AE回数の推移

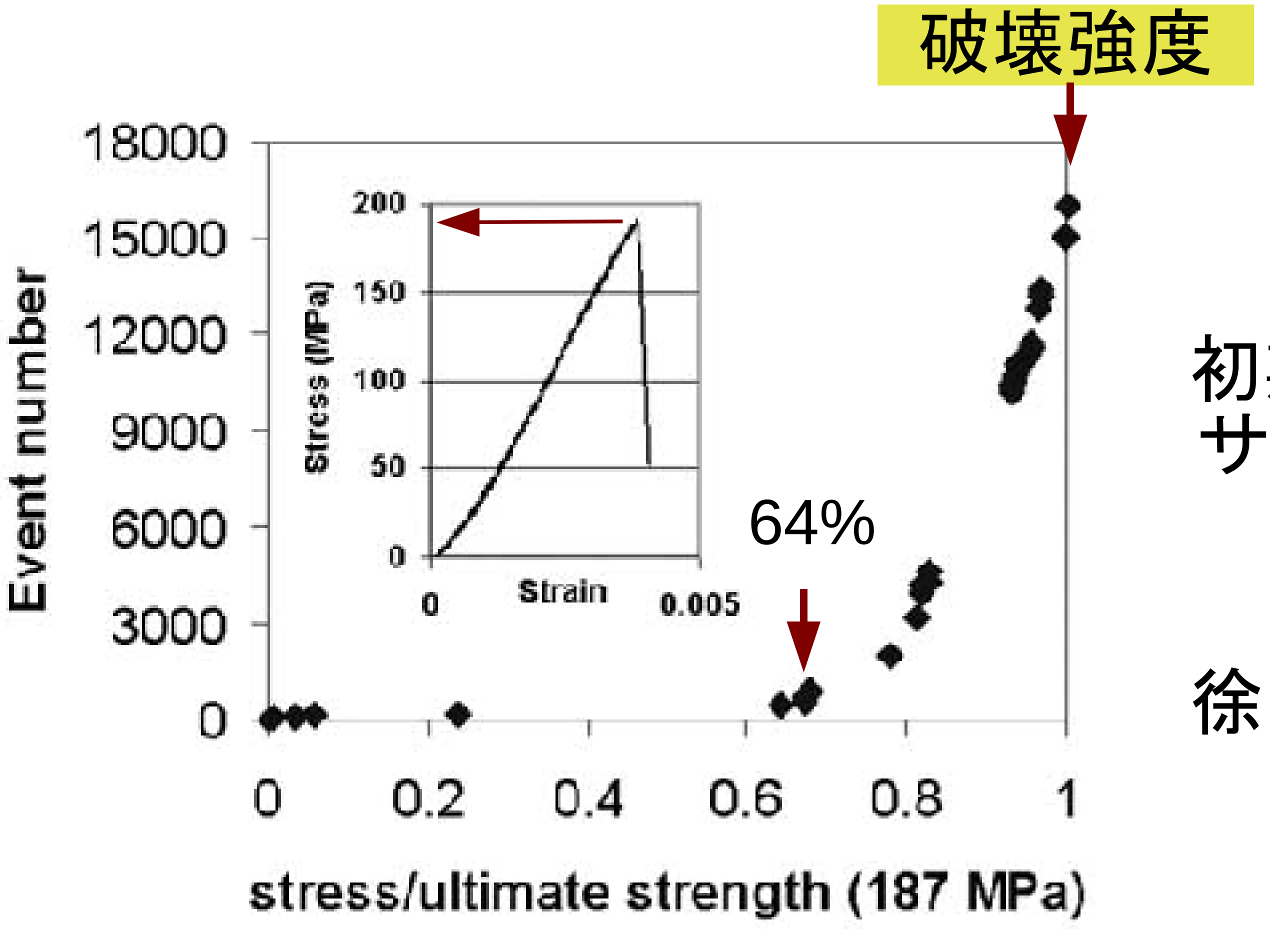


Figure 4. Number of acoustic emissions (AE) related to the ratio of stress to ultimate strength. The inset graph indicates the stress-strain curve.

AE回数増加

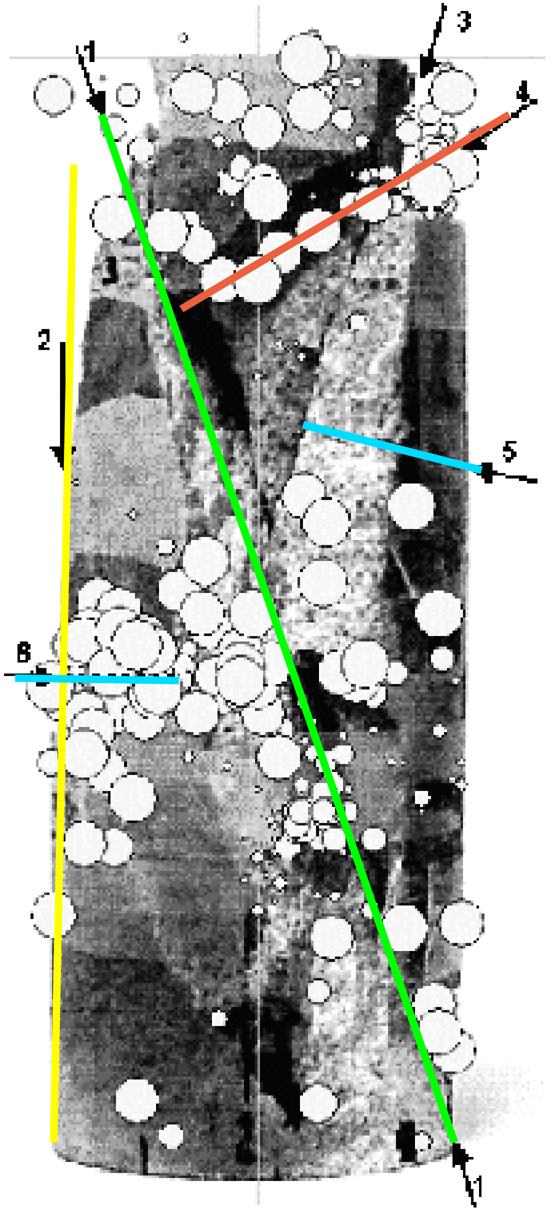
初期段階では震源はサンプル全体に分布

↓

徐々に最終破断面に沿って並ぶ

AEの分布

低傾斜面



ほぼ水平面

垂直に近い面

最終破断面

Figure 5. AE locations (circles scaled in area to event number) in the unconfined compression test, superimposed on a photograph of the (reconstructed) failed specimen. Horizontal banding results from tape marks, not sample anisotropy. Arrows indicate the main failure planes.

モーメントテンソル解

8つのクラスター

(1) 主破断面のAE

面とほぼ一致・走向が異なる

一軸・円筒サンプルでは方向性の影響は余り強くならない

(2) その他のAE

結構ばらばら

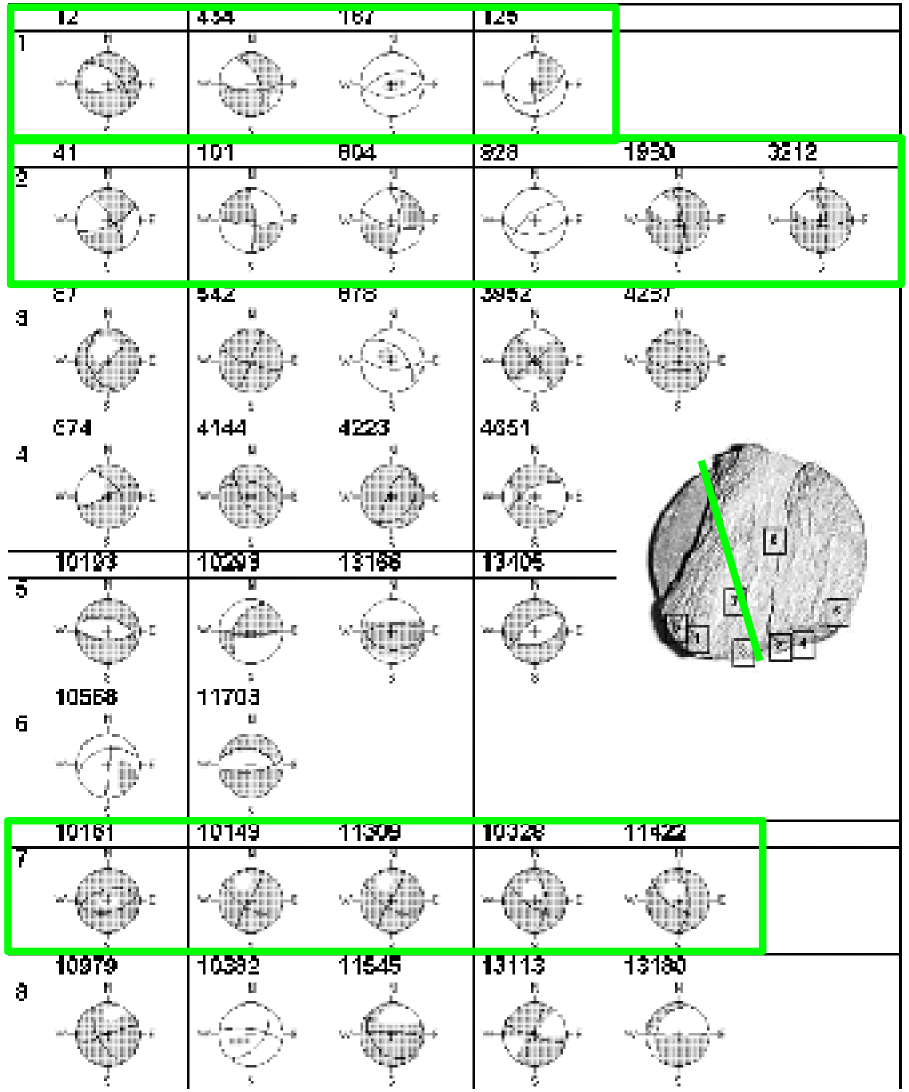


Figure 7. Focal plane plots of the moment tensor solutions for the eight clusters of events and a top view of the sample showing the cluster positions. A lower hemisphere equal area projection is used, where the shaded area represents the region of compressional P wave motions.

モーメントテンソル解 (2)

Table 1. Moment Tensor Results for Events Used in This Study

Cluster	Event ID	M_0, Nm	σ_{ult}[a] %	%ISO	%DC	ε	Strike 1	Dip 1	Rake 1	Strike 2	Dip 2	Rake 2
1	12	0.002	0	35	73	0.11	[illegible]	[illegible]	[illegible]	[illegible]	64	−124
1	434	0.005	1	31	70	0.15	[illegible]	[illegible]	[illegible]	[illegible]	64	140
1	187	0.022	3	−44	52	0.24	[illegible]	[illegible]	[illegible]	[illegible]	47	82
1	125	0.007	1	40	66	0.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	36
2	41	0.030	6	−10	49	0.25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	−28
2	101	0.023	21	4	99	0.0[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	160
2	804	0.018	64	−16	65	0.08	359	59	−28	10[illegible]	67	−145
2	528	0.033	67	56	44	0.28	[illegible]	[illegible]	[illegible]	[illegible]	59	69
2	1980	0.054	6[illegible]	45	77	0.12	[illegible]	[illegible]	[illegible]	[illegible]	70	−153
2	3310	0.11[illegible]	68	31	65	0.18	[illegible]	[illegible]	[illegible]	[illegible]	67	139
3	67	0.010	68	39	21	0.24	42	2[illegible]	208	[illegible]	79	−69
3	542	0.105	68	40	44	0.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	878	0.050	78	−51	68	0.06	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	3952	0.094	8[illegible]	41	17	0.42	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	4287	0.040	82	61	60	0.2	311	46	18	94	[illegible]	6[illegible]
4	674	0.038	83	36	44	0.[illegible]8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	414[illegible]	0.060	83	63	26	0.37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	4223	0.049	83	70	78	0.11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	1631	0.045	80	7	65	0.08	[illegible]	[illegible]	[illegible]	[illegible]	58	−41
5	10[illegible]93	0.03[illegible]	9[illegible]	3[illegible]	74	0.33	[illegible]	[illegible]	[illegible]	[illegible]	5[illegible]	89
3	10293	0.017	90	14	91	0.03	[illegible]	[illegible]	[illegible]	[illegible]	7[illegible]	119
5	13[illegible]66	0.013	91	33	59	0.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	66	84
5	13105	0.026	93	22	61	0.09	78	39	−69	232	54	−106
6	10508	0.087	92	−42	61	0.19	254	32	−34	5	78	−119
6	11703	0.012	90	28	12	0.29	285	30	−71	83	62	−101
7	10[illegible]61	0.020	9[illegible]	46	49	0.[illegible]5	81	41	85	254	49	95
7	10[illegible]15	0.020	90	55	97	0.0[illegible]	121	55	186	28	85	36
7	1309	0.02[illegible]	91	60	65	0.18	345	36	−40	108	68	−119
7	10928	0.022	90	46	10	0.[illegible]5	356	45	−19	12[illegible]	58	−124
7	11422	0.013	92	54	76	0.12	104	41	179	195	89	49
8	10975	0.013	91	54	95	0.01	153	50	170	250	82	41
8	10382	0.003	95	44	34	0.38	39	4[illegible]	38	279	66	126
8	11343	0.022	93	41	58	0.2[illegible]	133	21	129	27[illegible]	71	77
8	13113	0.034	96	37	23	0.33	200	79	190	108	80	−11
8	17[illegible]80	0.013	96	0	93	0.03	200	20	202	85	83	71

[a] Percentage of ultimate uniaxial strength.

等方成分が負

crushing events

等方成分が正

tensile crack formation

大きいダブルカップル成分

shear

等方成分

ダブルカップル成分

コーナー周波数

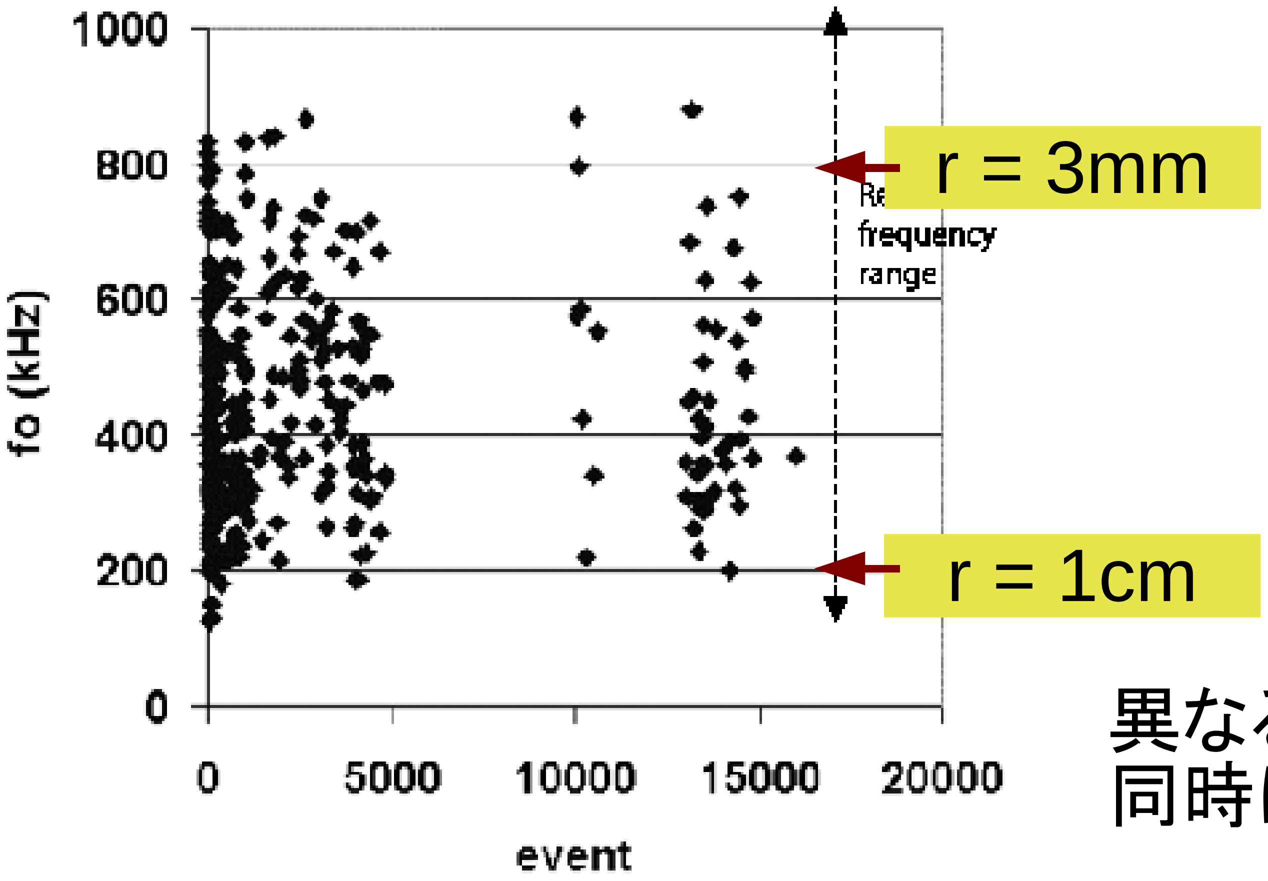


Figure 8. Plot of f_0 versus event number.

$$r = \frac{2.34}{\pi} \frac{\beta}{f_0}$$

異なるサイズのイベントが
同時に起こっている

見かけ応力 (apparent stress), 放射エネルギー

- 放射エネルギー

$$E = 4\pi\rho R^2 \left(\alpha \int_{t_p}^{t_s} v(t)^2 dt + \beta \int_{t_s}^{t_f} v(t)^2 dt \right)$$

- 見かけ応力

$$\tau_a = \frac{G E}{M_0}$$

- 放射効率

$$\eta = \frac{\tau_a}{\tau_0}$$

← Applied shear stress

地震モーメント v.s. 放射エネルギー

Mw -9.4 -2.7 3.9 10.6?

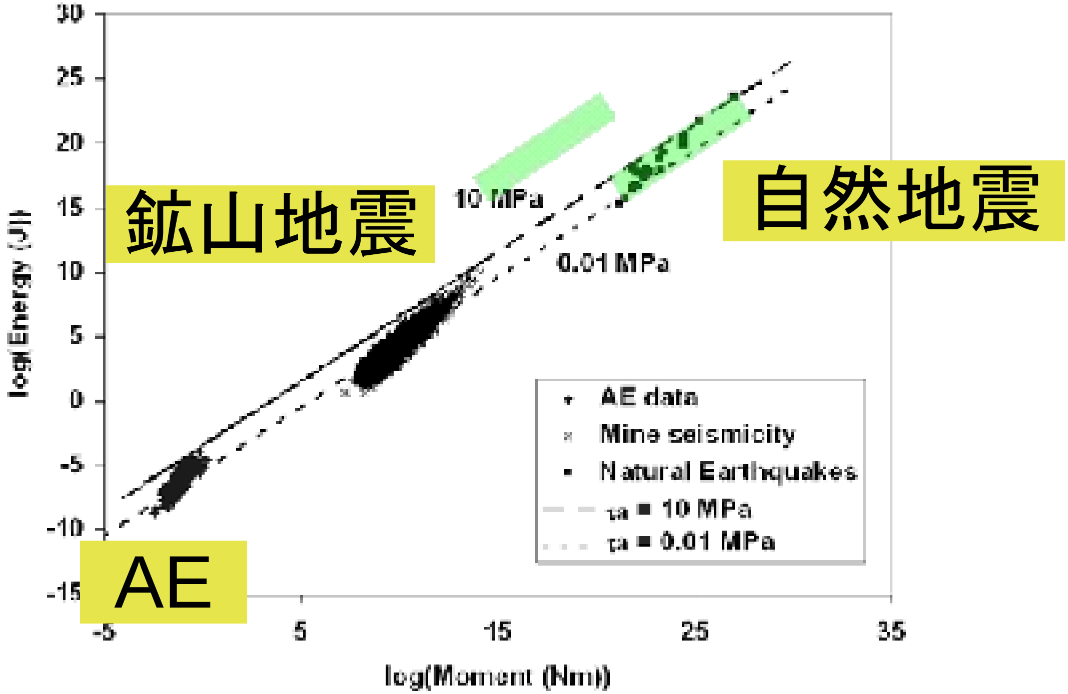
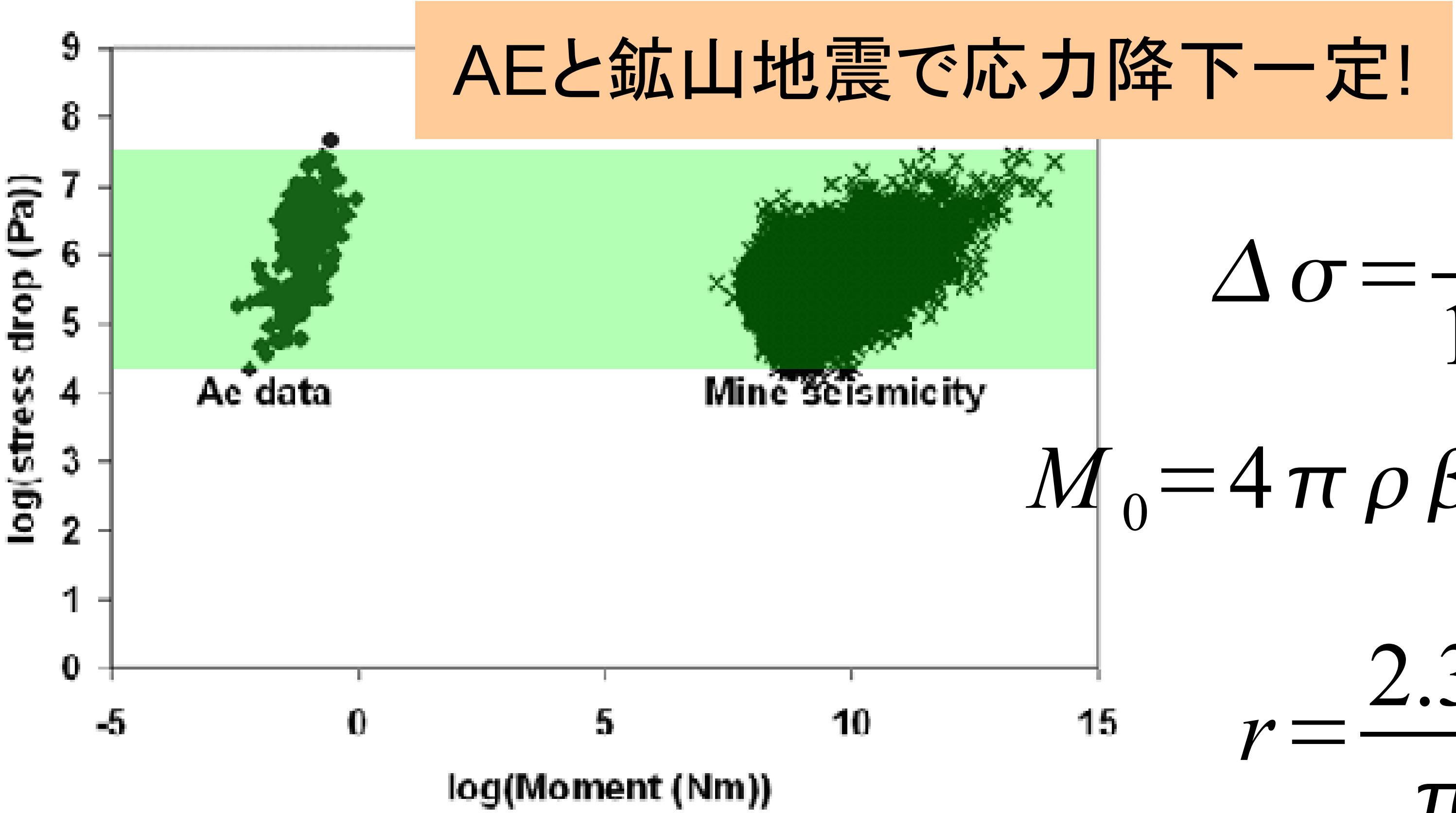


Figure 9. Plot of log (energy) versus log (moment) for AE (diamonds) and mining-induced events (crosses) from 5 years of mining at a site on a deep-level gold mine in South Africa [*McGarr*, 1984b] and natural earthquakes (squares) from the work of *Kanamori et al.*, 1993. Dashed lines are lines of constant apparent stress.

応力降下量の規模依存性



Mw -9.4 -6.1 -2.7 -0.6 3.9

Figure 10. Plot of log (stress drop) against log (moment). Diamonds represent AE data and crosses represent mine data from 5 years of mining at a site on a deep-level gold mine in South Africa.

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r^3}$$

$$M_0 = 4\pi\rho\beta^3 R\Omega_0 / f^{\beta}_{\theta\phi}$$

$$r = \frac{2.34}{\pi}\frac{\beta}{f_0}$$

断層サイズの規模依存性

AEと鉱山地震で同じスケーリング則にのる!

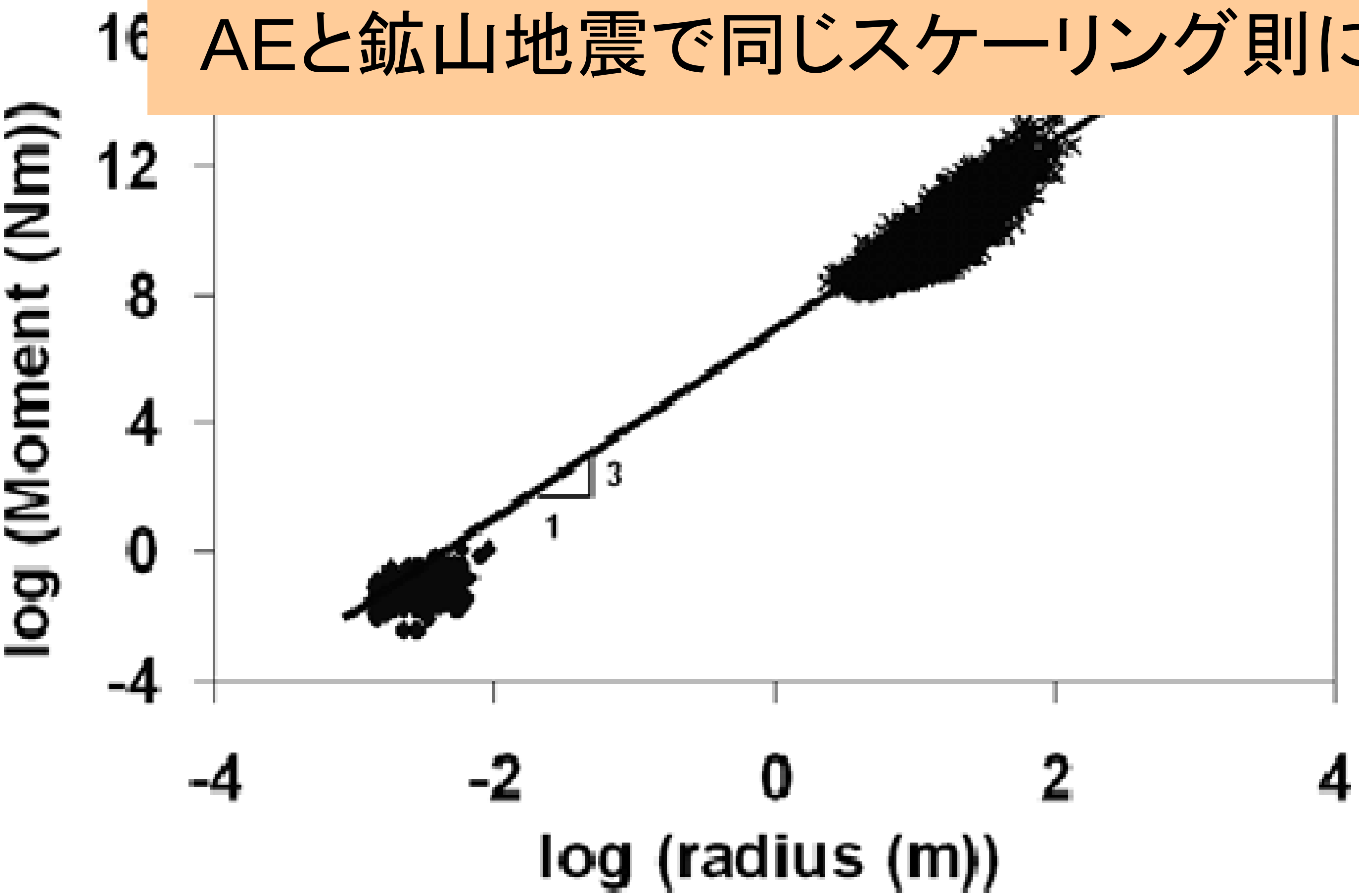


Figure 11. Log of seismic moment compared to event radius.

$$M_0 \propto r^3$$

↓ $M_0 \equiv G A U$

$\Delta \sigma$ 一定

Peak ground velocity

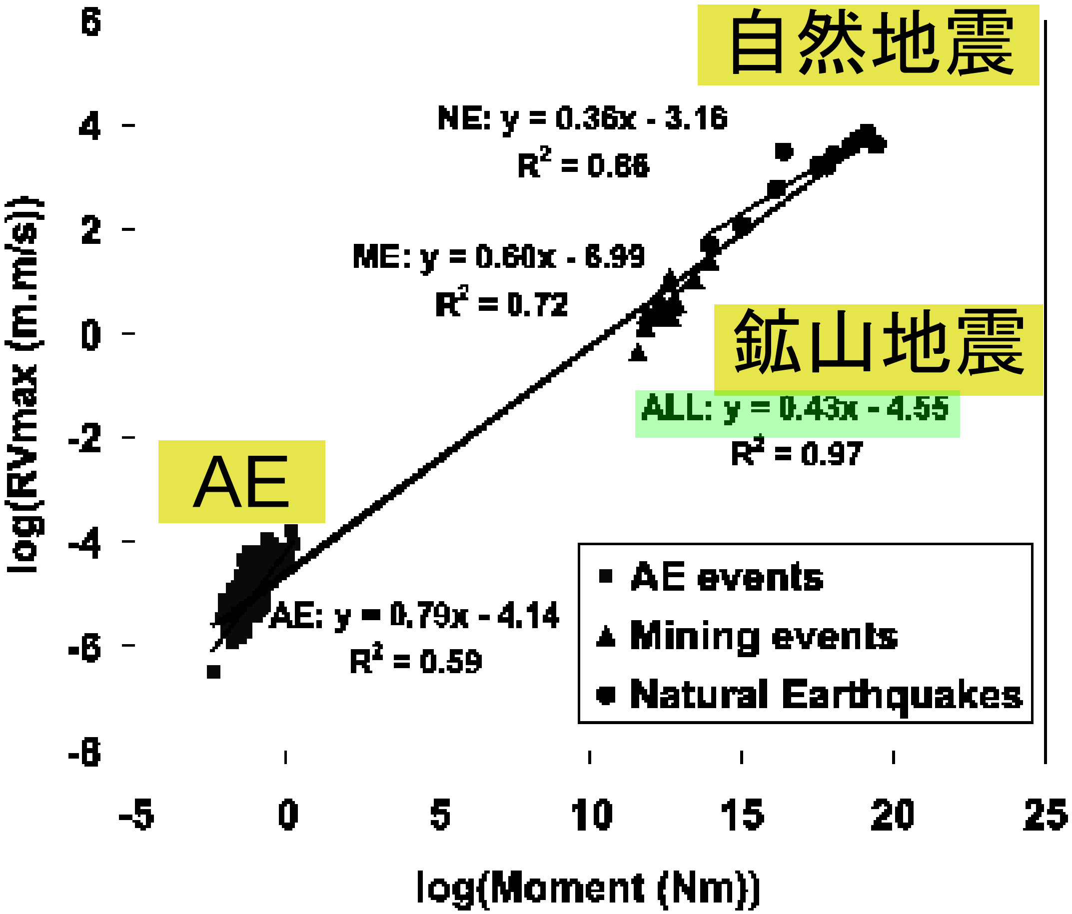


Figure 12. Measured peak velocity parameter versus moment. Filled squares represent AE, triangles represent mine events, and circles represent natural earthquakes (mine and earthquake data are from the work of *McGarr* [1993]).

$$RV_{max} = \frac{0.57\beta\Delta\sigma r}{G}$$

↑ 距離

$\Delta\sigma$ 一定なら、

$M_0 \propto r^3$ なので

$$RV_{max} \propto M_0^{1/3}$$

全データでは

$$RV_{max} \propto M_0^{0.43}$$

AEと鉱山地震で同じスケーリング則にのる!

地震規模累積頻度分布

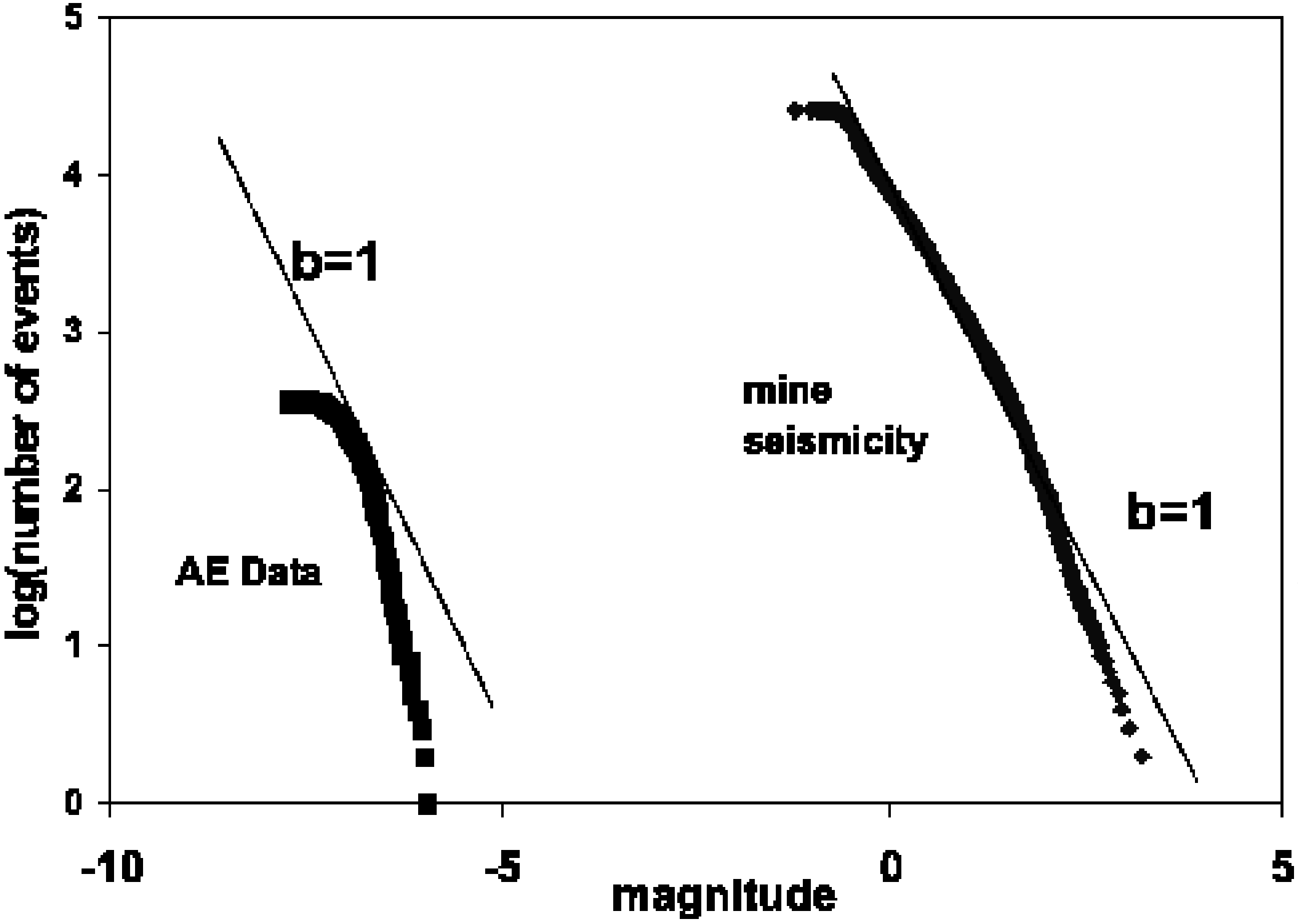


Figure 14. Frequency-magnitude relationship plot for AE and mine data from 5 years of mining on a deep-level gold mine in South Africa.

b=1？

狭い規模のレンジしか捉えられていない

センサーの周波数レンジが狭い影響

まとめ

メカニズム: ほとんどのイベントでダブルカップルが卓越

shear の存在

AE, 鉱山地震, 自然地震で単一のスケーリング則

震源は自己相似的

感想:
・示されているスケーリング関係は、AEと地震との両者をつなげられているが、AEデータだけの傾向とはあまり一致していない
・もっと広いレンジで調べて欲しい

Peak acceleration

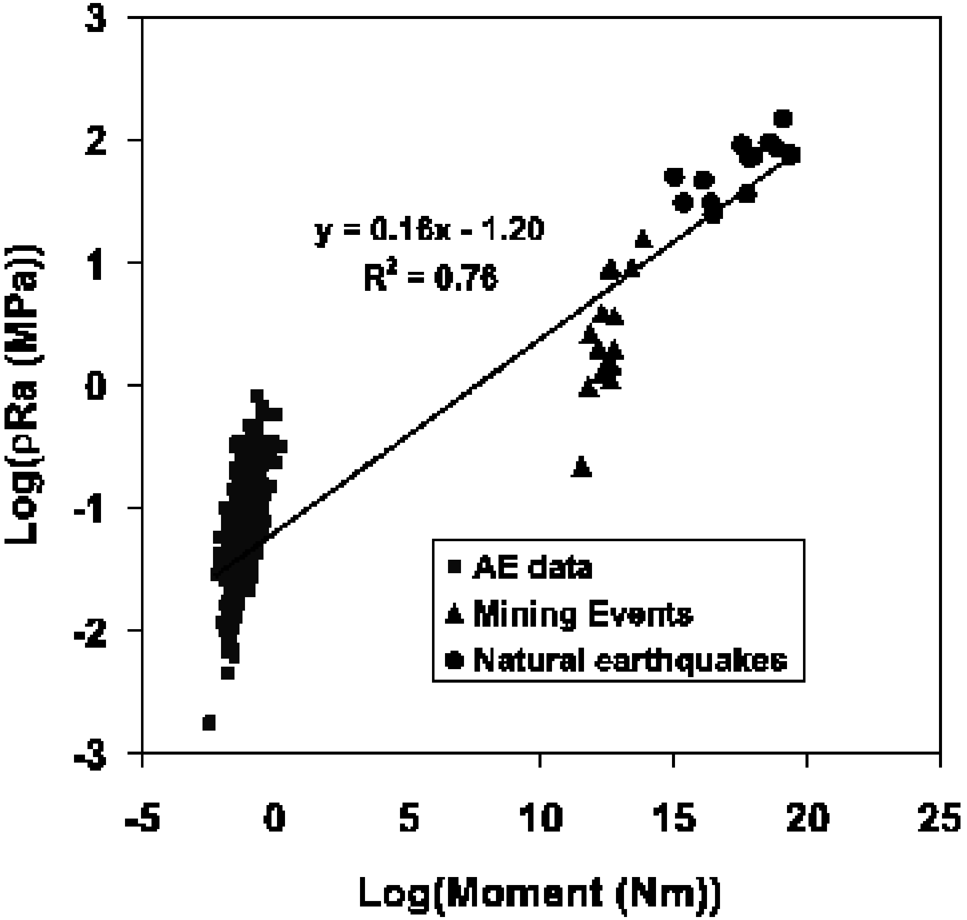


Figure 13. Measured peak acceleration parameter versus moment. Filled squares represent AE, triangles represent mine events, and circles represent natural earthquakes (mine and earthquake data are from the work of *McGarr* [1993]).

Fracture surface

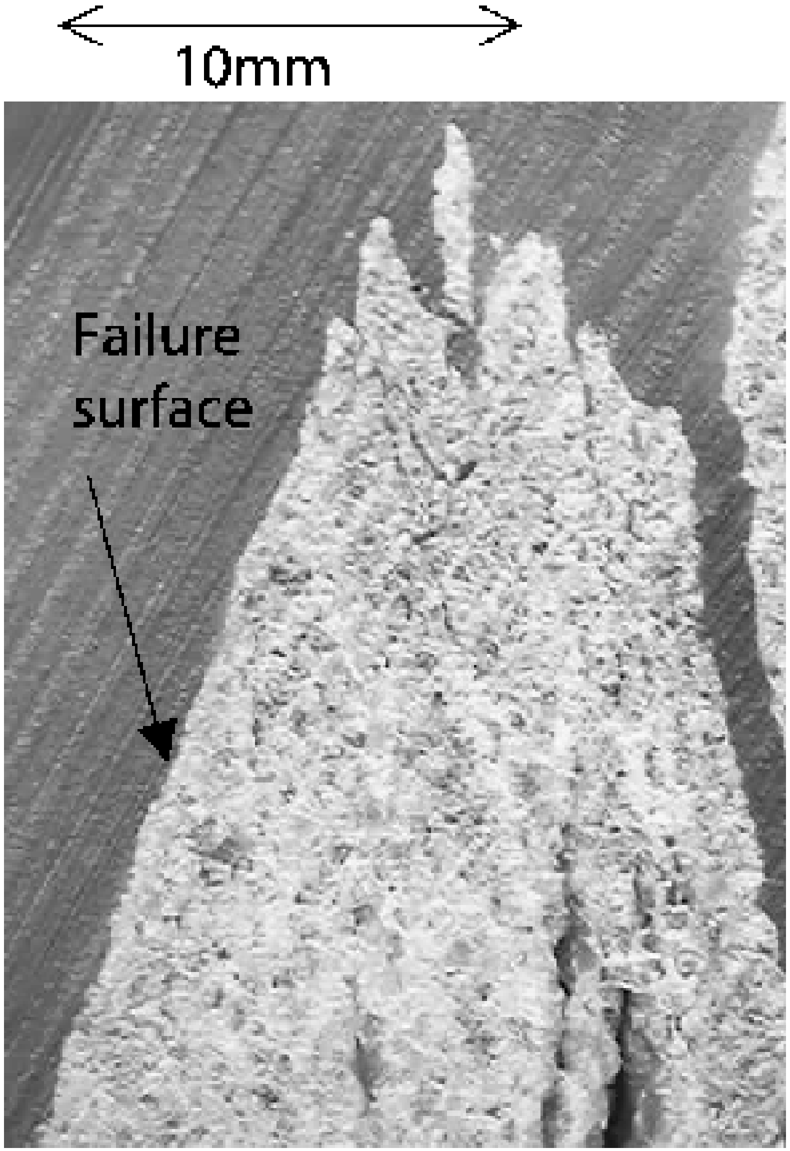


Figure 6. Photograph of a section through a part of the failed sample showing the vertical fractures associcted with the steeply dipping failure surface.

センサーの検定

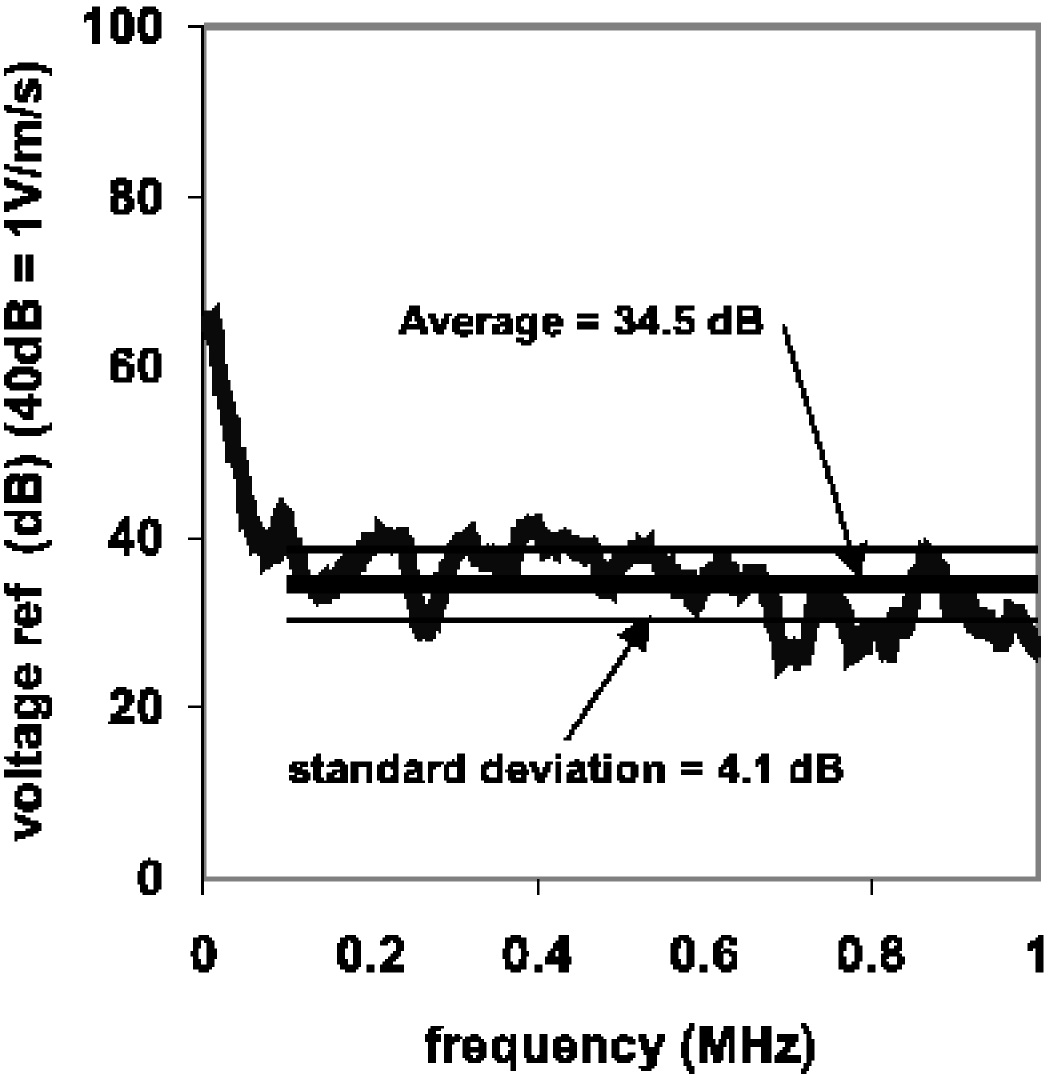


Figure A1. Velocity sensitivity of a typical S9225 sensor.