S41B-0966 INVITED Thursday 0800h

Semi-controlled Earthquake-generation Experiments to Monitor the Entire Life Span of an Earthquake in South African Deep Gold Mines

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This poster reviews previous activity since 1992 and introduces our new attempts in 2003.

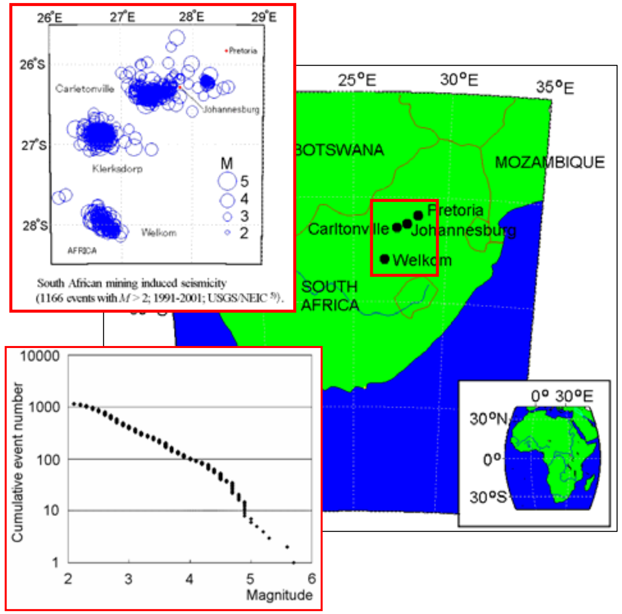
1. Experimental purpose = Seismogenic process monitoring (Iio 1995, Sumitomo 1998)

To investigate

- Scale-dependency & variability of the process
  Target = M = 2~3 events
  (a few times a year at each experimental site)
- With sensors installed ahead of time
- Within 100 m from anticipated sources

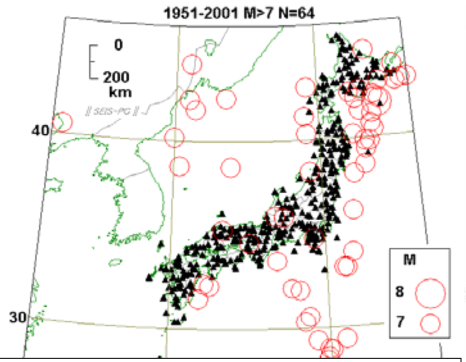
We monitor:

- Fault behavior (geodetically & seismologically)
  with high-resolution, wide-dynamic-range systems
- Environment (stress, strain, temperature)
- Material (Geological, mechanical properties)

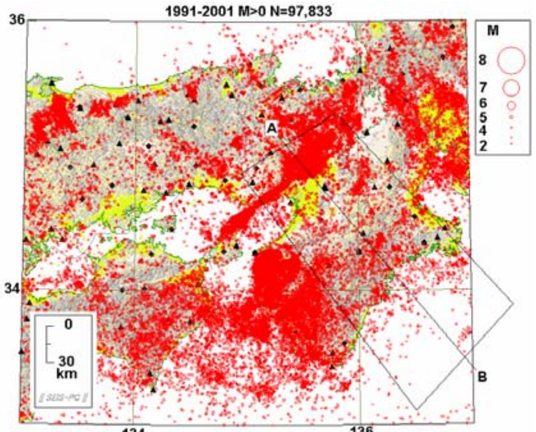


South African mining induced seismicity (1166 events with M > 2; 1991-2001; USGS/NEIC [5]).

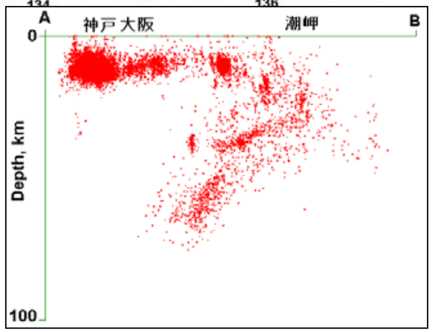
M>7 in a 50-yr period
(Data after JMA; drawn with SEIS=PC)



Smaller events in a 10-yr period
(Data after JMA; drawn with SEIS=PC)



- More events offshore with less stations
- Little events inland with denser stations
  Recurrence > a few thousand years
- causing **Chronic lack of experience**



- Too deep to reach the most active area
  causing **chronic lack of experience**

10-yr seismicity in South Africa	10-yr seismicity in Japan
M5 ~yearly	M7 ~Yearly
M2 ~Daily	M4 ~Daily
Causality Daily	Causality Yearly
	Catastrophe a few decades
More experience chances	Less experience chances
Closest to foci	Too distant from foci

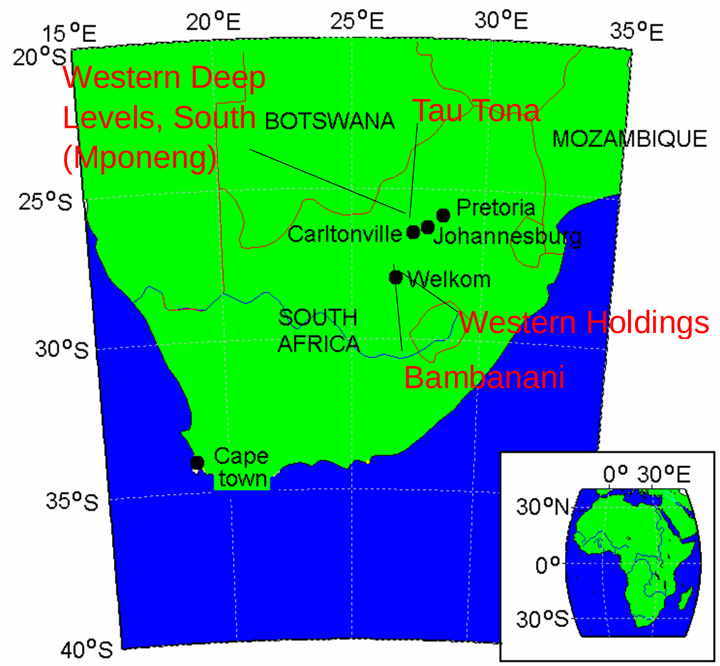
Table 1 Comparison of related projects of sensitive strain monitoring

Mine/ generation	EPRM	W. Holdings/ Our pilot site	WDL/ Our 1st site	Bambanani/ Our 2nd site
References	McGarr (1982)	Ishii *et al*; Eden Ogasawara *et al*	Ishii *et al* Ogasawara *et al*	Ishii *et al* Ogasawara *et al*
Instruments				
type	Sacks-Evertson	Ishii	Ishii	Ishii
quantity	3	1	4	1
component	Only dilatation	3	3	4
sensitivity	1E-9	1E-9	1E-9	1E-9
dyn. range	5E-6	2E-4	7.5E-4	7.5E-4
diameter	114 mm	66 mm	66 mm	66 mm
Length	1.5 m	1.1 m	1.1 m	1.3 m
Hole				
diameter	141 mm	92 mm	92 mm	92 mm
length	6-7 m	10 m	10 m	15 m
Monitoring				
intermission	Everyday for zeroing	Only on a failure in power or communication	Same as left	Same as left
sample period	4 s	15 minute	15 minute	0.04 second
recording	Paper or magnetic tape	Digital	Digital	Digital
resolution	8E-9/mm	12-bit A/D with manual zeroing	12-bit A/D	24-bit A/D
Site				
depth	~ 3 km	~1.5 km	~2.6 km	~2.4 km
location	Above advancing face	At a dyke adjacent to mining	Beneath advancing face	At a fault-loss
geological feature	No faults documented	Dyke	No faults	~100 m fault
Close event				
magnitude	Max 3.7	>0	Max 2.0	Max 3.5
distance	~100 m	< 75 m	~100 m	~100 m
Strain change				
long term	Unable to record	~1E-4 over a month	~3E-4 over 8 months	~2E-4 over 2 years
coseismic	Clipped if step > 5E-6	~3E-6	~3E-5	~1E-4
preseismic	Even if it exists, < 1E-8 or within 10 s before the event			See text
postseismic	Logarithmic	Logarithmic	-	Logarithmic
Remarks		Strain consistent with theory and and seismic parameter change	Semi 3-dimentional strain monitoring with a pair of strainmeters	**Problems solved in the projects at Mponeng & Tau Tona from 2003**

2. History

1970s-80s pioneering work by McGarr *et al.*
1990 ISSI established
1991 IASPEI endorsed
1992 Nicolaysen (Wits Univ.) visited Japan
1993 1st Japanese Grant-in-aid (PI: Sumitomo)
1995 W. Holdings pilot experiment
1996 W.D.L. 1st experiment
1998-2003 Bambanani 2nd experiment
2002- Mponeng Trough dike

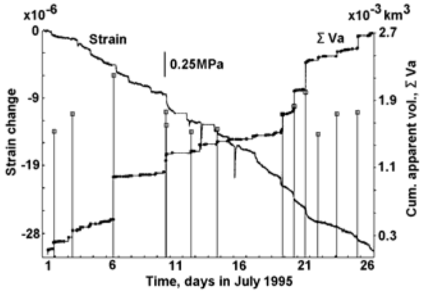
2003- Tau Tona & Mponeng experiments
Eighteen Japanese worked underground to construct multidisciplinary monitoring sites
2005- Collaboration with DAFSAM & NELSAM

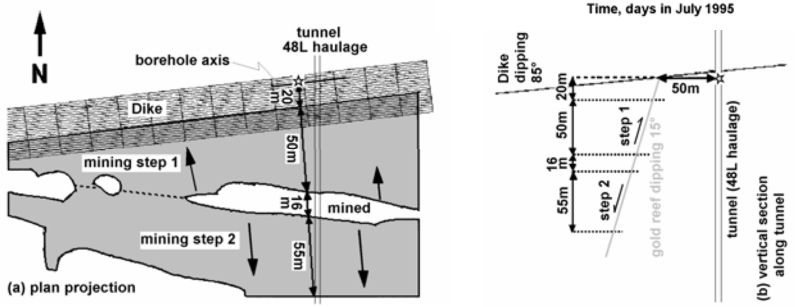


3. Previous projects

Western Holding (1995)

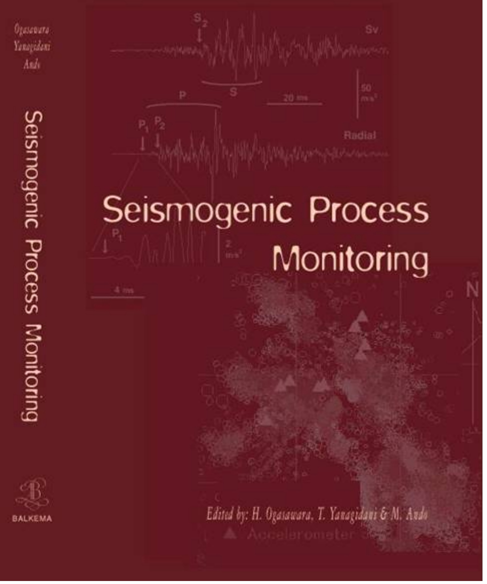
(After Eden 1995)





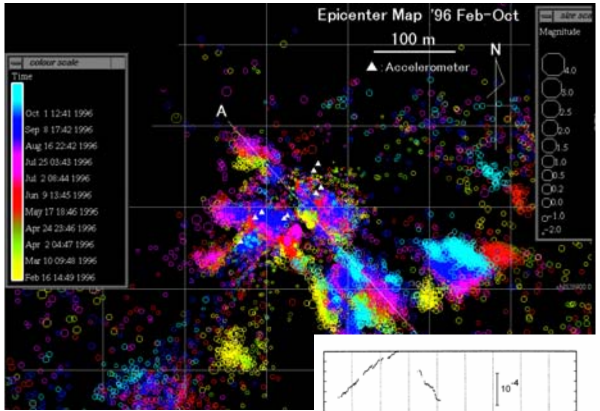
Refer further details on previous project to Ogasawara et al. (eds) Balkema, 2002

- Scaling
- Initial phase
- Seismic parameter change
- S-wave splitting

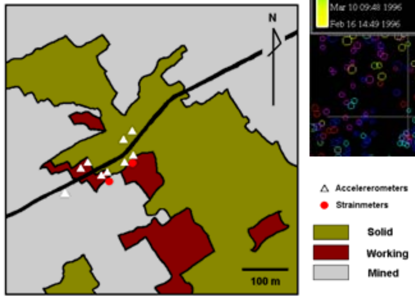


Western Deep Levels, South (1996-97)

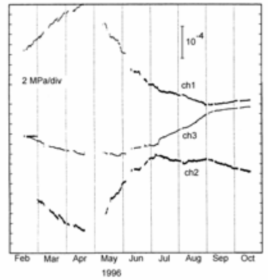
>20k M>-1 events

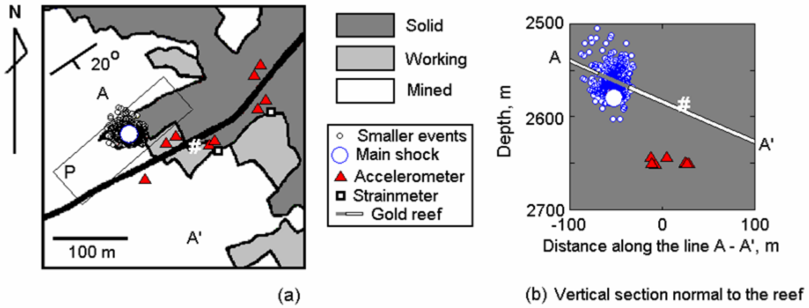


Dense accel. array

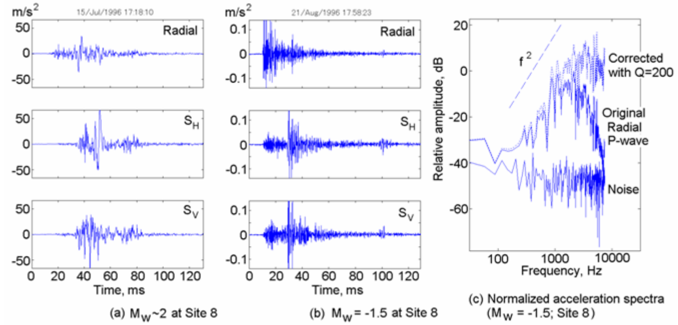


> 10^{-4} strain change



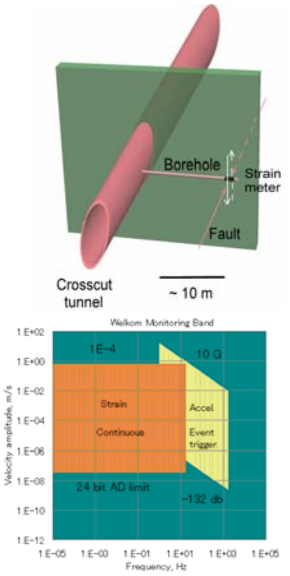


An M2 and the associated smaller events (M> - 1.5) were successively recorded with 9 tri-axial accelerometers



4. Bambanani Project (1998-2003) (Ishii *et al*. 2000, Takeuchi *et al*. 2003, Shimoda *et al*. 2004, Ogasawara *et al*. 2005a)

>10^{-4} strain change associated with two M>2 events within 100 m with 25Hz 24bit resolution

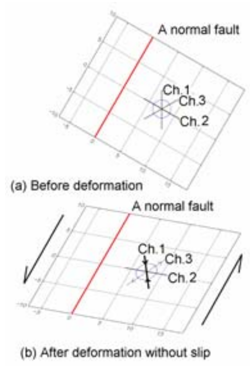


A 3-yr period continuous monitoring of slip-driving shear & normal strains on a 100-m fault with a 4-component borehole Ishii strainmeter

The meter accommodates strain larger than 10^{-4}, and sensitive enough to detect the Earth tide

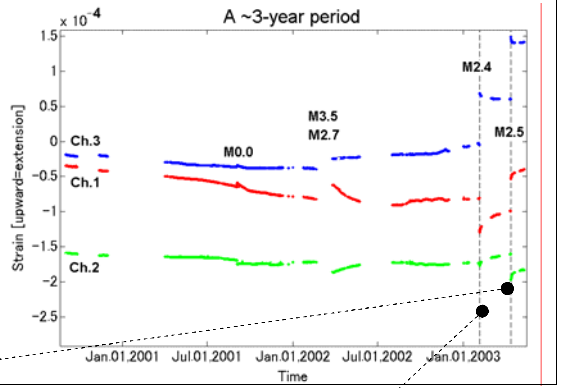
Installed at a15-m depth in a 92-mm diameter hole in quartzite (Vp=5.5km/s)

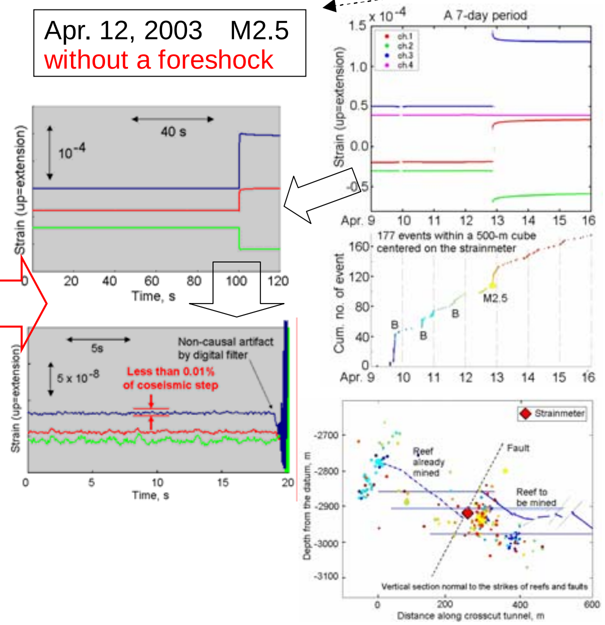
With a combination of accelerometer, the entire life span of an earthquake is monitored without any blind frequency band.

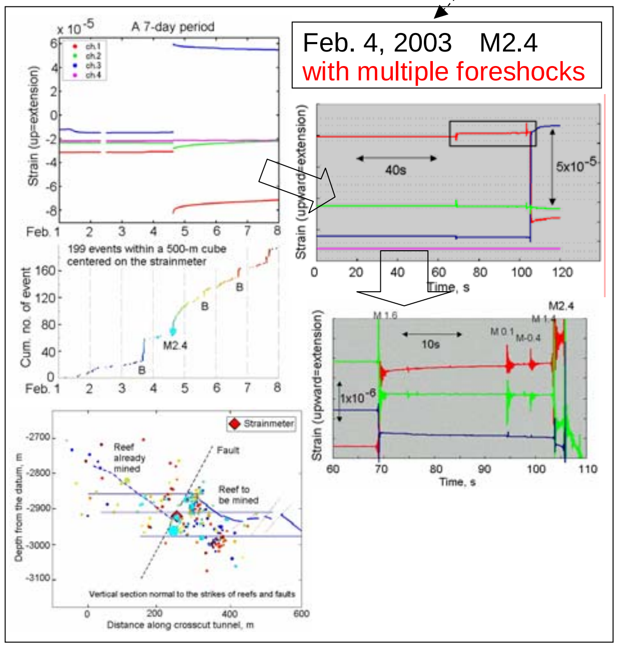


Until Jul. 2002,
Ch 1 (//σ_1) contract =>σ_1 increase several MPa
After which
Ch 3 extension; Ch 1 ~constant
=> shear increase as shown left
Meanwhile
Ch 2 (fault-normal) constant

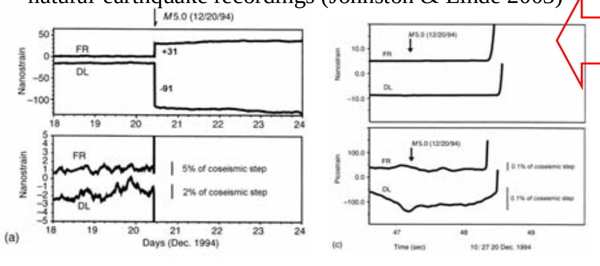
M0.0 in 2001 nearer than 20 m
M3.5 & 2.7 in 2002 relatively far
M2.4 & M2.5 in 2003 < 100 m
Coseismic steps > 10^{-4}
(~7MPa ~ a stress drop)







Comparison with a highest resolution example of natural-earthquake recordings (Johnston & Linde 2003)



Problems

Single strainmeter, source not locatable; No closest seismic station to strainmeters to discuss onset accurately

No dense seismic array to accurately locate hypocenters; No stress measurements

which we tried to address at new sites at Tau Tona and Mponeng mines from 2003.

5. Tau Tona Project (2003- (Ogasawara *et al.* 2005b)

A site at a fault-bracket pillar 2.9 km deep (Figs.1&2)
Two faults (light grey) intersect gold reef (mottling brown; dark grey: already mined; dipping 20 degree to SE)
Two cubbies A & B along a so-called T-shape slot (a tunnel (yellow) covered with a thin waste-slot (red))
Target = Ken's fault. An M2.5 took place before our experiment, being well exposed in the eastern stope (Photo 1) or newly excavated tunnel (Photo 2)
Drilling into the pillar to install instruments was difficult because of severe borehole breakout at a depth of several meters (photos 3 & 4).
In June 2003, the borehole breakout was not so severe. So, we grouted the strain cell for overcoring (Fig.3)
However, a considerable increase in stress and deformation and M2 occurred associated with quick mining advance (Photo 5), not allowing us to recover the cell.
One continuous-monitoring Ishii strainmeter, two strong motion meters were finally installed.

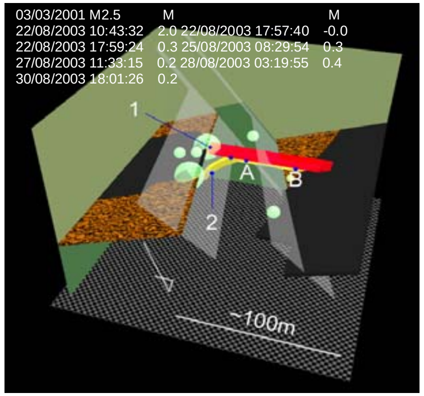


Fig.1 ←

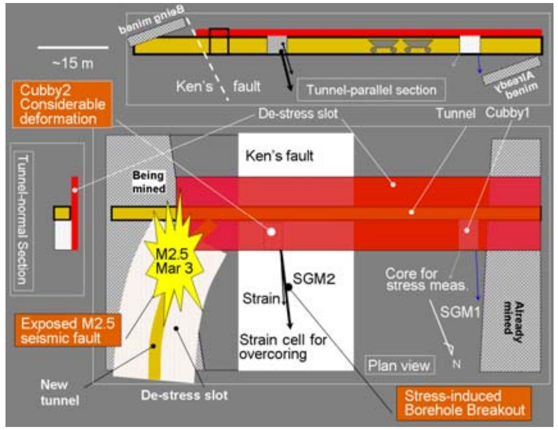


Fig.2 →

Photo 1. Ken's fault at Site 1 in Fig.1

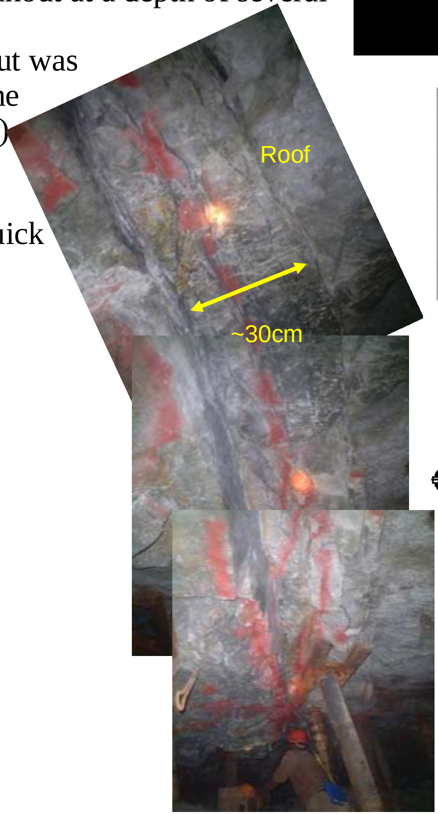


Photo 2. Ken's fault exposed on the roof at Site 2 in Fig. 1

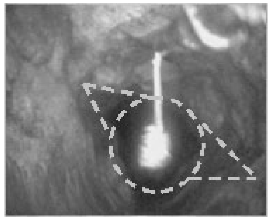


Photo 3. borehole breakout in a 114 mm diameter hole

Photo 4. An example of drill core with borehole breakout

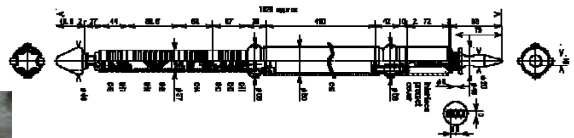


Fig. 3. Recoverable, intelligent Ishii strainmeter for overcoring with a diameter of 38 mm.

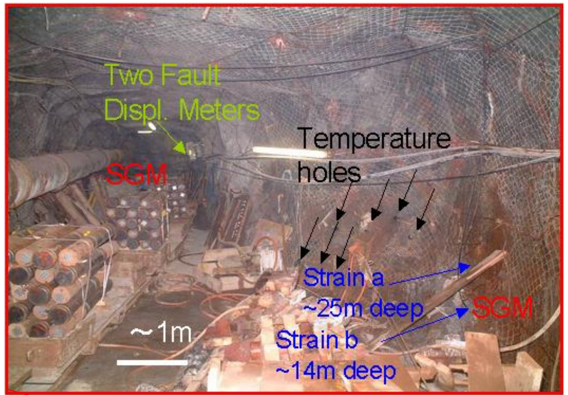
Lessons at the highly-stressed pillar:
Mining was faster than drilling.
Instruments and procedures specially designed for an adverse condition are needed.

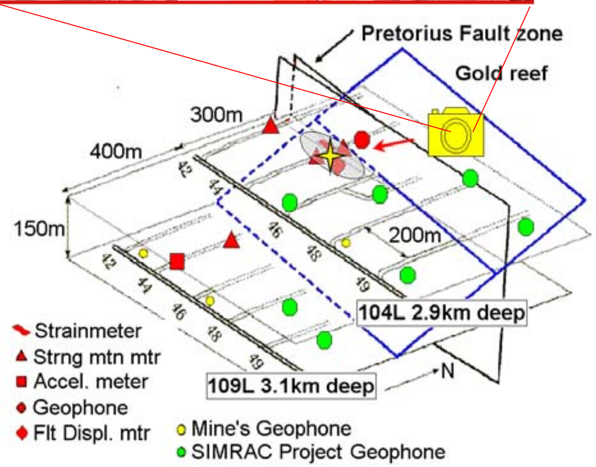
Photo 5. Considerable roof deformation associated with mining advance.

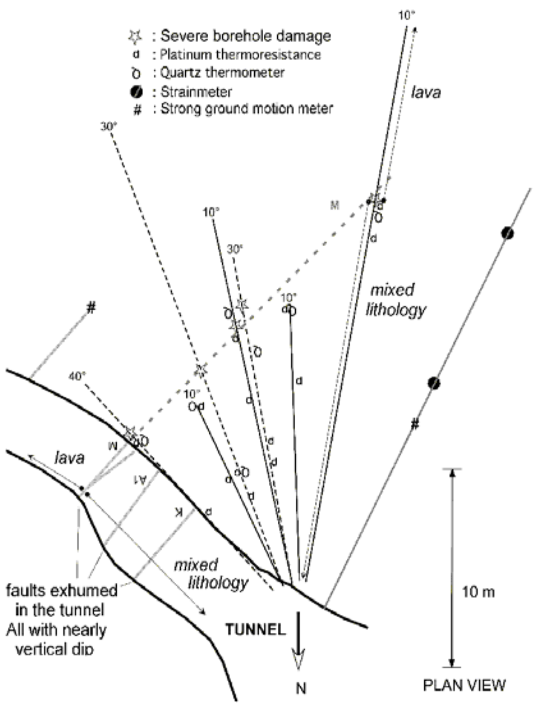
6. Mponeng Project (2003-

(Nakatani *et al*. 2004, Kita *et al*. 2004, Morishita *et al*. 2004, Ogasawara *et al*. 2005)

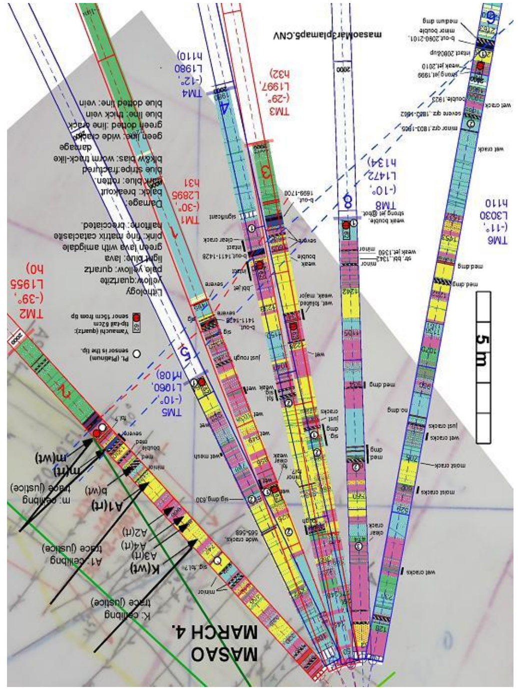
A site at a planned fault-bracket pillar
 in the Pretorius fault zone with mixed lithology
 ~ several tens m wide
 with only a waste slot being mined
 adjacent to a dense geophone array (~200m spacing)
Target = a distinctive week plane 3-D located
 by 2-20 cm wide damages in seven 15-30m holes.
Two Ishii strainmeters, 16 sensors for temperature,
 2 for strong motion and 2 for fault displacement



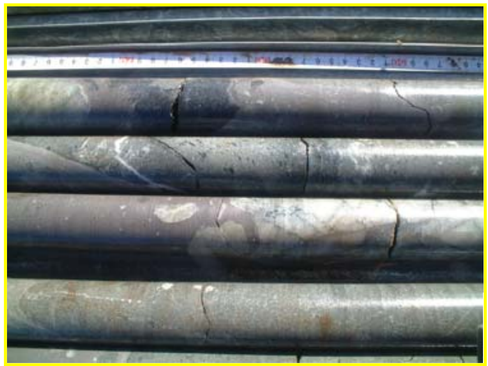


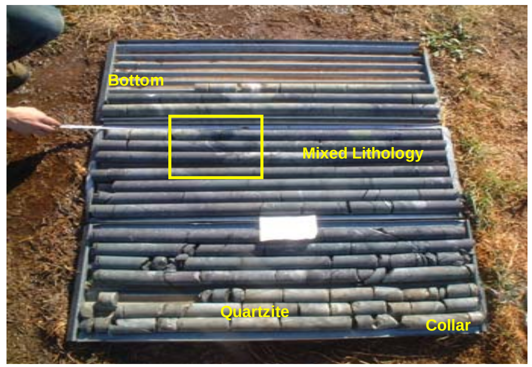


Configuration of sensors. Displ. meter at M & K.



Simplified lithology (yellow: quartzite, green/blue: basaltic lava, pink: cataclasite)

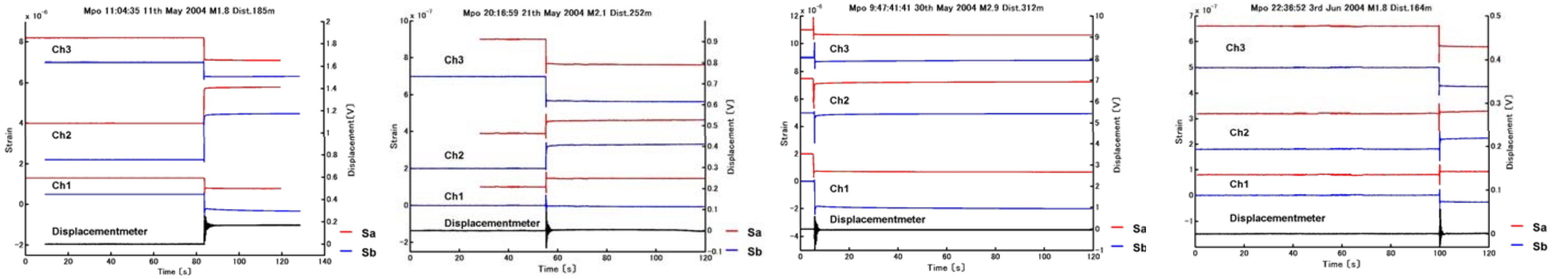




A typical example of the complicated lithology in the fault zone, with fragmented patches in every size, consisting of country rock (basaltic lava (hanging wall; light green) and quartzite (footwall; light gray)), fill-up with cataclasite (dark gray).

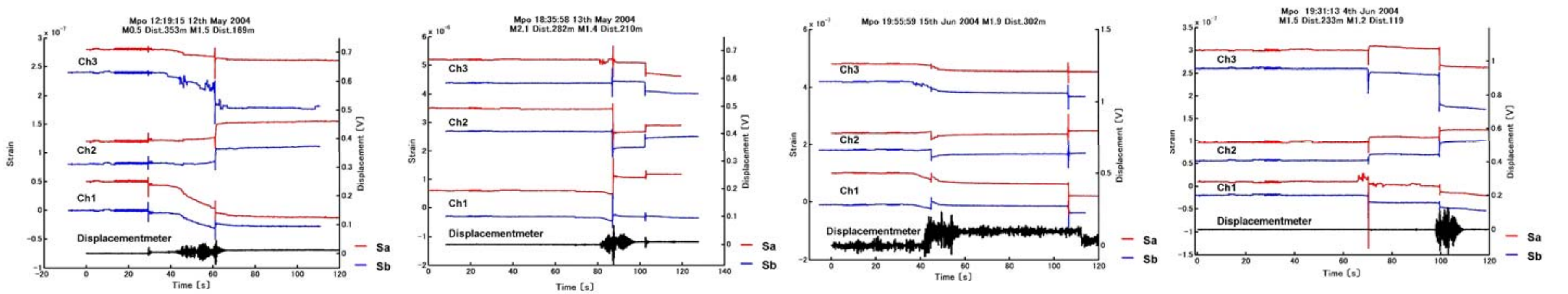
Examples of recordings

a) Strain change with seismic events off blasting time (Ch1: vertical//σ_1. See ch configuration in Bambanani diagram)



b) Strain change with seismic events on blasting time

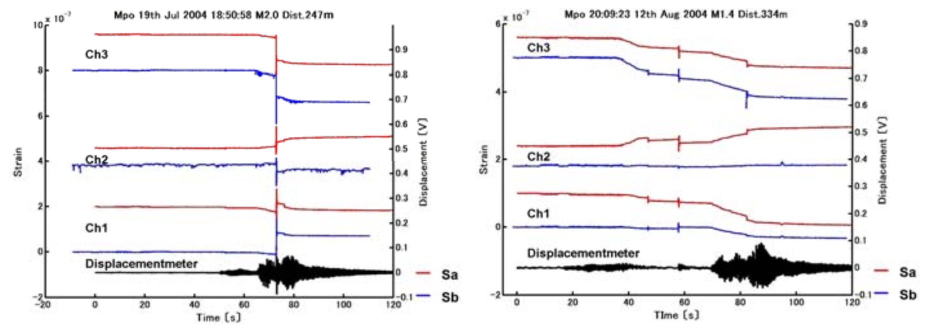
If transient change is enlarged, sequences of minute stairs corresponding to every detonation are seen



c) Temperature change

Records obtained so far indicate a slow cooling (0 to 6 mK/day), presumably due to tunnel development (two years ago), and air conditioning following it.

Heating equivalent to a 2-cm slip at a 5-MPa frictional will be clearl detected with the array.



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