Small slow-strain steps and their forerunners observed in gold mine in South Africa

Makoto Naoi,[1] Hiroshi Ogasawara,[2] Junichi Takeuchi,[3] Akihito Yamamoto,[1] Naoyuki Shimoda,[4] Ken Morishita,[1] Hiroshi Ishii,[5] Shigeru Nakao,[6] Gerrie van Aswegen,[7] Aleksander J. Mendecki,[7] Patrick Lenegan,[7] Rookshana Ebrahim-Trollope,[8] and Yoshihisa Iio[9]

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[1] The Research Group for Semi-controlled Earthquake-generation Experiments in South African deep gold mines (SeeSA) has continuously monitored strain changes with a resolution of 24 bit 25 Hz at the Bambanani mine near Welkom. An Ishii borehole strainmeter was installed at a depth of 2.4 km near the potential M $\sim$ 3 earthquake source area. Instantaneous strain steps of $\sim 10^{-4}$ strains associated with two M2 events were observed within a length of seismic fault. These steps were followed by significant post-seismic creep-like drift, but not preceded by forerunners. Analysis of the continuous 25 Hz data reveals many smaller steps with much longer durations (100 ms $\sim$ 100 s) than seen in normal earthquakes ($-1 < M < 2$) with source durations of 1 ms$\sim$50 ms. Some of the especially slow steps were preceded by accelerations in strain, the maximum being as large as one-third of the step. **Citation:** Naoi, M., et al. (2006), Small slow-strain steps and their forerunners observed in gold mine in South Africa, *Geophys. Res. Lett.*, *33*, L12304, doi:10.1029/2006GL026507.

1. Introduction

[2] A stable rupture preceding an unstable rupture has been reproduced in laboratory experiments [e.g., *Ohnaka et al.*, 1986]. This is called "earthquake nucleation process," and is considered to be a preparation process of earthquakes. Seismologists have attempted to record the nucleation process of natural earthquakes [e.g., *Johnston and Linde*, 2003], but have not done so as yet. Therefore, it is an unanswered question whether the knowledge from the laboratory experiments can be applied to natural earthquakes. If we observed rock-mass behavior near the source, we could answer this question. It is not possible to install instruments near the hypocenter of natural earthquakes.

[3] South African deep gold mines are the best experimental sites for such near-source observations. Many M < 3 earthquakes are induced by mining activity, which is usually planned ahead for years. Hence, sensors can be installed in the zone where high seismicity is anticipated in the near future.

[4] *McGarr et al.* [1982] installed three Sacks-Evertson dilatometers at a depth of 3.1km in the ERPM gold mine in South Africa, and monitored rock-mass behavior associated with earthquakes. The dilatometer recorded the strain changes associated with the earthquake, with a magnitude of 3.1 and at a distance of 150 m. However, the dynamic range of only $\pm 5 \times 10^{-6}$ did not fully accommodate the change. In recordings with a sampling frequency of 0.25 Hz, they were unable to identify a forerunner preceding the co-seismic step, and also were unable to discuss any changes at higher frequencies.

[5] In order to observe earthquake forerunners, the Research Group for Semi-controlled Earthquake-generation Experiments in South African deep gold mines (SeeSA) [*Iio and Fukao*, 1992; *Ogasawara and the Research Group for Semi-controlled Earthquake-generation Experiments in South African Deep Gold Mines*, 2002] attempted to continuously monitor strain changes with a resolution of 24 bit 25 Hz at the Bambanani mine, Welkom, beginning in 1998 [*Ishii et al.*, 2000]. An Ishii four-component borehole strainmeter [*Ishii et al.*, 1997] was installed at the mine, and many strain steps ($<10^{-4}$) were recorded associated with the seismicity (<Mw 2.9) within 100 m from the strainmeter [*Takeuchi*, 2005; *Ogasawara et al.*, 2005]. So we checked whether these steps were preceded by accelerations in strain. We also classified these steps by durations. In this paper, we detail the events that have longer duration than earthquakes, and discuss if the sources can be constrained near the high seismicity area.

2. Strain Measurement at the Bambanani Gold Mine

[6] Figure 1a shows the mining situation around the strainmeter. The gold reef inclines to the east-southeast at 35 degrees in this mine and is nearly perpendicular to the Tanton normal fault (dashed line in Figure 1a) where M $\sim$ 3 earthquakes had been expected. The reef on the western side of this fault (chain line in Figure 1a) had been mined when an M3.4 earthquake occurred on this fault. G. van Aswegen (one of the present authors) anticipated another event on this fault, associated with so-called eastern mining (solid line in Figure 1a), so we drilled a 15-m hole subparallel to the fault strike from the tunnel and installed the strainmeter about 10 m from this fault (a diamond in Figure 1a) [*Ishii et al.*,

[1]Graduate School of Science and Engineering, Ritsumeikan University, Kusatsu, Japan.
[2]Faculty of Science and Engineering, Ritsumeikan University, Kusatsu, Japan.
[3]National Instrument Corporation, Tokyo, Japan.
[4]Japan Oil, Gas and Metals National Corporation, Kawasaki, Japan.
[5]Tono Research Institute of Earthquake Science, Mizunami, Japan.
[6]Faculty of Science, Kagoshima University, Kagoshima, Japan.
[7]ISS International Ltd., Stellenbosch, South Africa.
[8]Geohydroseis CC, Klerksdorp, South Africa.
[9]Disaster Prevention Research Institute, Kyoto University, Uji, Japan.

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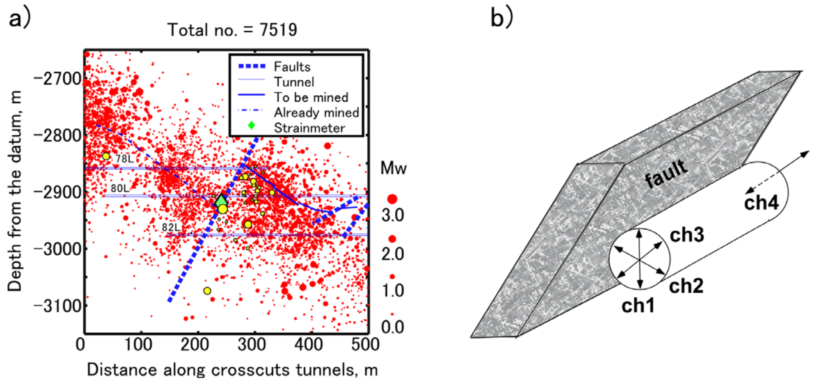

Figure 1. (a) Seismicity within 400m of the strainmeter ($-0.5 < \mathrm{Mw} < 3$; detected at more than four stations; from June 2001 to June 2003; vertical cross section; data supplied by the mine). Yellow-circle; earthquakes with strain steps $>10^{-7}$. The location accuracy is relatively low in a direction normal to the reef along the fault because the station configuration is almost planer along the reef [*Shimoda et al.*, 2005]. (b) Schematic illustration of normal fault and configuration of sensor directions in the Ishii strainmeter.

2000; *Ogasawara et al.*, 2001, 2005; *Ogasawara and the Research Group for Semi-controlled Earthquake-generation Experiments in South African Deep Gold Mines*, 2002]. As anticipated, the mining of the reef on the eastern side of the fault induced seismicity.

[7] About 700 earthquakes ($-0.5 < \mathrm{Mw} < 3.0$) occurred within 100 m of the strainmeter during a 3-year period from 2001 to 2003. Figure 1b illustrates the configuration of the fault and the sensor directions of the strainmeter. As shown in Figure 1b, Ch. 2 monitors normal strain on the fault. When shear strain accumulates to drive normal faulting, Ch. 1 contracts and simultaneously Ch. 3 extends, whereas the opposite happens during strain release. The recorded of Ch. 4, which is parallel to the fault strike, is not used in the present analysis because the channel did not record either earth tides or coseismic strain steps [*Takeuchi*, 2005].

[8] The strainmeter accommodates strain larger than 10^{-4} and detects strain as subtle as 10^{-9} (see more details in the work of *Ogasawara et al.* [2001, 2005] and *Ogasawara and the Research Group for Semi-controlled Earthquake-generation Experiments in South African Deep Gold Mines* [2002]). The strainmeter has mechanical impulses and step responses that looks like a poorly-damped oscillation lasting for periods of 1 to 2 seconds.

[9] We used a recording system (MS$^{(R)}$ from ISS International, Ltd.) that initially samples strain at a sampling frequency of 102.4 kHz, with multiple FIR-filtering and decimating, to make 25 Hz recordings. The digital process also has impulse and step responses lasting for periods of 1 to 2 seconds [*Takeuchi*, 2005].

[10] We observed the accumulation and release of 10^{-4} strain (Figure 2), which was recorded only within the extent of the seismic fault. This corresponds to a stress change of ~7 MPa, considering Young's modulus (70 GPa) for the rock mass. We recorded more than 2000 strain steps ($10^{-9} \sim 10^{-4}$), including a 5.7×10^{-6} instantaneous strain step (associated with an Mw0.2 earthquake in September 2, 2001), a 7×10^{-5} (Mw2.9; Feb. 4, 2003), and a 10^{-4} (Mw2.0; Apr. 12, 2003) [*Takeuchi*, 2005; *Ogasawara et al.*, 2005].

[11] These events occurred within 100 m of the strainmeter but were not preceded by a detectable accelerated strain-rate, although multiple foreshocks did precede the event of February 4, 2003. No such detectable accelerated strain-rate preceded 449 smaller catalogued earthquakes [*Takeuchi*, 2005]. A large number of co-seismic steps were sometimes followed by post-seismic creep-like drifts, but not always. The sense of the co-seismic steps varied from event to event, and post-seismic drifts had either the same or opposite senses as the co-seismic steps. *Yamamoto et al.* [2005] claimed that such behavior is possible when the strainmeter is very close to the fault because the back-azimuths to those faulting planes can be significantly

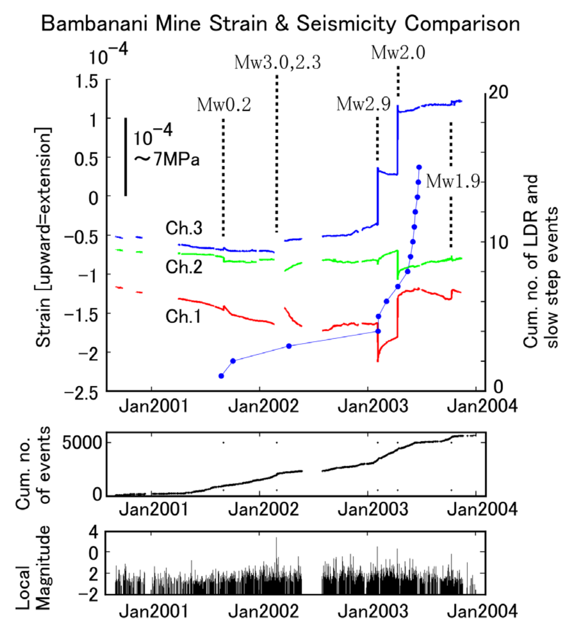

Figure 2. Long-term strain changes and seismicity within 250m of our strainmeter at the Bambanani mine (after *Ogasawara et al.* [2005]), and the occurrence of LDR (Little Dynamic Response) events, which is central in this article, as detailed in Section 3, with steps of $>10^{-7}$. Connected blue dots show cumulative number of LDR events highlighted in this study. LDR events frequently occur after the onset of large strain changes, except for the event of August 2001 prior to the Mw0.2 earthquake in September 2001.

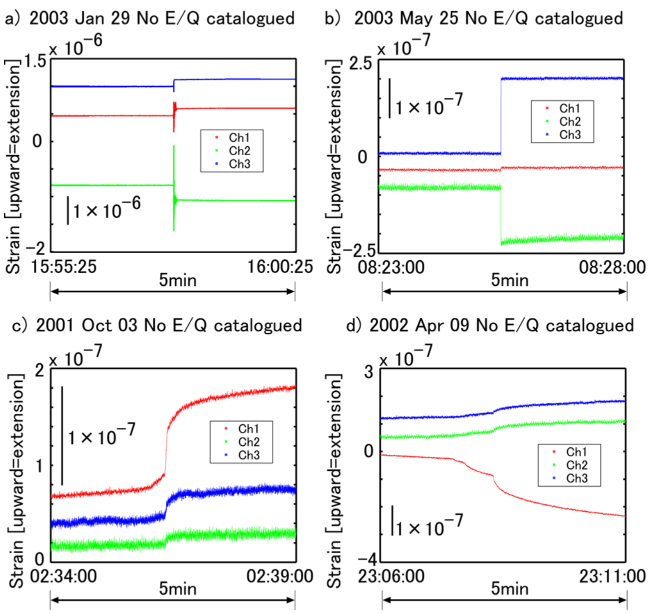

Figure 3. Examples of strain events in 5-minute periods (a) with dynamic strain change, (b) with static strain change only, (c) slow-step with forerunner (see Figure 6b for different time scales), and (d) slow-step (see Figure 6b for different time scales).

variable from event to event. In addition, we discovered striking characteristics to the smaller steps, as detailed in the following sections.

3. Classification of Aseismic Events in Continuous 24 bit, 25 Hz Recordings

[12] In this study, we plotted continuous 25 Hz strain data, and checked them over a two-year period from June 2001 to June 2003. We detected 2031 examples of strain change with absolute amplitudes of $10^{-9} \sim 10^{-4}$, and durations of 10 ms to 1000s (hereafter referred to as "strain events"). We excluded changes associated with blasting, recorded in only one component, or smaller than 10^{-7}, after which we had 70 strain events to analyze.

[13] All Mw > −0.5 earthquakes can be detected and catalogued at the Bambanani mine with a seismic array having an average station spacing of about 500 m. It turns out that 38 out of 70 strain events with strain steps $>10^{-7}$ had corresponding catalogued earthquakes (hereafter referred to as "seismic events"). All 38 seismic events had impulse and step responses to far-field seismic waves and strain steps (hereinafter we refer to such responses as "DR"; Dynamic Response). The DR amplitudes were from several to dozens times greater than those of the steps (e.g., Figure 3a).

[14] The remaining 32 of 70 strain events (e.g., Figures 3a–3d) had no corresponding catalogued earthquakes. These strain events were further classified according to their Dynamic Response characteristics, as shown in Table 1. Six of these 32 strain events had a large Dynamic Response, which we refer to as "DR events" (Table 1 and Figure 3a). These events presumably correspond to earthquakes very close to the strainmeter, but smaller than the smallest earthquakes (Mw ∼ −0.5) catalogued by the mine's seismic network. Four events had much less significant DR than DR events (indicated by "?" in Table 1), but we detected 15 events with little DR (e.g., Figures 3b–3d), which is central in this study. We refer to these as "LDR events" (Table 1). Three of the LDR events had significantly longer durations, by four orders of magnitude, than the seismic events of typical earthquakes, and are hereafter referred to as "slow-step" events; e.g., Figures 3c and 3d).

[15] We found at least 16 slow-steps for strain events smaller than 10^{-7} (not listed in Table 1). However, we do not detail them further in this study. It is interesting to note that significant strain accelerations preceded some of the slow-steps (e.g., Figure 3c).

[16] Unfortunately, no data were recorded during the steps of seven events without corresponding catalogued earthquakes ("No data for steps" in Table 1), so there are not discussed here.

4. Characteristics of the Little Dynamic Response (LDR) Events

[17] The cumulative number of LDR events $>10^{-7}$ is shown as connected blue dots in Figure 2. The events occur within a short time after the largest strain steps (those by Mw 0.2, 2.9, 2.0 earthquakes in Figure 2a), one exception being the event in August 2001 prior to Mw0.2 (about 20m from the strainmeter) in September 2001.

[18] Figure 4 shows the four LDR events for a period of 2 seconds. The durations of the steps are ∼0.2 second, much longer than the earthquakes (−1 < M < 2) having source durations of 1 ms ∼ 50 ms.

[19] As stated, there were 19 slow-step events out of 2,031 strain events (the three largest are included in Table 1), and their durations and maximum strain rates varied. Figure 5 shows four characteristic examples.

Table 1. Classification of $>10^{-7}$ Strain Events and Their Frequency

Dynamic Response	Maximum Strain Step	Number	Name	Figures
		Catalogued		
Yes	9.91E-05	38	Seismic Event	Figure 6a
		Not Catalogued		
Yes	7.50E-07	6	DR event	Figure 4a
?	2.28E-07	4	?	
No	4.67E-07	12	LDR event	Figures 3b and 4
No	1.50E-07	3	LDR event; slow-step	Figures 4c, 4d, 6a, 6b, and 6d
No data during step	—	7		

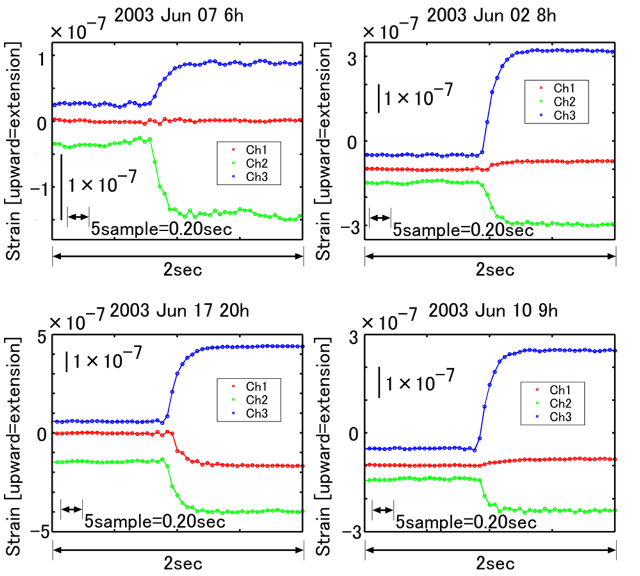

Figure 4. Four examples of LDR events with little impulse and step responses.

[20] It is noteworthy that some slow-steps were preceded by an acceleration in strain rate (Figures 5a and 5b), while others had sudden onsets (Figure 5c). The forerunners did not result from earth tides, because the latter have much longer durations. The most significant forerunners were recorded on August 24, 2001 (Figure 5a) and October 3, 2001 (Figure 5b), with amplitudes of ~1/10 and ~1/3 for the steps, respectively. It is interesting that a forerunner is

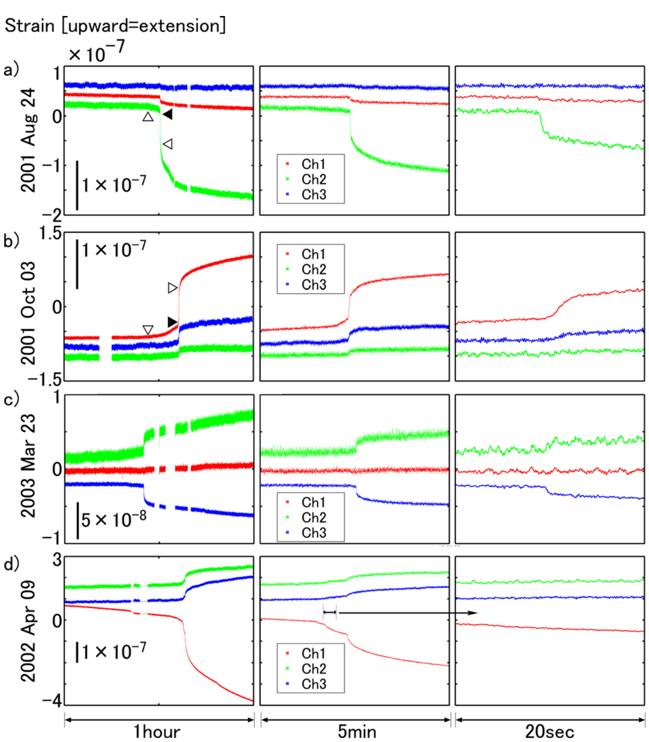

Figure 5. Four examples of slow-step events. Open triangles are onsets of forerunner and post-seismic drift. Solid triangles are onsets of co-seismic steps.

not seen in Figure 5c, even though the strain change during the step over a 20-second period (Figure 5c, rightmost) looks similar to the rightmost parts of Figures 5a and 5b.

[21] The changes over a 1-hour period look similar to each other for the four examples shown (compare the leftmost insets of Figures 5a–5d). However, Figure 5d shows two peculiarities: (1) it is too slow to be detected as a slow-step over a 20-second period (Figure 5d right most), and (2) it looks like a series of slow-steps over a 5-minute period (Figure 5d middle).

5. Discussion

5.1. Step Rise-Time of an LDR Event

[22] We investigated the possible step rise-time to account for the observed LDR events.

[23] Figure 6a shows impulse and step responses to the catalogued Mw0.1 earthquake on August 1, 2002 (at a distance of about 30m and with a maximum step of 2.2×10^{-7}). We roughly approximated the responses with a damped oscillation (a period of 3.85Hz; Q = 2.69; Figure 6b), synthesizing step responses by convolving with variable step rise-times (Figure 6c). The smallest seismic event that the mine network catalogues is Mw = −0.5, typically with a source duration of ~1 ms, and it must have a significant response as shown in the uppermost part of Figure 6c. We can account for a small-DR event with a step rise-time of ~0.1 second. The DR diminishes with an increase in rise time. An LDR is seen for rise times longer than ~0.2 s, which may in fact account for LDR events. A rise-time of 0.2 s is significantly longer than typical for the smallest catalogued earthquakes. Typical seismic events with source durations of ~0.2 s (Mw > ~3) are catalogued in and around mines, but no such record was found in this study. Consequently, an LDR event may be regarded as a slow/silent earthquake.

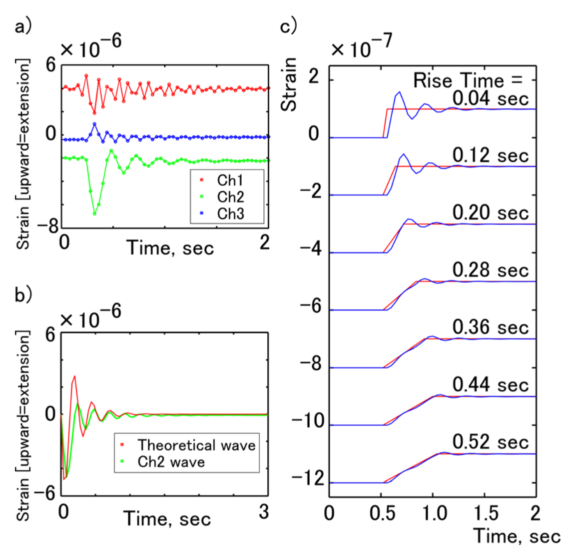

Figure 6. The change in DR with an increasing duration of the step rise-time. (a) An example of observed DR (for a 2-second period; Mw = 0.1 max. step = 2.2×10^{-7} on 2002 Aug. 1), (b) Ch 2 strain changes and approximated damped oscillation, and (c) synthesized strain steps for variable rise times from 0.04 to 0.52 second.

5.2. Noise or Signal

[24] Potential sources of the LDR events in the mine are as follows:

[25] 1) air pressure changed by artificial ventilation controls. In this case, the source location would always be the same, so this cannot account for the variable senses in strain change for the LDR events.

[26] 2) inelastic deformation ahead of the face of advancing mining can cause transient changes in strain. However, the source locations cannot move quickly, nor can they account for the variable strain changes seen in the LDR events.

[27] 3) failure of a support in a stope, or closure of a stope, can cause changes in strain. However, such changes tend to cause an increase in vertical strain (Ch. 1) at the strainmeter site (see configuration of the stopes and the strainmeter in Figure 1a), and therefore cannot explain the variability seen in the observed LDR steps.

[28] One potential source of the LDR events that we have not yet excluded is inelastic deformation at a distance less than 100 m from the strainmeter, which includes hundreds of catalogued earthquakes that have caused significant strain changes.

5.3. Reliability of Strainmeter Recordings

[29] The following three facts suggest that the strainmeter produced reliable recordings:

[30] 1) the strain meter clearly recorded earth tides on the order of 10^{-7}, which was in good agreement with the tide theoretically estimated [*Ogasawara et al.*, 2001, 2005; *Ogasawara and the Research Group for Semi-controlled Earthquake-generation Experiments in South African Deep Gold Mines*, 2002]. 2) strain changes associated with blasting ($\sim$7 times in a month) were clearly recorded. 3) for earthquakes having a lower relative error with distance, the amplitudes of the observed steps are consistent with those predicted by theory [*Okada*, 1992], and by the seismologically determined moment.

6. Concluding Remarks

[31] We attempted to continuously monitor strain changes at the Bambanani mine to a resolution of 24 bit 25 Hz.

[32] In a previous study, we confirmed the absence of significant acceleration in strain preceded by strain steps ($>10^{-8}$) for catalogued earthquakes [*Takeuchi*, 2005]. In the present study, the continuous 25 Hz data show that steps $>10^{-7}$ with significantly longer durations than in normal earthquakes cause Little Dynamic Response in the recordings. These events might be the smallest slow/silent earthquakes [e.g., *Kawasaki et al.*, 1995] ever found that radiate little seismic waves. We also observed that a significant forerunner precedes only very slow steps.

[33] A single strainmeter in the Bambanani mine was not sufficient for locating the sources of the slow events or determining their magnitudes. Multiple strainmeters would permit discussion of compartmentalization of the area of slow earthquakes versus normal earthquakes. In consequence, SeeSA is now observing strain changes with two strainmeters near sources in the Mponeng gold mine. In addition, whereas SeeSA has previously conducted such studies exclusively in dry environments, we are planning on monitoring rock-mass behavior in flooded deep mines.

[34] More-precise location of seismic events is also needed. We experimented with relative location methods for the current study site [*Shimoda et al.*, 2005]. The lack of a closer seismic station was a problem in the current study and will be resolved in the next phase of our work.

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R. Ebrahim-Trollope, Geohydroseis CC, Klerksdorp, 2571, South Africa.
Y. Iio, Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan.
H. Ishii, Tono Research Institute of Earthquake Science, Mizunami 509-6132, Japan.
P. Lenegan, A. J. Mendecki, and G. van Aswegen, ISS International Ltd., Stellenbosch, 7600, South Africa.
K. Morishita, M. Naoi, and A. Yamamoto, Graduate School of Science and Engineering, Ritsumeikan University, Kusatsu 525-8577, Japan. (rp013026@se.ritsumei.ac.jp)
S. Nakao, Faculty of Science, Kagoshima University, Kagoshima 890-0065, Japan.
H. Ogasawara, Faculty of Science and Engineering, Ritsumeikan University, Kusatsu 525-8577, Japan.
N. Shimoda, Japan Oil, Gas and Metals National Corporation, Kawasaki 212-8554, Japan.
J. Takeuchi, National Instrument Corporation, Tokyo 105-0011, Japan.