DTRA/SCC-WMD Scientific & Technical Review Information NT-14-097

1. PA CONTROL NUMBER: PA 14-108 12 Feb 14
1a. SUSPENSE: 15 Feb
2. PM / PHONE / EMAIL:
2a. DATE:
3. BRANCH CHIEF / PHONE /EMAIL:
3a. DATE:
4. DIVISION CHIEF / PHONE: D Carlson for C Stradling
4a. DATE: 6 Feb 2014
5. DEPARTMENTS / PHONE:
5a. DATE:
6. JDir/ OFFICE / PHONE:
6a. DATE: 11 FEB 14
7. PUBLIC AFFAIRS: RALOVNS
7a. DATE: 2/18/14

8. TITLE: Motivation for a High Explosive Testing Program in South Africa
9. CONTRACT NUMBER:
10. COMPANY/GOVT LAB/ AUTHOR'S NAME: Michael J. Shore
11. TYPE OF MATERIAL: ☒ PAPER ☐ PRESENTATION ☐ ABSTRACT ☐ OTHER
12. OVERALL CLASSIFICATION: ☒ CONTRACTOR RECOMMENDED CLASSIFICATION Unclassified ☒ PROJECT OFFICER RECOMMENDED CLASSIFICATION Unclassified

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13. MATERIAL TO BE: ☐ Presented ☒ Published Date Required: 16 February 2014
14. NAME OF CONFERENCE OR JOURNAL: N/A
15. REMARKS: Paper is intended for use during discussions with officials in the Provisional Technical Secretariat of the Comprehensive N

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **04 DEC 2015**	2. REPORT TYPE	3. DATES COVERED **00-00-2015 to 00-00-2015**

4. TITLE AND SUBTITLE **Motivation for a High Explosive Testing Program in South Africa**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Applied Research Associates,,8537 Six Forks Road, Suite 600,Raleigh,NC, 27605**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**18**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Contractor: Applied Research Associates
8537 Six Forks Road, Suite 600
Raleigh, NC 27605

Contract Number: HDTRA2-11-D-0001

Motivation for a High Explosive Testing Program in South Africa

4 December 2015

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Motivation for a High Explosive Testing Program

in South Africa

by

Michael J. Shore, PhD

The deep mines of South Africa have provided a unique research environment for several decades. Much has been learned about the impact of high in situ stress and its influence on rock bursts (violent rock fracture in deep mines due to the high stress environment). These rockbursts have provided seismic sources to develop accurate models of the crust and upper mantle. In addition, the release of stress through the use of high explosives has improved safety in mines and provided useful data for understanding earthquake source mechanisms. Of special interest to the research community associated with Comprehensive Test Ban Treaty (CTBT) activities is the possibility of evasive nuclear testing in deep mine environments where the release of high stress fields by an explosion can resemble a rock burst or natural earthquake. This paper provides background information on previous research in and around the deep mines of South Africa and lays out a conceptual plan of high explosive testing that extends this research activity while providing calibration data for the seismic and infrasound stations of International Monitoring System (IMS).

Research related to South African Mines

The seismicity of South Africa is relatively low and much of the observed activity is associated with mining and rockbursts (See Figures 1 and 2). The lithosphere of South Africa has high horizontal strains in large part due to its tectonic setting (See Figure 3). Southern Africa is composed of a number of ancient cratons separated by highly deformed, metamorphic shear zones (See Figure 4). Off the coast of South Africa to the west, south, and east are oceanic spreading centers including a triple junction to the southwest and a continental rift system to the northeast. The extensional strain associated with these

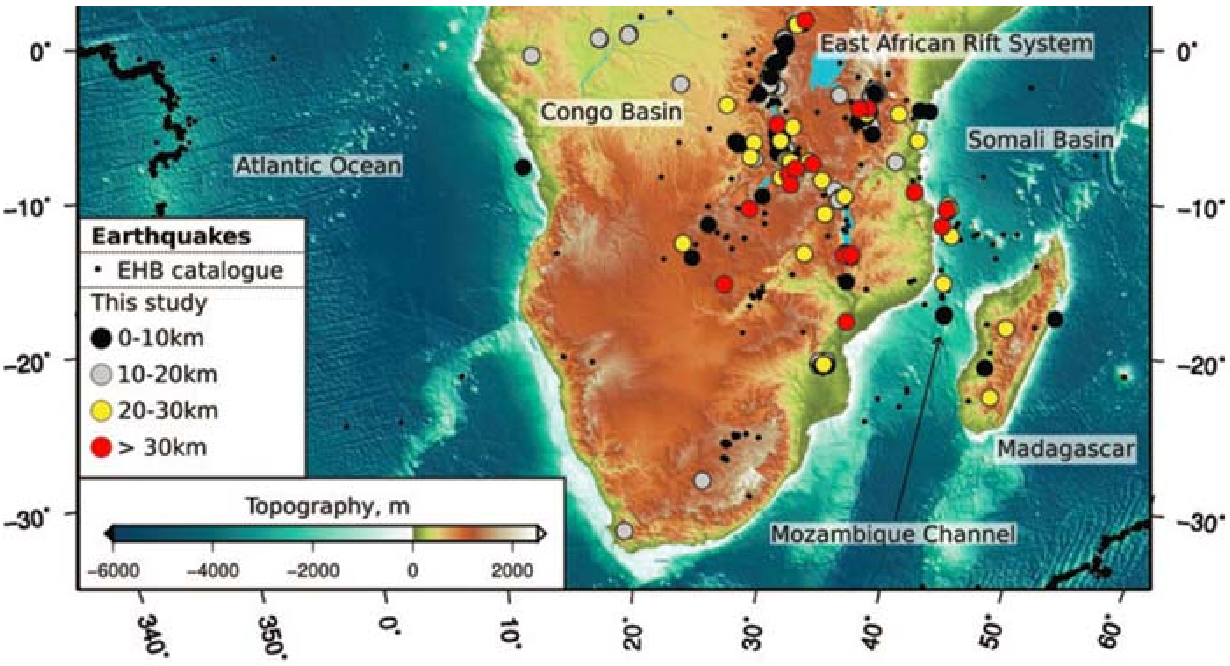

Figure 1. Seismicity of Southern Africa (Craig et al, 2011)

tectonic features are the primary source of the horizontal strain fields.

In constructing underground excavations either for permanent structures or mining, the in situ stress fields must be taken into account. It is typically assumed that horizontal stresses will be half of the vertical stress due to the rock load above the excavation. In the case of South African deep mines that can be in excess of 3 km deep, the horizontal stress fields can approach double the in situ vertical stress due to the overburden (Durrheim et al, 1998).

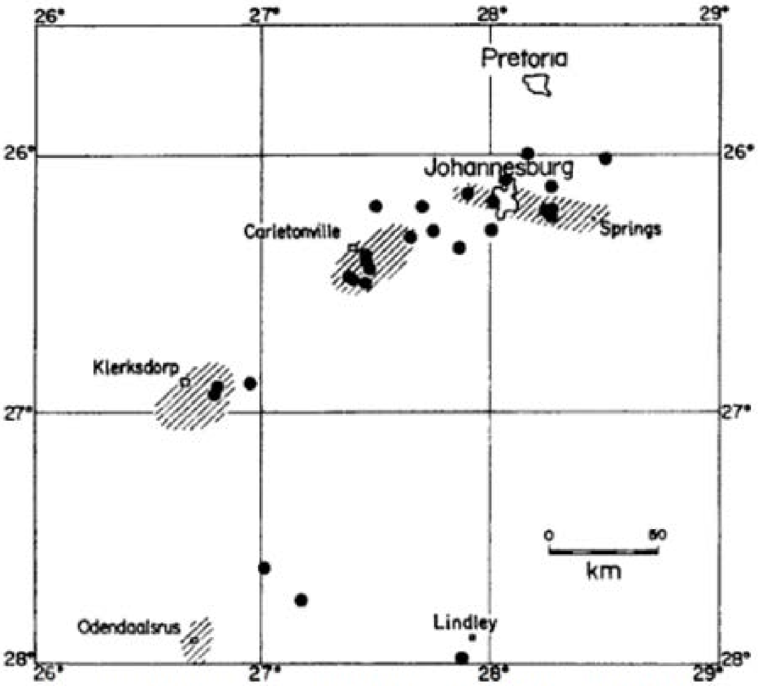

Figure 2. Seismic events between 1963 and 1971. Shaded areas are mining regions with known rockbursts.(Fairhead & Girdler, 1971)

McGarr et al (1990) compared the seismic body waves from three small chemical explosions, 50 to 150 kg at a depth of 2 km, with corresponding data from three mining-induced tremors to test discrimination methods. The three explosions generated P waves with low frequency spectral asymptotes that agreed well with corresponding results scaled down from nuclear explosions at the Nevada Test Site. “All three explosions generated S waves that appear to be a consequence of deviatoric stress release in the immediate environs of the explosions. The three [mining-induced] tremors analyzed here generated P and S waves whose spectra and source parameters agree well with standard earthquake source models.” The “explosions typically have higher corner frequencies than tremors or earthquakes, although counter examples certainly exist… The body wave spectra of [the 150-kg] explosion and those of a nearby tremor, however, were indistinguishable.”

Graham et al (1991) examined fracturing that is caused by the high stresses during normal mining processes. They determined that the “anisotropy observed at the surface appears to be due to microcracks aligned by the regional stress regime rather than local disturbances to the stress regime due to mining operations.”

During a nine-year period from 1971 to 1979, seismic events

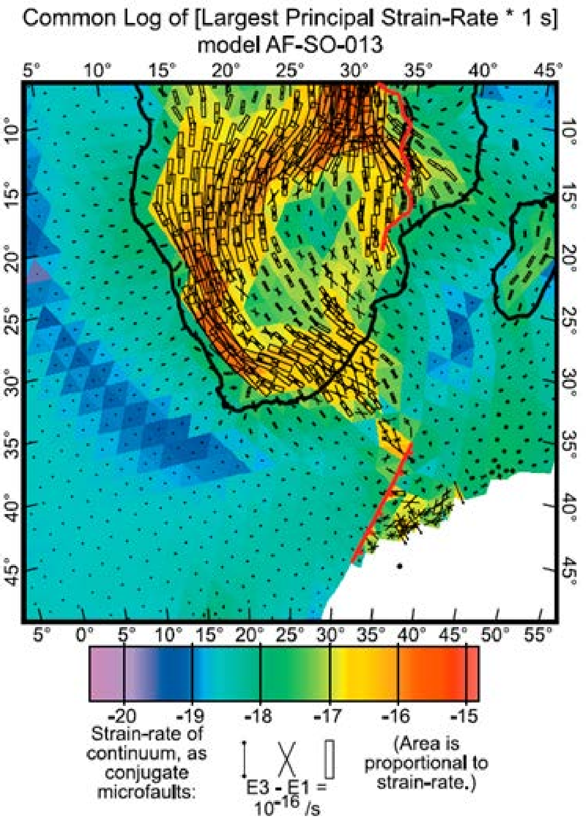

Figure 3. Strain Pattern in Southern Africa (Bird et al, 2006)

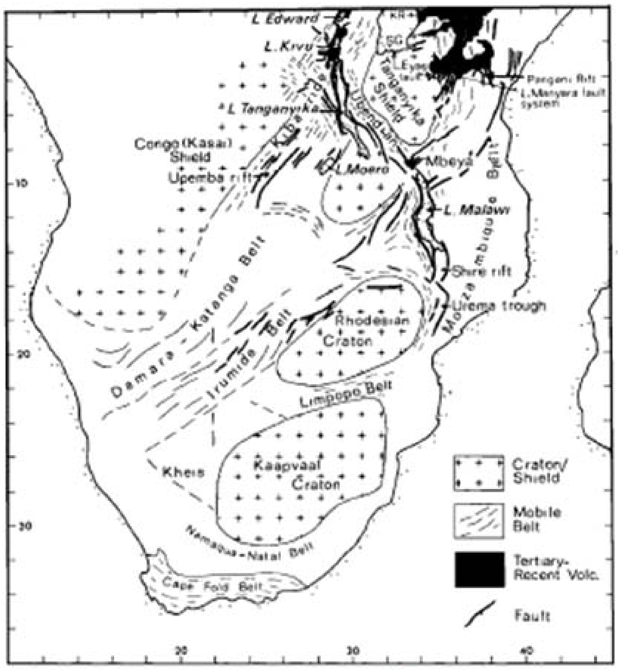

Figure 4. Basement Geology of Southern Africa (Fairhead & Stuart, 1982)

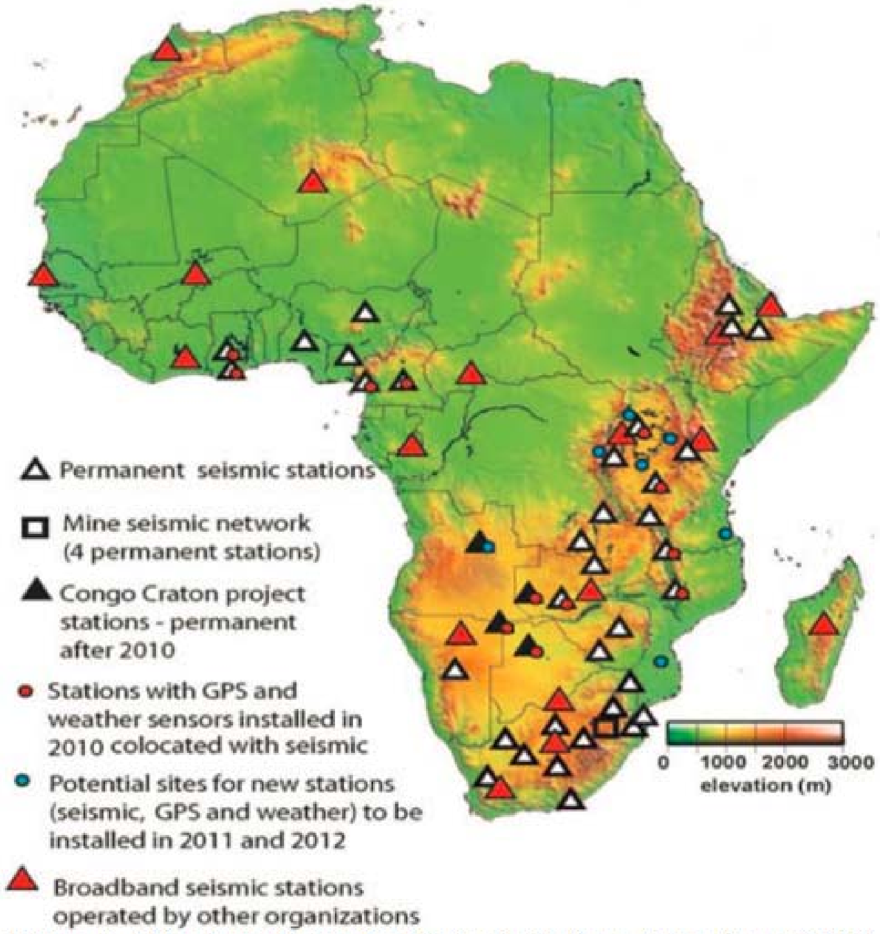

Figure 5. AfricaArray Network of Seismic Stations (AfricaArray, 2013)

located by the Geological Survey of South Africa show an average of 85 events per year occurring within the mining areas with magnitudes in the range from 3.4 to 5.9 ML, especially concentrated around Johannesburg. This large number of rockbursts, associated directly with gold mining, provides a unique opportunity to conduct seismic research on evasion scenarios. Most mining areas with rockbursts do not have the large events as in South Africa that can be detected at regional monitoring distances. Figure 5 shows the regional network of seismic stations that is available, beyond the IMS, to support research across Sub-Saharan Africa. Furthermore, the decades of published technical work on South African rockbursts, integrating data from near field seismic networks in the mining areas (see Figure 6), enables a better understanding of the source mechanisms for the events and establishes a solid technical foundation for further targeted research studies of direct interest to the nuclear monitoring community. “Based on the analyses which have been conducted to date, we conclude that rockbursts or other mine tremors could represent a significant problem for seismic discrimination monitoring at low-threshold levels throughout the world. We base this on reports indicating that rockbursts are frequent, occur in most mining areas, may show mechanism complexity, and may be controlled to some degree by mining practice." There is also evidence "that at least some small mine-induced events have had more complex source mechanisms, which depend more on details of the mining practice. It remains to be determined to what extent such complexity can be controlled by mining practice for larger events and how it will affect seismic signals. If the occurrence of large rockbursts can be controlled, as some studies indicate, they could present a potential problem for identification of a small nuclear test masked by a large rockburst which has been deliberately triggered in the same mining area" (Bennett et al, 1993).

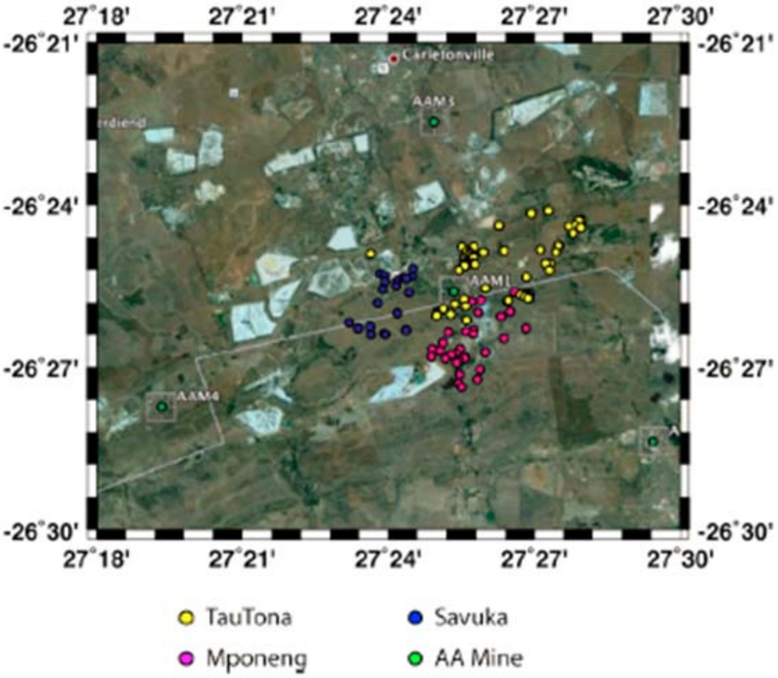

Figure 6. Google Earth image showing the Carletonville mining area with in mine seismic sensors and surface broadband stations (green dots). Julià et al, 2009)

Following the 1995 Kobe earthquake, the Japanese deployed seismic and GPS networks to support earthquake prediction and mitigation within Japan. However, the dominant depth of Japanese earthquakes of concern at 10 to 20 km was too deep to accurately monitor and define the interaction of geology and rupture processes. In order to gain a better understanding of earthquake mechanisms and the influence of in situ geology, Japanese scientists have teamed with their counterparts in South Africa to study these processes using mining-induced events (See Figure 7 for representative research results). This win-win cooperation to increase the understanding of mine-induced seismicity and rockbursts will lead to new techniques to improve mine safety. A continuation of this collaboration was recently approved and builds on previous studies carried out by Japanese and South African seismologists in South African mines. This new

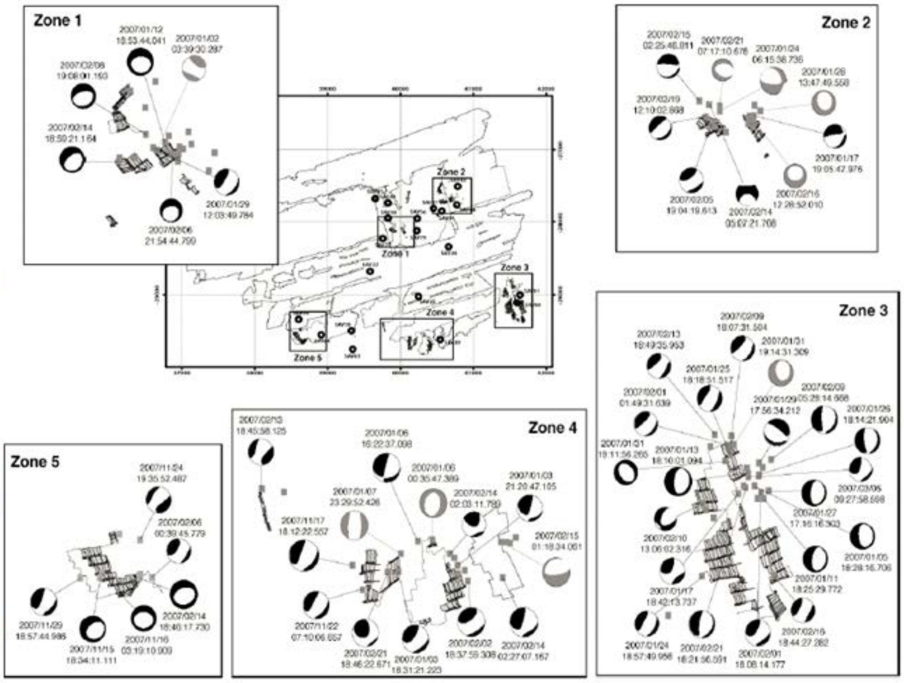

Figure 7. Spatial distribution of the deviatoric focal mechanisms for the Savuka mine events considered in this study (only those events with a well-constrained deviatoric part have been included). The black symbols represent those events with a significant volumetric component (more than 10% of the total scalar moment); the gray symbols represent those events with a near deviatoric. (Julià et al, 2010)

five-year research initiative will run until 2015 (Ogasawara et al, 2009).

In a related effort, South African seismologists installed tilt meters and seismic monitors in two areas of one of the deepest gold mines. “One of the sites was also instrumented by Japanese-German Underground Acoustic emission Research in South Africa (JAGUARS) with a small network, approximately 40m span, of eight Acoustic Emission (AE) sensors. The rate of tilt, defined as quasi-static deformations, and the seismic ground motion, defined as dynamic deformations, were analyzed in order to understand the rock mass behavior around deep level mining… A good correspondence between the dynamic and quasi-static deformations was found… During the blasting time and the subsequent seismic events the coseismic and aseismic tilt shows a rapid increase. Much of the quasi-static deformation, however, occurs independently of the seismic events and was described as ‘slow’ or aseismic events” (Milev et al, 2012).

Yoshimitsu et al (2012) used near-source recordings of S waves for repeating earthquakes in the Bambanani gold mine, South Africa, to estimate the temporal changes in the seismic attenuation of S waves passing through a fault zone that includes the focal regions of two M ~ 2 earthquakes. They found that the relative amplitude of vertical component S waves that passed through the fault decreased for higher frequencies (~100 Hz) after the M ~ 2 earthquakes. This decrease was explained by an increment of scattering attenuation with the characteristic scale of damage in the fault zone of ~3 m. They also found a weak increase in the S-wave attenuation across the fault zone before the M ~ 2 earthquakes, with a similar characteristic scale of damage.

Proposed High Explosive Testing Program in Support of CTBT Calibration

The U.S. government has supported a wide range of seismic experiments for several decades. The recent series of experiments began when the Defense Special Weapons Agency supported Kazakhstan in sealing underground nuclear testing tunnels at Degelen Mountain (Ewell, 1997). In association with this activity, a number of “calibration experiments were conducted in August 1998 in Tunnel 214 (Omega 1), in September 1999 (Omega 2) and in July 2000 (Omega 3) in Tunnel 160B of the Degelen Mountain Complex” (See Figure 8, NNC RK, 2006). Now that the IMS is nearly complete, discussions are currently underway to explore the possibility of performing a new series of calibration explosions near the Degelen Mountain Complex.

Figure 8. Omega Test at Degelen Mountain (NNC RK, 2006)

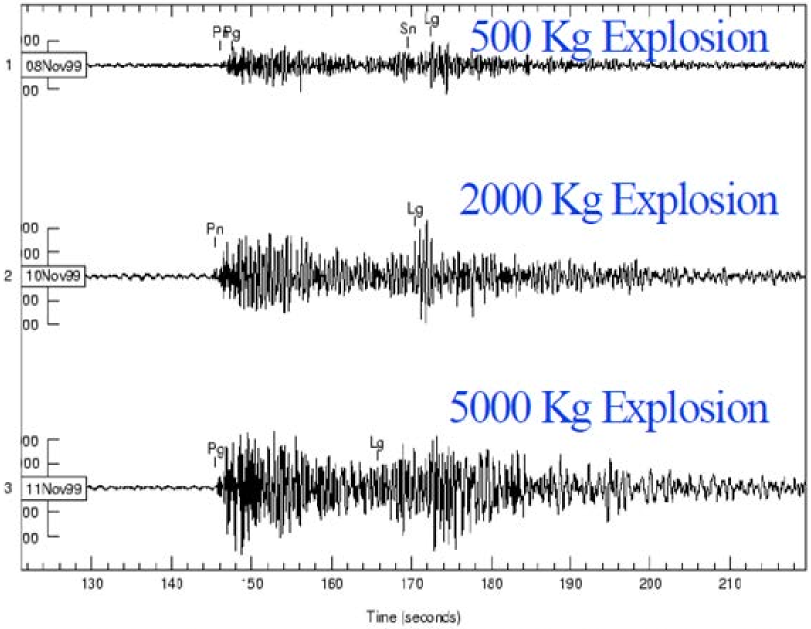

Figure 9. MRNI recordings of the November 8, 10, and 11, 1999, explosions in the Dead Sea (Baumgardt & Freeman, 2000)

A series of underwater explosions was detonated in the Dead Sea in November 1999 by the Geophysical Institute of Israel with funding from the Government of Israel and the U.S. Defense Threat Reduction Agency. The goal was of the explosions was to calibrate Israel's two IMS seismic stations along with its national seismic system. Seismic stations in neighboring countries recorded the tests as well. See Figure 9 for seismic signals recorded in northern Israel at a range of approximately 165 km (Nakanishi, 2000).

The CTBTO conducted a small test explosion at Sayarim, Israel, in August 2009 as an infrasound source. Then on 24 January 2011 a 10 ton explosion was detonated at the same site followed by a 100 ton explosion on 26 January 2011. The largest test was detected at IMS stations beyond 6,000 km. The infrasound propagation was observed to be very sensitive to stratospheric wind conditions resulting in wide variation in detection range (See Figures 10 and 11, Coyne et al, 2011).

The U.S. Department of Energy’s National Nuclear Security Administration’s (NNSA) is currently in the midst of conducting a series of high explosive Source Physics Experiments. These experiments are focused on improving our ability to predict ground motion, gas flow and nuclear cavity dynamics, and to enhance our ability for near-field monitoring and on-site inspection (Brunish et al, 2010). To date, three explosive tests have been conducted with yields up to 1,000 kg at the Climax Stock on the Nevada National Security Site. Up to four additional tests may be conducted in this series (Patton, 2012).

Possible High Explosive Testing Program in South Africa

Figure 10. Infrasound detections from August 2009 explosion (Coyne et al, 2011)

In order to have a successful seismic and infrasound calibration testing program that will also develop a database for evasion research, it is essential to have mine-induced activity, mining explosions, and the calibration explosions occurring in close proximity to each other and of sufficient size to generate signals to regional distances. In South Africa, "mining-induced seismic events range in local magnitude (M) from -6 to +5 on the Richter scale. … During the course of the deep seismic sounding experiment it was found that events with M > 3 were required to produce a satisfactory signal to noise ratio at distances exceeding 200 km… The Far West Rand goldfield is the most seismically active district, producing about 10 events with M >3 per month" (Durrheim & Green, 1992).

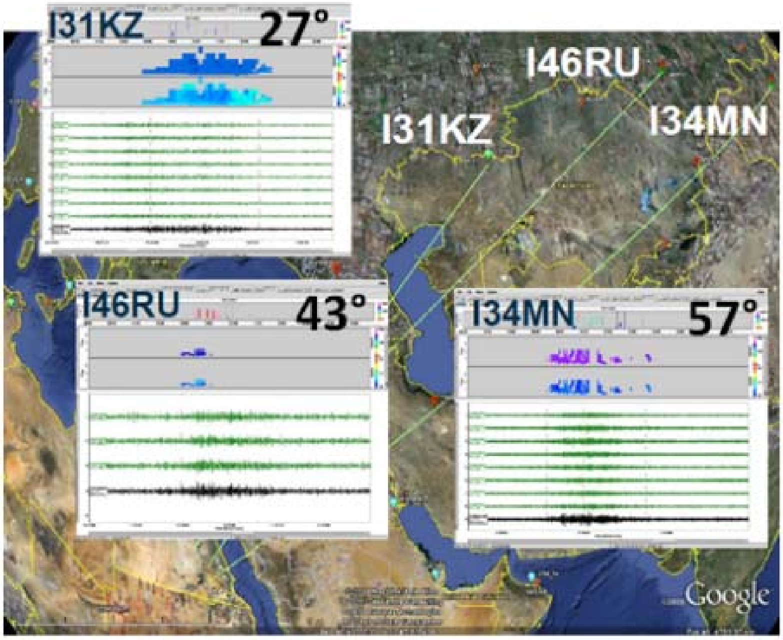

Figure 11. Infrasound recordings from January 2011 explosion (Coyne et al, 2011)

In order to complement the existing mining activity, a series of 100 metric ton explosions is envisioned with varying depth of burst from the surface to the maximum accessible

Figure 12. International Monitoring System in southern Africa (CTBTO Prep Com, 2013)

mining depth, hopefully in excess of 3 km. The surface explosion(s) will provide an excellent source for infrasound propagation studies as well as providing a low in situ stress field and no surface reflection for the seismic propagation. This surface explosion could be repeated several times to support research on varying atmospheric conditions and their effect on infrasound propagation. An additional three explosions could be conducted at 1 km, 2 km, and 3 km depth to provide a series of sources with increasing depth and in situ stress fields.

If the series of explosions described above were conducted in the South African gold mining area, it is anticipated that the seismic signals would be detectable at least as far as the Congo and Tanzania while the infrasound signals, assuming favorable wind conditions, would be detectable to the Sahara Desert. This test series would provide valuable data for calibrating IMS stations throughout much of Africa and possibly some in the Atlantic and Indian Oceans (See Figure 12).

Tangential Benefits to Other Disciplines

In addition to providing calibration data for IMS stations in southern Africa, an explosive test series as outlined above will serve a number of other related purposes. First and foremost, the activities associated with deploying supplemental sensors, enlisting the cooperation of other seismic and infrasound networks in the region, and the follow-on research that will be possible with the data from the test series, will build significant technical capacity in Sub-Saharan Africa. The explosions will extend the existing Japanese-South Africa research activities by enabling larger sources, thus larger in situ stress releases, to be evaluated. Finally, the testing will provide additional data to further research in mine safety so that improved mining and safety techniques and guidelines can be developed.

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