A summary of recent research in seismology in South Africa

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Abstract

This paper summarises the most important developments in South African research in earthquake, exploration and mine seismology for the period January 2003 to December 2006. The South African National Seismograph Network (SANSN) has been considerably improved, and the upgraded seismological stations now use the SeisComp recording system and GPRS cellular communication for retrieving data in quasi real-time. On 9 March 2005, the largest mining-related ever to occur in South Africa registered 5.3 on the local Richter magnitude scale (ML). An unusually large earthquake of ML = 7.3 occurred in Mozambique, at the southernmost end of the East African Rift System. Improved seismic location and source parameter calculation methods have been developed for the data recorded by SANSN, and significant research has been completed on seismic hazard and risk methodologies. The research in mining seismology has been wide-ranging in pursuit of increased understanding of the complex rock mass response to underground mining. Novel underground instrumentation has been developed. A new model of the Bushveld Complex using seismically determined crustal thickness values to assess its isostatic response has important economic implications

Introduction

Routine seismic monitoring in South Africa is undertaken by the Council for Geoscience (CGS) using the South African Seismograph Network (SANSN), which comprises 23 broadband and extended short-period seismometers. In recent years, CGS has invested significant resources in upgrading the network. To date, a total of 19 stations are equipped with GPRS cellular communication for retrieving data in quasi real-time.

Each quarter, CGS publishes comprehensive earthquake bulletins of the seismic events recorded by SANSN[1]. Most of the events are associated with deep-level gold mining of the reefs on the periphery of the Witwatersrand basin. The largest mining-related seismic event ever to occur in South Africa took place on the 9 March 2005 and registered 5.3 on the local Richter magnitude scale (ML). This event had far reaching socio-economic consequences because the mine was closed down and led to a comprehensive investigation commissioned by the Chief Inspector of Mines to investigate the risks to miners, mines, and the public posed by large seismic events in the gold mining districts[2].

More accurate epicentral locations of data recorded by SANSN have become increasingly important because of the incidence of large events in mining districts. There is a need to be able to identity the particular mine in which the event occurred. This has stimulated research on improved relocation methods at CGS, as well as in the fields of seismic risk and hazard assessment.

Not all the events listed in the earthquake bulletins are mine-related. An unusually severe earthquake, measuring 7.3 on the local Richter magnitude scale occurred in the southwestern part of Mozambique, on 23 February 2006, in the vicinity of a village named Massangena. The event was located using data recorded by SANSN and showed that the earthquake occurred at the southernmost extension of the East African Rift System. Although seismicity associated with the East African Rift is common, the magnitude was unexpectedly large since the faulting mechanism associated with diverging plate boundaries generally produces seismic events of smaller magnitude.

During the last four years, a number of ambitious, inter-institutional, international research programmes have been initiated. The AfricaArray initiative is a long-term (20 years) programme co-directed by the University of the Witwatersrand and the University of Pennsylvania[3]; Inkaba Ye Africa is a multidisciplinary initiative between South African and German earth scientists[4]; and the DAFSAM (Drilling Active Faults Laboratory in South African Mines)-NELSAM (Natural Earthquake Laboratory in South African Mines) project involves South African, German, Japanese and American scientists[5]. All of these initiatives couple research with capacity building in the geosciences. Research in seismology using regional events to determine earth structure is utilising the data recorded through Inkaba ye Africa and AfricaArray, as well as building on previous research from the Kaapvaal Project.

There have also been some high profile achievements by South African seismologists. The Department of Science and Technology has established the South African

Research Chairs Initiative to reinvigorate research at the country's institutes of higher education institutions and to develop research capacity. The first 21 research chairs were awarded under the Initiative in December 2006 in a highly competitive review process. One of these new research chairs (the joint University of the Witwatersrand / CSIR Chair of Earthquake, Exploration and Mining Seismology) was awarded to Dr Durrheim. Two South African seismologists have achieved international recognition for their doctoral research. In 2003 and 2005, respectively, Drs Linzer and Hildyard were each awarded the Rocha Medal by the International Society for Rock Mechanics for their PhD research projects. It is a unique achievement, since no other country worldwide has achieved more than three of these awards, while South Africa has achieved five. In exploration seismology, George Cameron Smith and Maurice Gidlow were each awarded a Krahman medal by the South African Geophysical Association in 2003, for their development of an AVO procedure that has withstood more than 15 years of scrutiny and still remains a critical seismic attribute employed routinely by geophysicists. This work achieved international acclaim the year before when Smith and Gidlow were each awarded the prestigious Reginald Fessenden Award by the Society of Exploration Geophysicists.

Rockbursts remain amongst the greatest challenges facing the South African mining industry owing to the ever-increasing depths at which gold and platinum mining occur. Rockbursts are those seismic events associated with mining that result in damage and cost the mining industry about one billion US dollars per year (in terms of ground lost in pillars, local support, difficult mining as well as other factors). Not surprisingly, most of the research in mining seismology is focussed on reducing the rockburst risk. The key contributors to research into mining-induced seismicity are employed by CSIR, Integrated Seismic Systems International (ISSI), various consulting groups and, to a lesser extent, the universities. Unfortunately, very few mining seismologists remain mine employees and the routine running of the in-mine systems has either been outsourced or is the responsibility of the rock engineering departments.

The review that follows attempts to summarise the most significant developments in South African seismological research and development for the period January 2003 to December 2006. These consist of: upgrades to the SANSN; a summary of recent international research initiatives; the conferment of a joint Research Chair of Earthquake, Exploration and Mining Seismology to the University of the Witwatersrand / CSIR; improvements to seismic location and source parameter calculation methods; developments to seismic hazard and risk methodologies; research in mining seismology; a summary of the investigation into the risks posed by large seismic events in gold mining areas; and, a review of studies performed using earthquakes to determine earth structure.

Improvements to the South African Seismograph Network (SANSN)

The SANSN comprises 23 seismological stations (Figure 1), most of which were installed in the 1970s and early 1980s. The SANSN network is operated and maintained by the Council for Geoscience (CGS), mandated by the Department of Mineral and Energy (DME) to report on earthquakes in South Africa through quarterly seismological bulletins[1]. Waveform data from three stations of the International Monitoring System (IMS), viz. Boshof, Sutherland and Lobatse, are also routinely used in data analysis.

CGS has invested significant effort and resources in upgrading and restructuring the entire network. In early 2006, the delay in transmitting waveform data recorded by the SANSN to the CGS offices in Silverton was addressed. General Packet Radio System (GPRS), a mobile data service for wireless communications that operates at speeds up to 115 kilobits per second, compared with Global System for Mobile Communications (GSM) that operates at 9.6 kilobits per second, proved to be the most attractive in both transfer speed and cost. GPRS additionally supports a wide range of bandwidths that is particularly suited for sending and receiving large volumes of data. A total of 19 stations have been equipped with GPRS communication to date. The use of near real-time data communication has shortened the response time of the CGS to release earthquake data to shareholders. A refitting programme to phase out 18-bit digitizers and replacing Stand Alone Quake Systems (SAQS) with in-house developed Earthquake Acquisition Recording System (EARS) was executed in parallel with the communication program. The need to replace the SAQS recorders was paramount as spare parts for the equipment were becoming difficult to obtain. Presently the SANSN is equipped with 5 broadband (100 second) and 14 extended short-period (30 second) seismometers.

The CGS implemented the SeisComp data acquisition software, developed by the GeoForschung Zentrum (GFZ) (Potsdam, Germany), during the last quarter of 2005, which records waveforms in the internationally accepted MiniSEED format and additionally has a feature for automatic earthquake location. Presently, waveform data is communicated at 20 samples per second (sps) continuous data and 100 sps for triggered data.

Two stations were installed in the gold mining areas of the Central Rand and Far West Rand, respectively, under a Department of Minerals and Energy (DME) funded project. These stations are located on the East Rand Property Mines and Kloof Mine properties and are equipped with 24-bit digitizers, GPRS communication and three-component short-period sensors.

The CGS has pledged 5 stations of the SANSN to the Indian Ocean Tsunami Warning System (IOTWS). These stations are equipped with broadband sensors and record continuous waveform data at 20 sps. It is foreseen that waveform data from these stations would be channelled through the GFZ to the International Data Center (IDC) in Indonesia.

Figure 1: Distribution of stations comprising the SANSN network.

Research initiatives

AfricaArray Initiative

The name “AfricaArray” encapsulates the essence of this initiative and describes the array of shared training programs, shared scientific observatories, shared projects worked on by scientists across the continent. Most importantly, AfricaArray refers to a vision shared between the project partners that Africa will retain capacity in an array of scientific fields critical to the development of its natural resource sector[3]. The founding partners of AfricaArray are the University of the Witwatersrand, the

University of Pennsylvania in the USA and CGS. The programme was launched officially in January 2005.

The initial focus of AfricaArray is on geophysics education and research because of the high demand for geophysicists in the strategically important fields of oil and gas exploration, mineral exploration, geothermal energy development, water resource development, and earthquake hazard mitigation (including mine tremors)[3]. Seismic stations belonging to participating countries are being either installed or upgraded and technical personnel are being trained to maintain the stations. The network consists of 24 permanent broadband stations to date and forms a "backbone" network for recording earthquakes across eastern and southern Africa (Figure 2). The eleven stations in South Africa belong to the SANSN.

The seismic data is being used in student M.Sc. and Ph.D. research projects as well as in collaborative research projects between South African and American seismologists. One project is funded by the US Department of Energy and involves building a network of five broadband seismic stations around the deep gold mines in the Carltonville district. These data will be interpreted in combination with the data recorded by the in-mine networks as well as the AfricaArray stations with the aim of studying the source properties of mining-related events and how seismic energy propagates at regional distances (200 – 1000km). To date, three temporary stations have been installed by CGS whilst preparations for the permanent stations of the project continue. Data from these temporary stations are sent to IRIS to supplement the data obtained from the noise tests performed during the site surveys for the new stations.

The AfricaArray initiative is not just limited to capacity building and research in geophysics, but will be extended to other science fields crucial to development in the natural resource sector. Monitoring equipment such as GPS, meteorological, hydrologic and other environmental sensors will be added to the existing observatories[3]. The anticipated network of scientific observatories after 10 years is shown in Figure 3.

Figure 2: Distribution of current and planned AfricaArray broadband stations (from ref 3).

Figure 3: Current permanent seismic stations of the GSN/FDSN network (triangles) and planned observatories (circles) after 10 years (from ref 3)

Inkaba ye Africa initiative

Over 100 earth and space scientists from a consortium of 15 government and academic institutions in South Africa and Germany are involved in the Inkaba ye Africa initiative[4]. The teams of scientists aim to survey a cone-shaped sector of the earth from core to space, encompassing South Africa and the Southern Oceans.

The overall project consists of 12 projects which contribute to three main research themes: the “Heart of Africa”, the “Margins of Africa” and “Living Africa”[4]. A number of seismic reflection and refraction surveys have been performed in 2004 and 2005 by teams from various institutions to collect data both onshore and offshore along the Agulhas–Karoo transect. These surveys contribute to the “Margins of Africa” component the main scientific objective of which is to investigate the causes and consequences of the break-up of Gondwana. The other objective is to provide training and mentoring for local earth scientists in a collaborative environment. The data recorded by these surveys are currently being interpreted.

DAFSAM-NELSAM

DAFSAM (Drilling Active Faults Laboratory in South African Mines)-NELSAM (Natural Earthquake Laboratory in South African Mines) is a large, long-term international programme to examine the fundamental physics of earthquakes[5]. The deep gold mines in the Carletonville District provide a unique opportunity to make direct and near-field seismic observations at the focal depth. The projects focus on building an earthquake laboratory at a depth of 3540 m in the vicinity of the Pretorius fault at TauTona Gold Mine. Internationally recognized scientists from research organizations in the USA, Germany and Japan are involved in the research in collaboration with scientists from the following South African institutes: ISSI, TauTona Gold Mine, University of the Free State and CSIR.

Chair of Earthquake, Exploration and Mining Seismology

The Department of Science and Technology established the South African Research Chairs Initiative to reinvigorate research at the country's higher education institutions and to develop research capacity in support of the National Research and Development Strategy and other national initiatives. The Minister of Science and Technology announced the first 21 chairs awarded under the Initiative in December 2006. One of these new research chairs is the joint University of the Witwatersrand / CSIR Chair of Earthquake, Exploration and Mining Seismology, which has been awarded to Dr Durrheim. It is envisaged that Dr Durrheim will provide scientific leadership to the AfricaArray and Minimizing the Risk of Rockbursting research programmes, and develop partnerships with the hydrocarbon and mineral sector, as well as science councils and universities in South Africa, Africa, and abroad.

Developments in regional seismology

Improved seismic location methods

A study recently conducted by CGS showed that errors in locating mine-related events recorded by SANSN could be as large as 20 km. At present, the CGS is able to specify merely the district in which the event occurred, e.g. Klerksdorp, Far West Rand, West Rand or Welkom. However, there is pressure to be more specific, i.e. the SANSN should be able to identify the particular mine where the events occurred.

Relocation techniques have also been applied to the automatically-picked first arrivals of the P- and S- waves. Two different relocation methods and the double-difference method were applied to a cluster of mining induced events using data recorded by the in-mine networks[6].

A new method referred to as the multi-reference relocation technique has been tested by CGS for locating newly recorded earthquakes[7]. This method uses the accurate location of several events to constrain the relocation process in contrast to the arrival-time difference (ATD) method which uses only one master event. The first tests with synthetic and real earthquakes have showed that the method is effective in reducing the location errors.

New software has also been developed at CGS to calculate stable source parameters from the SANSN on a routine basis[8]. The software performs three major tasks. Firstly, the full synthetic seismogram is calculated for a one-dimensional layered velocity model, which includes P-waves, S-waves and the surface waves. In the second step, all observed waveforms are filtered to allow an appropriate and consistent treatment of the propagation effects. Finally, an inversion process is used to calculate several source parameters by matching data with the synthetic seismogram enabling the deformation in the source region (seismic moment) and the duration of the rupture to be computed. A stable magnitude and static stress drop can then be simply calculated from these parameters. The first results indicate that source parameters can be reliably achieved for distances between seismic source and stations of less than 200 km. Future developments will focus on extending the software to include a complex seismic source model.

Research in seismic hazard and risk assessment

A large body of research has been completed in the field of seismic hazard and risk at CGS. The scope of work has involved seismic hazard and risk for sites of crucial engineering structures like dams, tall buildings, bridges, nuclear power plants, gas and coal terminals, pipelines and mining regions.

The highlights in research in 2004 involved producing maps of maximum earthquake magnitudes for stable continental regions in Africa using several statistical methods[9, 10]. The lack of completeness in earthquake catalogues in Africa is still a major problem and this work will be revised as more data becomes available.

Procedures and software for the generation of Monte Carlo catalogues for use in probabilistic seismic hazard assessment have been produced[11]. These synthetic catalogues are used by seismic hazard practitioners in the insurance industry for risk analyses. The Seismic Hazard Assessment and Risk Program (SHARP) is a user-friendly application, released for the first time in 2004, which assesses the maximum possible earthquake magnitude with or without a seismic event catalogue[11]. In addition, earthquake recurrence parameters can be calculated for the seismotectonic province or seismogenic fault of interest, for any region in the world. Monte Carlo catalogues can be generated and seismic hazard curves (that provide return periods of peak ground acceleration) can be computed using the Parametric-Historic procedure and/or the Cornell McGuire approach. In 2005, the SHARP software was compiled from the MATLAB format and is now available as stand-alone software.

Attenuation models have been developed for South Africa based on recorded intensities from several isoseismal maps produced for large earthquakes that occurred throughout South Africa dating as far back as 1912[12]. A report on building vulnerability curves for typical buildings in South Africa was produced[12]. This work formed the basis of newly released code: D-SHARP[13] and P-SHARP[14]. D-SHARP provides maps of seismic risk for a user-specified earthquake anywhere in South Africa (Figure 4). This toolbox is similar to that of the USGS Shake map that provides near-real-time maps of shaking intensity following significant earthquakes. P-SHARP provides probabilistic seismic risk assessment for any place in South Africa.

Figure 4. D-Sharp, Deterministic Seismic Hazard and Risk Programme, display with initial datatips removed.

Developments in mine seismology

SIMRAC projects

The following list highlights some of the recent research projects funded by the Mine Health and Safety Council (MHSC) where seismology was used to help understand the complex rock mass response to underground mining. A complete listing of the research projects, as well as the completed reports, can be downloaded from ref 15.

1. SIM040302 "The determination of loading conditions for crush pillars and the performance of crush pillars under dynamic loading" [16]. The mechanisms involved in crush pillar behaviour are complex and many factors influence their performance, including local and regional geology, rock mass characteristics, nearby seismicity and mining. Seismic monitoring of crush pillars showed that the pillars were not affected by nearby seismic events, but that micro-seismicity (indicative of brittle fracture) occurs over the duration of the pillar's life.

2. SIM020307 “Calibration of integration-ready numerical models to real seismic data” [17]. In this project, the numerical stress modelling codes MAP3Di and IDRM (Integrated Damage Rheology Model) were compared to identify common advantages and potential problems associated with the integration of the modelling with real seismic data. The main result was the demonstration that the calibration of integrated models to observed seismicity is possible. This changes the status of the integration concept from that of an interesting idea to the level of a practical tool.

3. SIM020302 “Proactive approaches to rockmass stability and control” [18]. The aim of this project was to implement the findings of research around tap-tests and panel sequencing, as well as to report on the trials of Integration for Controlled Mining, a technique in which numerical modelling is combined with seismic information to provide short-term guides for mining. Quantitative acoustic emission information was recorded within two hours after blasting at a variety of sites, and compared with the levels of seismic activity recorded by mine-wide networks over three month periods. It emerged that the short- and long-term seismic responses are correlated, and that tap-tests can be easily implemented. The trials of the Integration for Controlled Mining technique were inconclusive.

4. SIM040303 “Quantification of optimum lead-lag distances between adjacent panels in longwall, scattered and sequential grid layouts with respect to seismicity patterns and rockburst damage related to abutment shear events” [19]. This project aimed to quantify the effects of lead-lags on fracturing, stability, support and seismicity to either confirm or modify current design guidelines. Seismicity associated with lead-lags was identified from mine seismic catalogues. Moment tensor inversions were used to calculate the source mechanisms of the lead-lag events. Fault plane solutions were used to confirm the selected seismicity as lead-lags events and to determine the focal mechanisms. The ambiguity of fault plane solutions was resolved using the Doppler shift in corner frequencies.

5. SIM020203 “New methodologies for quantifying remnant extraction hazards in deep mines” [20]. The term “remnant” refers to reef that has not been mined due to low grades or the presence of hazardous geological features. This project investigated the

rock mass behaviour occurring within remnant blocks in an attempt to quantify the hazard.

6. SIM040301 “Evaluation of the design criteria of Regularly Spaced Dip Pillars (RSDP) based on their in-situ performance”. This project is currently in progress and aims to evaluate the design criteria of Regularly Spaced Dip Pillars (RSDP) based on their in-situ performance and to identify the conditions under which RSDP mining works best as a rockburst control method. The observed long-term tilt and strain will be compared to elastic and inelastic results obtained by modelling using MINF.

7. SIM 050302 “Minimizing the Rockburst Risk” is a 5-year research programme which commenced in April 2005. Collaborators include the CSIR, ISSI, and the CGS. The programme encompasses both fundamental research on topics such as seismic source mechanisms, dynamics of fault zones and rock burst damage mechanisms, and applied research on methods to estimate seismic hazard and to assess the vulnerability of excavations to rockburst damage. The deep mines in South Africa are unique in the world, as they represent the only place on the globe where ruptures related to earthquakes and seismic events can be viewed and studied in situ.

Developments in underground instrumentation

A device called GoafWarn has been developed at CSIR in consultation with coal mine stakeholders. GoafWarn monitors microseismicity associated with the formation and extension of fractures prior to the collapse of the roof strata. Recent research in coal mines using this event detection device has been successful in giving warnings prior to goafing[21]. A more recent prototype, renamed FogWarn is being tested in the platinum industry and results show that reliable early warning of roof instability prior to falls of ground (FOG) in platinum mines can be achieved. It is envisaged that this technology could reduce accidents and in exceptional circumstances prevent the damage to infrastructure.

Considerable progress has been made by CSIR scientists in the study of strong ground motion and site effect surrounding underground mining excavations. A stand-alone instrument, known as the Peak Velocity Detector (PVD) especially designed for recording strong ground motions underground was used to create a large database of peak particle velocities measured on stope hangingwalls. A total number of 58 sites located in stopes mining the Carbon Leader Reef, Ventersdorp Contact Reef, Vaal Reef and Basal Reef were monitored. The peak particle velocities were measured at the surface of the excavations. Based on these measurements, the generally accepted velocity criterion of 3 m/s was found to be an adequate value to meet the requirements of support systems during a rockburst. The data recorded on the skin of the excavations were compared to the data recorded by the mine seismic networks to determine the site response. It was found that the peak ground velocity measured on the skin of the excavations was on average 9 ± 3 times greater than the peak ground velocity inferred from the mine seismic data[22].

Another unique and recently established research area is that of in-stope micro-seismic monitoring. This area encapsulates a wide range of research such as: regional and local support behaviour, mechanism of pillar failure[23], quasistatic and dynamic deformations of the rocks[24], as well as rockburst and rockfall control.

Sixth International Symposium on Rockbursts and Seismicity in Mines (RaSiM6)

The RaSiM Symposia are held every four years and are arguably the best single source of papers on mining-induced seismicity. South Africans have followed their colleagues in other countries by concentrating their efforts on publishing papers on mining-induced seismicity in the RaSiM proceedings.

The RaSiM symposium in Perth, Australia in 2005 included a wide range of papers from South Africa. Examples of topics include: assessing the success or otherwise of mine layout design[25,26], failure mechanisms[23] and providing hazard assessment on a daily or even hourly basis[27]. 23 out of a total of 80 papers in RaSiM6 were written by South Africans as first or sole author.

Although most of the South African papers were on seismicity or rockbursts in deep-level gold mines, four papers were related to other types of mining, namely underground platinum[23,28] and copper[29] as well as open pit mining [30]. RaSiM7 is due to be held in China in 2009.

Tenth Congress of the International Society for Rock Mechanics (ISRM)

This congress was held in South Africa in September 2003. Although the focus of this congress is mostly on rock mechanics, nine papers by South Africans on mining seismology research and case studies were presented on a wide variety of topics: strong ground motion and site response[31]; improved seismic location methods[32]; seismic hazard assessment methods[33]; seismic risk of mining layouts[34,35]; the fractography of rockbursts and impact structures[36]; dynamic failure of pillar remnants[37]; and, dynamic numerical modelling[38].

It worth mentioning two South African seismologists have been awarded the Rocha Medal by the ISRM for their PhD research projects. The Rocha Medal is a bronze medal that may be awarded annually by the ISRM for an outstanding doctoral thesis in rock mechanics or rock engineering. Dr Linzer was awarded the medal in 2003 for her thesis entitled "A relative moment tensor inversion technique applied to seismicity induced by mining" in which she developed a robust moment tensor inversion method that compensates for the various types of systematic error (or noise) that influence seismograms recorded underground [39]. In 2005, Dr Hildyard was awarded the medal for his thesis on "Wave interaction with underground openings in fractured rock", in which he implemented novel numerical and theoretical developments to address the problem of rockbursts in mining and the interpretation of fracturing in rock[40].

Second International Seminar on Deep and High Stress Mining

This seminar was held in Johannesburg in February 2004. The aim of the seminar was to gather the latest information on mining conditions in deep and high stress situations. In addition to seismicity, issues such as cooling and ventilation were also addressed. Papers by South African authors with a significant seismological component included a seismic and modelling analysis of dip-pillar mining[41], a laboratory investigation of the rock-mass response to mining[42], a case study of rockburst mechanisms[43], and a description of strategies to manage seismicity at depth[44].

Investigation into the risks posed by large seismic events in gold mining areas

A large seismic event, with a magnitude of 5.3 on the local Richter magnitude scale (ML) occurred on 9 March 2005 at DRDGOLD's North West Operations in the

Klerksdorp District. The event damaged several buildings and injured 58 people in the nearby town of Stilfontein. Two mineworkers were killed while 3200 others had to be evacuated. It was the largest mining-related seismic event ever to occur in South Africa.

Figure 5. Damage in Stilfontein caused by the ML = 5.3 tremor on 9 March 2005

The Chief Inspector of Mines appointed a team of experts, led by Dr Ray Durrheim of CSIR, to investigate the risks to miners, mines, and the public posed by large seismic events in the gold mining districts[2]. The team included local seismologists, mining and rock engineers, a hydrologist, and a seismic public safety specialist and seismologist from California.

It was found that the seismic event that occurred on 9 March 2005 could be ascribed to past mining. The chance that the event and its aftershocks were solely due to natural forces was considered extremely small. Seismic events would continue to occur as long as mining continues, and for some time after mining activities cease, as events are likely to be triggered when worked-out mines flood. It is unlikely that the magnitudes of the events and intensity of the shaking would be significantly greater than the levels that have been experienced so far. Nevertheless, it is recommended that seismic monitoring networks be improved, and that monitoring continues after mines close. The seismic hazard should be taken into account when the future use of mining land is being considered or any new buildings are designed. Municipal officials are aware of the risks posed by seismicity, and are incorporating these risks in their disaster management plans.

Reflection seismology

South Africa has been a pioneer in adapting the reflection seismic method to the hard rock environment to explore for gold and platinum deposits. Two review papers were included in a special volume on hardrock seismic exploration published by the Society of Exploration Geophysicists[45,46]. Deep seismic reflection data were also used to image crustal structures across the central Kaapvaal craton[47].

Research in earth structure

Seismological results have also inspired additional work in other fields. Recent research has demonstrated the value of seismically determined crustal thickness values for assessing the isostatic response due to the load of the Bushveld Complex in the crust[48]. These crustal thickness values confirmed earlier predictions of crustal thickness based purely on geological and gravity data arguments[49,50]. This new model[48] has important economic implications. If the Bushveld Complex can be shown to have economic horizons at shallow depth in the centre of the Complex, this would greatly increase the platinum resources of southern Africa. For such an economically important resource, surprising little research has been conducted on the 3D geometry of the Bushveld Complex. Ideally, research Vibroseis lines should be collected across the entire extent of the Bushveld Complex to fully delineate this important resource. A less expensive alternative would be the placement of an array of passive broadband seismometers focused on resolving crustal structure.

In another research project using crustal thickness results[51] and seismic velocity variations[52] beneath the Kaapvaal Craton, it has been shown that the crustal thickness variations at the Moho give a strong contribution to the gravity signal of southern Africa[53]. Interestingly, the seismically determined crustal thickness variations are not strongly correlated with topography - there is a stronger correlation with regional geology. Surprisingly the contribution to the gravity signal from the seismic velocity variations in the mantle is about the same order of magnitude as the gravity variations due to the Moho variations. However, the seismic velocity variations in the mantle keel beneath the Kaapvaal Craton appear to be dominated by composition variations as opposed to more commonly supposed temperature variations. These gravity models lend additional support to the isopycnic hypothesis[54], who suggested that Archean Cratons are underlain by thick, depleted mantle keels with high Mg#s.

Conclusions

The SANSN has been upgraded enabling data to be retrieved in quasi real-time. The location accuracy of data recorded by SANSN has been improved by replacing the short-period instruments with broadband and extended short-period seismometers, as well as by developing a multi-reference relocation technique. Stable source parameter calculation methods have been developed for the data recorded by SANSN, and a large body of research on seismic hazard and risk for sites of essential engineering structures has been completed. Two short-period instruments have been installed in the gold mining areas of the Central Rand and Far West Rand to improve the location accuracy of mine tremors.

An investigation into the ML = 5.3 event near Stilfontein concluded that the event could be attributed to past mining, that further seismicity would occur due to present mining activities and would continue for some time after mining activities ceased due to flooding. The unusually large earthquake of ML = 7.3 that occurred in Mozambique was related to southernmost extension of the East African Rift System.

Several MHSC research projects involving large components of mining seismology research have been completed. The highlights include: insights into the behaviour of crush pillars; further work on the integration of seismicity and numerical modelling; research in proactive approaches to rock mass stability; the quantification of the effects of various lead-lag distances between adjacent panels on fracturing, stability, support and seismicity; new methodologies for quantifying the hazards association with remnant extraction. Seismic event detection devices have been developed to give prior warnings to goafing in coal mines and falls of ground in platinum mines. The site response has been evaluated from measurements of peak velocity and found that the peak ground velocity of the skin of excavations was an average of nine times higher than the velocity in the rock mass, which was inferred from the in-mine networks.

New models of the structure of the Bushveld Complex used seismically determined crustal thickness values to assess the isostatic response due to the load of the Complex in the crust postulates the existence of economic horizons in the centre of the Complex. The impact of this research has the potential to vastly increase the platinum resources of southern Africa.

References

1. Graham G. (ed.). (2006). *Seismological Bulletins* (produced quarterly). Council for Geoscience, Pretoria, January – March, April – June, July – September, October – December issues.

2. Durrheim R. J., Anderson R. L., Cichowicz A., Ebrahim-Trollope R., Hubert G., Kijko A., McGarr A., Ortlepp W. D. and Van der Merwe N. (2006). The Risks to Miners, Mines, and the Public posed by Large Seismic Events in the Gold Mining Districts of South Africa, In: Proceedings of the Third International Seminar on Deep and High Stress Mining, eds J. Hadjigeorgiou and M. Grenon, Université Laval, Canada, Section 30.

3. Nyblade A. (2003). White Paper. AfricaArray: Training a Scientific Workforce for Africa's Natural Resource Sector. 15p. http://www.africaarray.psu.edu/about_us/africa_array_white_paper.pdf

4. http://www.hartrao.ac.za/inkaba/index.php
   http://www.gfz-potsdam.de/pb4/pg3/projects/INKABAyeAFRICA/

5. http://www.icdp-online.de/contenido/lakedb/front_content.php

6. Cichowicz A. (2005). Automatic processing and relocation methods. *Controlling Seismic Risk, Sixth International Symposium on Rockburst and Seismicity in Mines Proceedings*, Australian Centre for Geomechanics, 547 – 554.

7. Cichowicz A. (2006a). *Location of mine related seismic events using characteristic appearances of the waveform*, Report, Council for Geoscience.

8. Cichowicz A. (2006b). *Investigation of the spectral parameters of the mine related seismic events*, Report, Council for Geoscience.

9. Bejaichund M., Kijko A., and Hattingh E. (2004). Estimation of Maximum Earthquake Magnitudes for Stable Continental Regions of Africa. CGS Report no: 2004-0065.

10. Kijko A. (2004). Estimation of the Maximum Earthquake Magnitude, $m_{\max}$, *Pure Appl. Geophys*, **161,** 1655-1681.

11. Kijko A., Bejaichund J. and Ramperthap J. (2004). *SHARP: Seismic Hazard Assessment and Risk Program. Software Package for Seismic Hazard and Risk Assessment.* CGS Report No.: 2004-0285.

12. Kijko A., Hattingh E., Ramperthap J., Pule T. and Bejaichund M. (2006a). *Intensity Attenuation Models and Vulnerability Curves for South Africa.* CGS Report no: 2006-0335.

13. Kijko A., Ramperthap J., Bejaichund M. and Saunders I. (2006b). *D-Sharp, Deterministic Seismic Hazard Assessment and Risk Program. Software Package for Deterministic Seismic Hazard and Risk Assessment.* Report No.: 2006-0312.

14. Kijko A., Ramperthap J., Bejaichund M., and Saunders I. (2006c). *P-Sharp, Probabilistic Seismic Hazard Assessment and Risk Program. Software Package for Probabilistic Seismic Hazard and Risk Assessment*. Report No.: 2006-0326.

15. http://www.simrac.co.za.

16. Canbulat I., Grodner M., Lightfoot N., Ryder J., Essrich F. Dlokweni T., Wilkinson A., Krog C. and Prohaska G. (2006). *The determination of loading conditions for crush pillars and the performance of crush pillars under dynamic loading*. SIM040302 Final Project Report, Department of Minerals and Energy, South Africa.

17. Ilchev A.S. and Mendecki A.J. (2005). *Calibration of Integration-Ready Numerical Models to Real Seismic Data.* SIM 020307 Final report SIM020307-REP-020, 89pp.

18. Lynch R.A. (2003) *Proactive approaches to rockmass stability and control*. SIM 020302 Final report. Department of Minerals and Energy, South Africa. 69p.

19. Goldbach O.D., Rangasamy T., Linzer L.M., Kataka M.O., Spottiswoode S.M. and du Pisani P. (2006). *Lead-lag design criteria and seismicity patterns*. SIM 040303 Final report, Department of Minerals and Energy, South Africa.

20. Sellers E.J., Kataka M.O., Singh N., Ebrahim-Trollope S., Handley R., Milev A. and Spottiswoode S.M. (2005). *New methodologies for quantifying remnant extraction hazards in deep mines.* Final report under review.

21. Makusha G. (2004). Stooping low safety factor pillars at Goedehoop Colliery – 12 months later. In: *Proceedings of the 23rd International Conference on Ground Control in Mining*, Morgantown, West Virginia, August 3–5.

22. Milev A.M. and Spottiswoode S.M. (2005). Strong ground motion and site response in deep South African Mines, J. of South Afric. Inst. Min. and Metall., **105** (7), 515 – 525.

23. Milev A.M., Hildyard M.W., Linzer L.M. and Spottiswoode S.M. (2005). Underground microseismic monitoring of pillar systems to evaluate mechanism of failure. In: *Rockbursts and Seismicity in Mines, RaSim 6.* eds Y. Potvin and M. Hudyma. Perth, Australia, 239 – 246.

24. Spottiswoode S.M. and Milev A.M. (2006). A study of mine stability using records of ground tilting. In: *Proceedings of ARMA/USRMS, the 41st U.S. Symposium on Rock Mechanics,* Golden. Colorado, CD-ROM, Paper no: 06 – 1168.

25. McGill R.B. (2005). Strategies to Manage Seismicity in a Deep VCR Environment on Mponeng. In: *Rockbursts and Seismicity in Mines, RaSim 6.* eds Y. Potvin and M. Hudyma. Perth, Australia, 419 – 424.

26. Spottiswoode S.M. (2005). Mine Layout Design and Medium-Term Prediction of Seismicity. In: *Rockbursts and Seismicity in Mines, RaSim 6.* eds Y. Potvin and M. Hudyma. Perth, Australia, 211 – 217.

27. Van Aswegen G. (2005). Routine Seismic Hazard Assessment in Some South African Mines. In: *Rockbursts and Seismicity in Mines, RaSim 6.* eds Y. Potvin and M. Hudyma. Perth, Australia , 437 – 444.

28. Singh N., Naidoo K., Milev A.M. and Urcan H. (2005). Evaluation of the rockburst potential in platinum mines in shallow to intermediate depths when mining beneath overlying remnants. In: *Rockbursts and Seismicity in Mines, RaSim 6.* eds Y. Potvin and M. Hudyma. Perth, Australia, 165 – 173.

29. Glazer S.N. and Hepworth N. (2005). Seismicity Induced by Cave Mining, Palabora Experience. In: *Rockbursts and Seismicity in Mines, RaSim 6,* eds Y. Potvin abd M. Hudyma, Perth, Australia, 281 – 289.

30. Lynch R.A., Wuite R. Smith R.S. and Cichowicz A. (2005). Microseismic Monitoring of Open Pit Slopes. In: *Rockbursts and Seismicity in Mines, RaSim 6.* eds Y. Potvin and M. Hudyma. Perth, Australia, 581 – 592.

31. Milev A.M., Spottiswoode S.M., Murphy S.K, and Geyser D. (2003). Strong ground motion and site response of mine-induced seismic events. In: *International Society for Rock Mechanics, 10th Congress, Technology Roadmap for Rock Mechanics*, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 817 – 822.

32. Spottiswoode S.M. & Linzer L.M. (2003). Improved seismic event locations. In: *International Society for Rock Mechanics, 10th Congress, Technology Roadmap for Rock Mechanics*, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 1141 – 1146.

33. Van Aswegen G. (2003). Applications of seismic hazard assessment methods in mines. In: *International Society for Rock Mechanics, 10th Congress, Technology*

Roadmap for Rock Mechanics, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 1261 – 1268.

34. Vieira F.M.C.C. and Budavari S. (2003). Evaluation of four layouts for gold mining at a depth range of 3500 and 5000m. In: *International Society for Rock Mechanics, 10th Congress, Technology Roadmap for Rock Mechanics*, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 1299 – 1310.

35. Klokow J.W., Reimer K.L. and Ferreira R.I.L. (2003). An initial assessment of the closely spaced dip-pillar mining layout as practised at Driefontein Gold Mine. In: *International Society for Rock Mechanics, 10th Congress, Technology Roadmap for Rock Mechanics*, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 655 – 664.

36. Armstrong R., Reimold W.U. and Charlesworth E.G. (2003). Comparison of the fractography of rockbursts and impact structures. In: *International Society for Rock Mechanics, 10th Congress, Technology Roadmap for Rock Mechanics*, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 49 – 56.

37. Bosman J.D. and Van Aswegen G. (2003). Dynamic failure of pillar remnants. In: *International Society for Rock Mechanics, 10th Congress, Technology Roadmap for Rock Mechanics*, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 143 – 150.

38. Kataka M., Hildyard M.W. and Sellers E.J. (2003). Integration of seismic observations from deep level gold mines with dynamic numerical modelling. In: *International Society for Rock Mechanics, 10th Congress, Technology Roadmap for Rock Mechanics*, eds M. Handley and D. Stacey. SAIMM, Johannesburg, September 2003, 617 – 624.

39. Linzer L.M. (2005). Manuel Rocha Medal Recipient: A relative moment tensor inversion technique applied to seismicity induced by mining. *Journal of Rock Mechanics and Rock Engineering*. **38** (2), 81 – 104.

40. http://www.isrm.net/fotos/gca/1153998415rocha_medal_2005_mhildyard_summary.pdf

41. Spottiswoode S. M. (2004). A seismic and modelling analysis of dip-pillar mining, *Proc. 2nd Int. Seminar on Deep & High Stress Mining*, SA Inst. Min. Metall. Symposium Series S37, 67-78.

42. Durrheim R. J. and Labrie D. (2004). Data-driven simulation of the rock mass response to mining (part 1): Laboratory experiments using Nepean sandstone models, In: *Proceedings of the Second International Seminar on Deep and High Stress Mining*, SA Inst. Min. Metall. Symposium Series S37, 365 – 394.

43. Ortlepp W. D., Murphy S. and Van Aswegen G. (2004). The mechanism of a rockburst - an informative case study, *Proc. 2nd Int. Seminar on Deep & High Stress Mining*, SA Inst. Min. Metall. Symposium Series S37, 23-40.

44. McGill R.B. (2004). Strategies to manage seismicity in a deep VCR environment on Mponeng. *Proc. 2nd Int. Seminar on Deep & High Stress Mining*, SA Inst. Min. Metall. Symposium Series S37, 79-94.

45. Pretorius C.C., Muller M.R., Larroque M. and Wilkins C. (2003). A review of 16 years of hardrock seismics on the Kaapvaal Craton. In: *Harddrock Seismic Exploration*, eds D.A. Eaton, B. Milkereit and M.H. Salisbury, Geophysical Development Series, No. 10, 247 – 268.

46. Stevenson F., Higgs R.M.M. and Durrheim R.J. (2003). Seismic imaging of precious and base-metal deposits in Southern Africa. In: *Harddrock Seismic Exploration*, eds D.A. Eaton, B. Milkereit and M.H. Salisbury, Geophysical Development Series, No. 10, 141 – 156.

47. De Wit M. and Tinker J. (2004). Crustal structures across the central Kaapvaal Craton from deep-seismic reflection data. *S. Afr. Jour. Geol.*, **107**, 185 – 206.

48. Webb S.J., Nguuri T.K., Cawthorn R.G. and James D.E. (2004). Gravity modelling of Bushveld Complex connectivity supported by southern African seismic experiment results. *S. Afr. Jour. Geol.*, **107**, 207 – 218.

49. Cawthorn R.G., Cooper G.R.J. and Webb S.J. (1998). Connectivity between the western and eastern limbs of the Bushveld Complex. *S. Afr. Jour. Geol.* **101**, 291 – 298.

50. Cawthorn R.G., and Webb S.J. (2001). Connectivity between the western and eastern limbs of the Bushveld Complex. *Tectonophysics*, **330**, 195 – 209.

51. Nguuri T.K., Gore J., James D.E., Webb S.J., Wright C., Zengeni T.G., Gwavava O., Snoke J.A., and Kaapvaal Seismic Group (2001). Crustal structure beneath southern Africa and its implications for the formation and evolution of the Kaapvaal and Zimbabwe cratons. *Geophys. Res. Lett.* **28**, 2501 – 2504.

52. James D.E., and Fouch M.J. (2002). Formation and evolution of Archean Cratons: Insights from Southern Africa. In *The Early Earth: Physical, Chemical and Biological Development: Geological Society,* eds C.M.R. Fowler, C.J. Ebinger and C.J. Hawkesworth., London, Geol. Soc. Spec. Publ. **199**, 1 – 26.

53. Webb S.J. and James D.E. (2005). Contributions to the gravity field of southern Africa from crustal thickness variations and mantle seismic velocity variations. In: *Extended abstracts of the South African Geophysical Association Ninth Biennial Conference*. Cape Town, CD-ROM.

54. Jordan T.H. (1979). Mineralogies, densities and seismic velocities of garnet lherzolites and their geophysical implications. In *The mantle sample: inclusions in kimberlites and other volcanics*, eds F.R. Boyd and H.O.A. Meyer. Washington D. C., American Geophysical Union, 1 – 14.

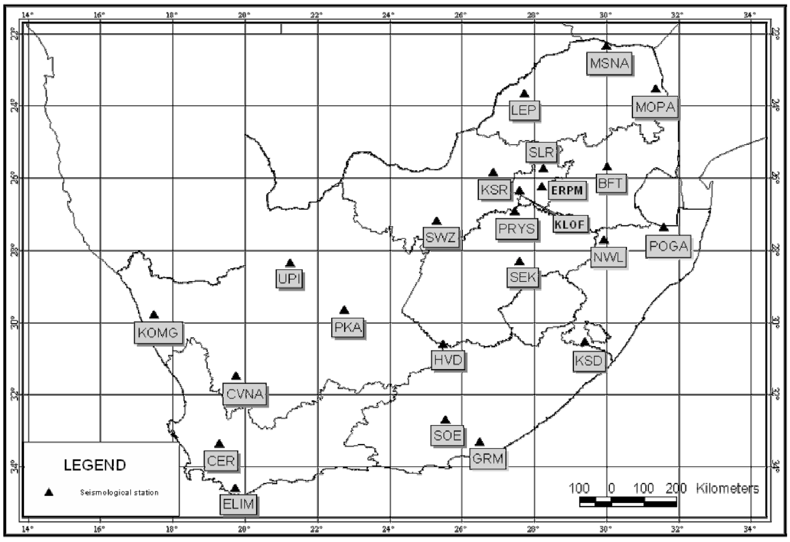

Figure 1: Distribution of stations comprising the SANSN network.

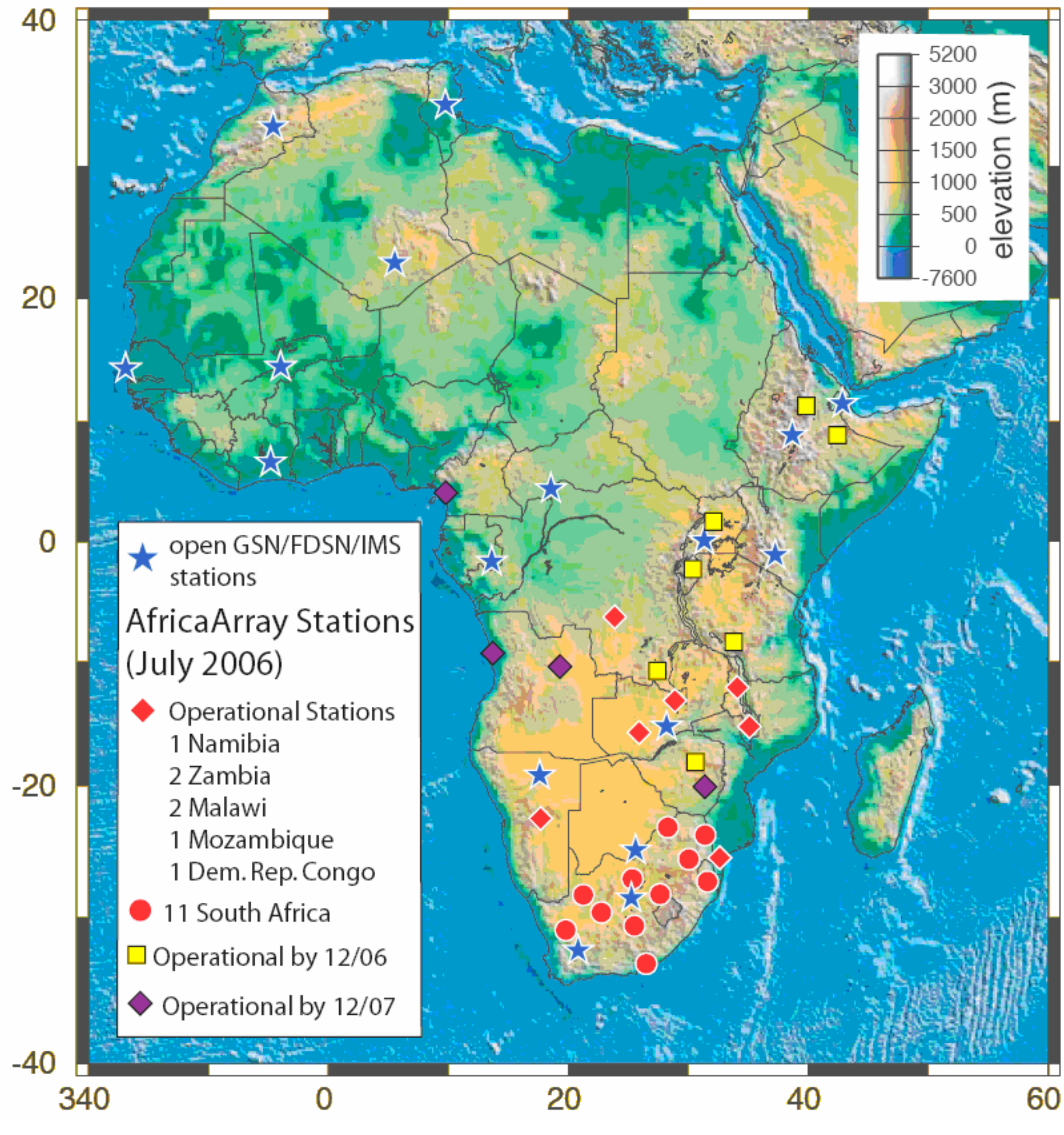

Figure 2: Distribution of current and planned AfricaArray broadband stations (from AfricaArray Newsletter, 2006).

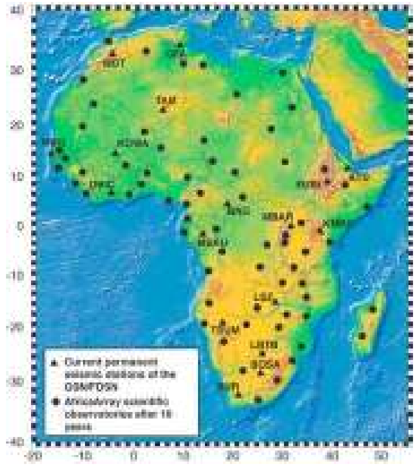

Figure 3: Current permanent seismic stations of the GSN/FDSN network (triangles) and planned observatories (circles) after 10 years
(from http://africaarray.psu.edu/about_us/overview.htm)

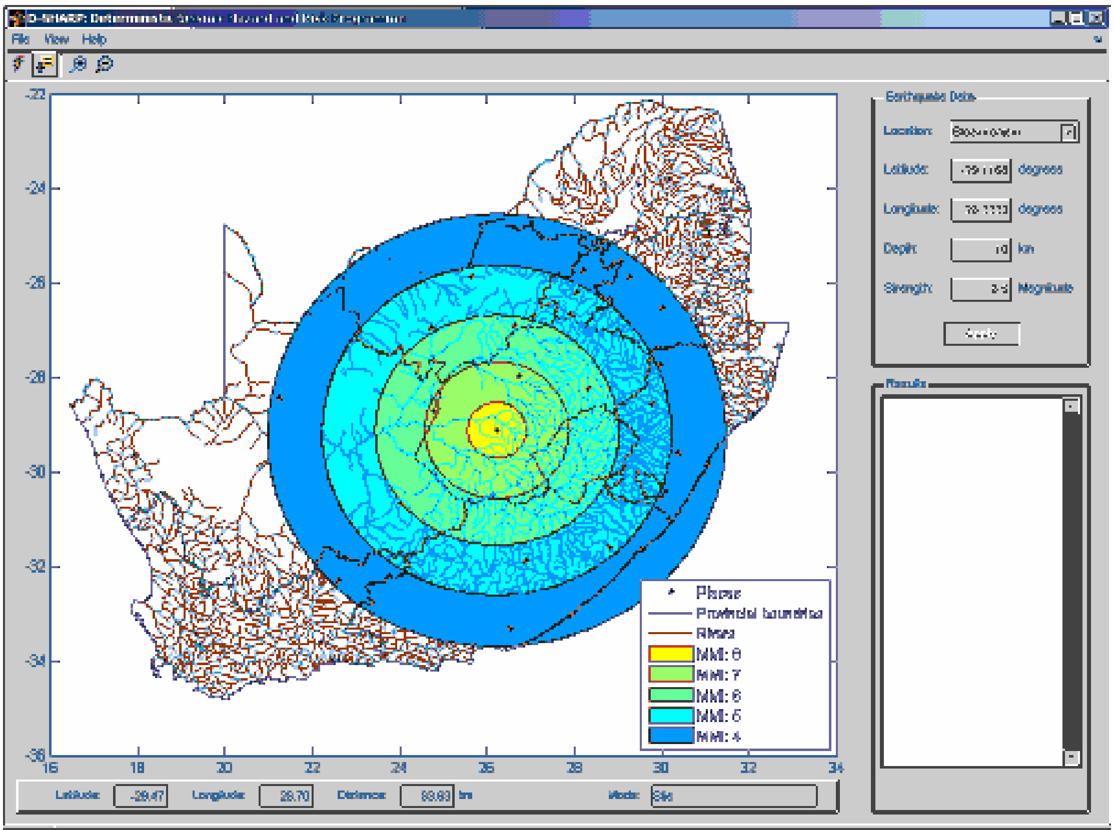

Figure 4. D-Sharp, Deterministic Seismic Hazard and Risk Programme, display with initial datatips removed.

Figure 5. Damage in Stilfontein caused by the ML = 5.3 tremor on 9 March 2005