Recent research in seismology in South Africa

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This paper summarizes 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 in this time, and the upgraded seismological stations now use the SeisComp recording system and GPRS cellular communications for retrieving data in quasi-real time. The largest mining-related ever to occur in South Africa registered 5.3 on the local Richter magnitude scale (M_L) on 9 March 2005. An unusually large earthquake of M_L = 7.3 occurred in Mozambique on 23 February 2006, 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 the SANSN, and significant research has been completed on seismic hazard and risk methods. The work in mining seismology has been wide-ranging in pursuit of improved understanding of the complex rock mass response to underground mining. Novel underground instrumentation has been developed. A new model of the Bushveld Complex uses seismically determined crustal thickness values to assess its isostatic responses and 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. The CGS has invested substantial resources in upgrading the network in recent years. To date, 19 stations are equipped with GPRS cellular communications for retrieving data in quasi-real-time.

The CGS publishes quarterly 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 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 for several months, and this led to a comprehensive investigation commissioned by the Chief Inspector of Mines. The brief was 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 more frequent incidence of large events in mining districts. There is a need to be able to identity the particular mine in which an event occurred. This has stimulated research at the CGS on improved relocation methods, as well as in the fields of seismic risk and hazard assessment.

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Not all the events listed in the earthquake bulletins are mine-related. An unusually severe earthquake, measuring 7.3 ML, 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 because the faulting mechanism associated with diverging plate boundaries generally produces smaller seismic events.

Several ambitious, inter-institutional, international research programmes have been initiated during the last four years: the AfricaArray initiative is a long-term (20-year) 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 programmes couple research with capacity building in the geosciences. Research in seismology is using regional events to determine earth structure from the data recorded through *Inkaba ye Africa* and AfricaArray, as well as by building on previous research from the Kaapvaal Project.

There have also been high profile achievements by local seismologists. The Department of Science and Technology has established the South African Research Chairs Initiative to reinvigorate research at the country's higher education institutions and to develop research capacity. The first 21 chairs were awarded in December 2006 through a highly competitive review process. One of these (the joint University of the Witwatersrand/CSIR Chair of Earthquake, Exploration and Mining Seismology) was conferred on R.J. Durrheim. It is envisaged that he will provide scientific leadership to the AfricaArray and Minimizing the Risk of Rockbursting research programmes, and will develop partnerships with the hydrocarbon and mineral sector, as well as with science councils and universities in South Africa, elsewhere in Africa, and abroad.

Two South African seismologists were awarded the Rocha Medal by the International Society for Rock Mechanics for their Ph.D. research projects. Lindsay Linzer received 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, M. 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] No other country has achieved more than three of these awards, whereas South Africa has now collected five. In exploration seismology, George

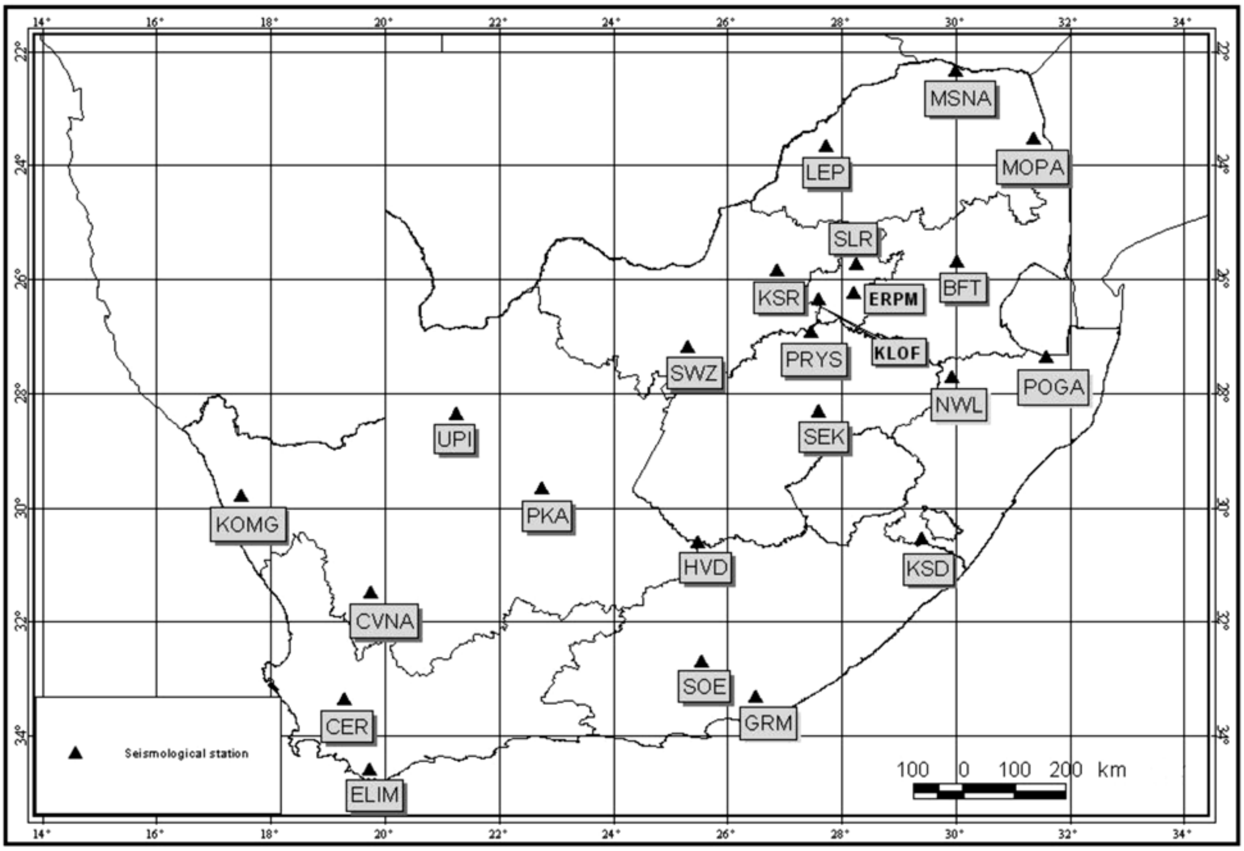

Fig. 1. Distribution of seismological stations comprising the SANSN network.

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 (Amplitude Variations with Offset) procedure. After more than 15 years of scrutiny, it remains a critical seismic attribute that is employed routinely by geophysicists. This work has achieved international acclaim: the year before, Smith and Gidlow were each presented with the Reginald Fessenden Award by the Society of Exploration Geophysicists.

Rockbursts remain among the greatest challenges facing the South African mining industry. This arises from the ever-increasing depths at which gold and platinum mining occur. Rockbursts are seismic events associated with mining that result in damage, costing the industry about US$1 billion a year (in terms of ground lost in pillars, local support, difficult mining as well as other factors). Consequently, most of the research in mining seismology is focused on reducing the rockburst risk. The key contributors to research on mining-induced seismicity are CSIR employees, Integrated Seismic Systems International (ISSI), various consultants and, to a lesser extent, the universities. Very few mining seismologists remain as mine employees, with the routine running of the in-mine systems either being outsourced or becoming the responsibility of the rock engineering departments.

The review that follows attempts to summarize 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
- improvements to seismic location and source parameter calculation methods
- developments in seismic hazard and risk methods
- 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

The SANSN comprises 23 seismological stations (Fig. 1), most of which were installed during the 1970s and early 1980s. The network is operated and maintained by the Council for Geoscience, mandated by the Department of Minerals 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), namely, Boshof, Sutherland and Lobatse, are also routinely used in data analysis.

The CGS has invested significant effort and resources in upgrading and restructuring the entire network. The delay in transmitting waveform data recorded by the SANSN to the CGS offices in Silverton, Pretoria, was addressed in early 2006. 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 terms of transfer speed and cost. GPRS additionally supports a wide range of bandwidths that are suitable for sending and receiving large volumes of data. A total of 19 stations have been equipped with GPRS to date. The use of near-real-time data communication has shortened the response time of the CGS to release earthquake data to interested parties. A refitting programme to phase out 18-bit digitizers and replacing Stand Alone Quake Systems (SAQS) with the Earthquake Acquisition Recording System (EARS) developed in-house, was executed in parallel with the communication programme. The need to replace the SAQS recorders was paramount as availability of spare parts has been an increasing problem. The SANSN is currently equipped with five broadband (100-second) and 14 extended short-period (30-second) seismometers.

The CGS implemented the SeisComp data acquisition software, developed by the GeoForschungsZentrum (GFZ) in Potsdam, Germany, during the last quarter of 2005. This records waveforms in the internationally accepted MiniSEED format and has an additional feature for automatic earthquake location. Waveform data are presently communicated at 20 samples per second (sps) for continuous data and 100 sps for triggered data.

A station was installed in each of the gold mining areas of the Central Rand and Far West Rand, under a DME-funded project. These stations are located at East Rand Proprietary Mines and Kloof Mine, and are equipped with 24-bit digitizers, GPRS communications and three-component short-period sensors.

The CGS has pledged five 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. There are plans to channel waveform data from these stations through the GFZ to the International Data Center in Indonesia.

Research initiatives

AfricaArray Initiative

The name 'AfricaArray' encapsulates the essence of this enterprise and describes the suite of training programmes, scientific observatories, and projects of scientists across the continent. Most importantly, AfricaArray refers to a vision that is shared between the project partners, so that Africa can retain capacity in an array of scientific fields that are critical to the development of its natural resources.[3] The founding partners of AfricaArray are the University of the Witwatersrand, the University of Pennsylvania and the CGS. The programme was launched officially in January 2005.

AfricaArray's initial focus is on geophysics education and research, due to 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 these stations. The network currently consists of 24 permanent broadband stations and forms a backbone network for recording earthquakes across eastern and southern Africa (Fig. 2). The eleven stations in South Africa belong to the SANSN.

Seismic data are being used for student M.Sc. and Ph.D. research projects as well as in collaborative research programmes involving 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 Carletonville district, west of Johannesburg. These data will be interpreted in combination with those 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 (200–1000 km). Three temporary stations have been installed by the CGS to date, while 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 that are crucial to development in the natural resources sector. Monitoring equipment such as GPS, and meteorological, hydrological and other environmental sensors will be added to the existing observatories.[3] The projected network of scientific observatories, in 10 years' time, is shown in Fig. 3.

Inkaba ye Africa

More than 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 Ocean.

The enterprise consists of 12 projects that contribute to three main research themes: the 'Heart of Africa', the 'Margins of Africa' and 'Living Africa'.[4] Some seismic reflection and refraction surveys were 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. Another objective is to provide training and mentoring for local earth scientists in a collaborative environment. The data recorded by these surveys are currently being evaluated.

DAFSAM–NELSAM

This 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 for making direct and near-field seismic observations at the focal depth. The projects aim to build 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 US, Germany and Japan are involved in the research in collaboration with scientists from ISSI, TauTona Gold Mine, the University of the Free State and the CSIR in South Africa.

Developments in regional seismology

Improved seismic location methods

A study recently conducted by the CGS shows that errors in locating mine-related events recorded by SANSN could be as large as 20 km. The CGS is currently able to specify only the district in which the event occurred, such as Klerksdorp, the Far West Rand, the West Rand or Welkom. However, there is a need to be more specific; namely, that the SANSN should be able to identify the particular mine where 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, have been 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 the CGS for locating newly recorded earthquakes.[7] This technique 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 shown that the method is effective in reducing location errors.

New software has been developed at the CGS to calculate stable source parameters from the SANSN on a routine basis.[8] The software performs three main tasks. First, 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 easily 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 at the CGS in the field of seismic hazard and risk. The scope of the work has involved sites of crucial engineering structures like dams, tall buildings, bridges, nuclear power plants, gas and coal terminals, pipelines and mining regions. The research highlights 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 become available.

Procedures and software have been produced for the generation of Monte Carlo catalogues for use in probabilistic seismic hazard assessment.[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, first released 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. The SHARP software was compiled from the MATLAB format in 2005, and is now available as stand-alone software.

Attenuation models have been developed for South Africa based on recorded intensities from several isoseismal maps created for large earth-

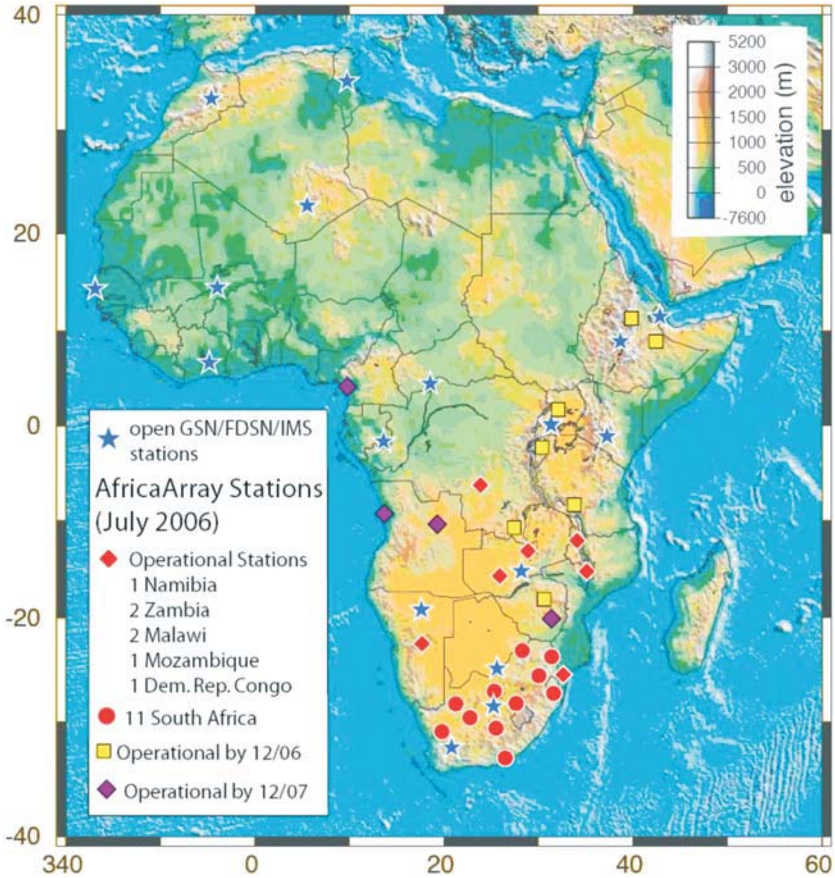

Fig. 2. Distribution of current and planned AfricaArray broadband stations (from ref. 3).

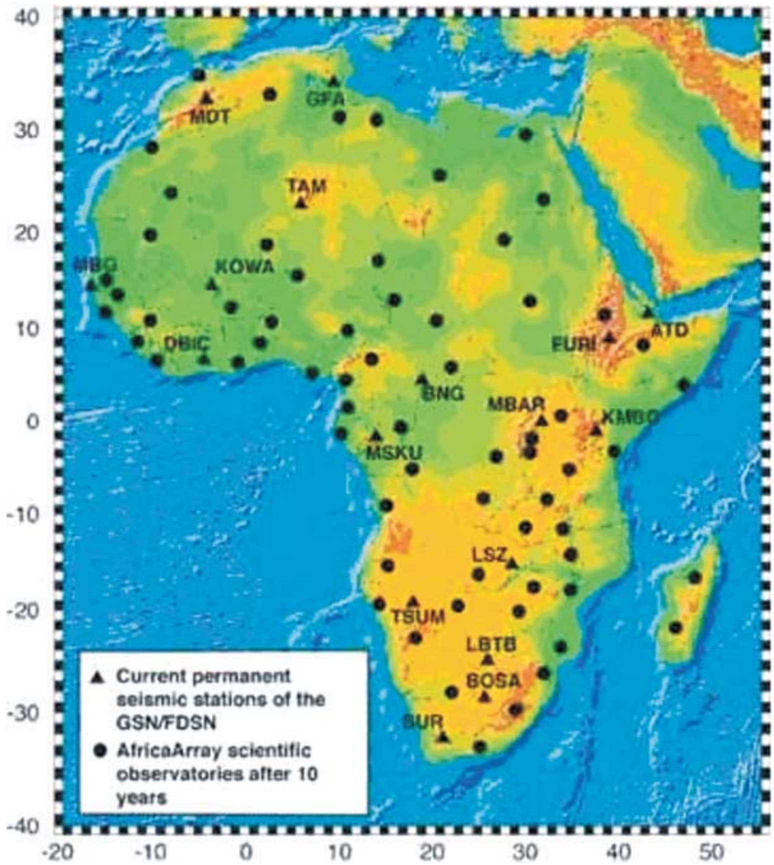

Fig. 3. Current permanent seismic stations of the GSN/FDSN network (triangles) and observatories planned for the next 10 years (circles) (from ref. 3).

quakes 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 codes: D-SHARP[13] and P-SHARP.[14] D-SHARP provides maps of seismic risk for a user-specified earthquake, anywhere in South Africa (Fig. 4). This toolbox is similar to that of the USGS Shake map that provides near-real-time maps of shaking intensity that follows significant earthquakes. P-SHARP provides probabilistic seismic risk assessment for any location in South Africa.

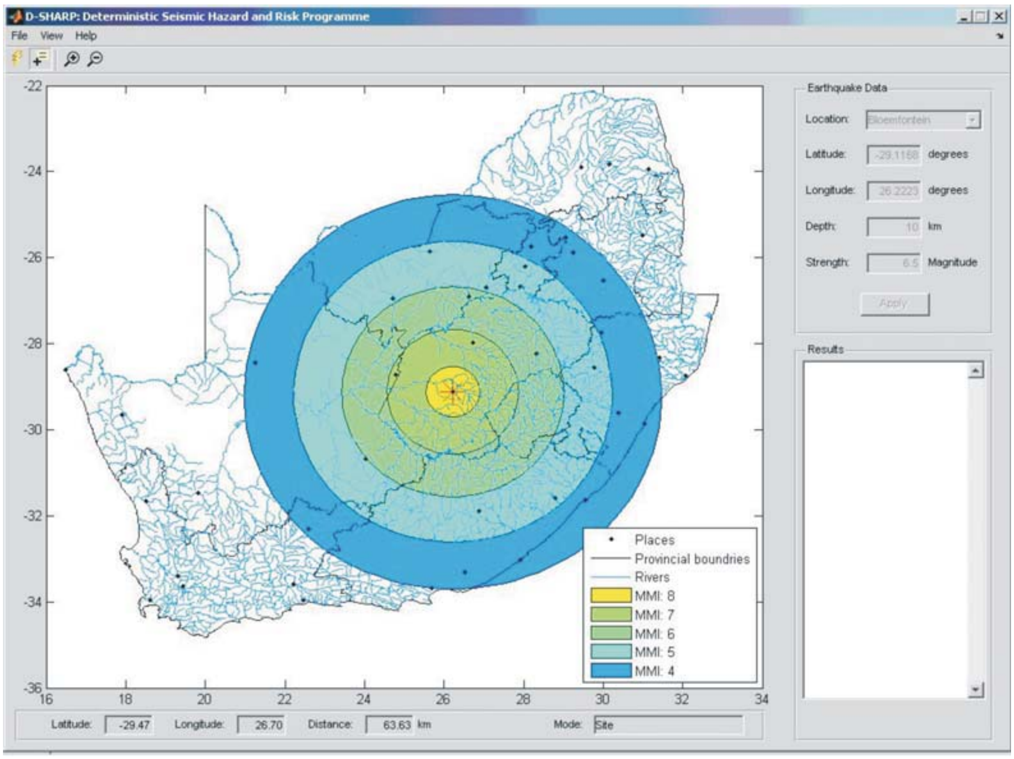

Fig. 4. D-SHARP (Deterministic Seismic Hazard and Risk Program) display with initial data tips removed.

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 the source given in 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 shows that the pillars are 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] The numerical stress modelling codes MAP3Di and IDRM (Integrated Damage Rheology Model) were compared in this project to identify common advantages and potential problems associated with the integration of modelling with real seismic data. The significant 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 rock mass 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 of blasting at a variety of sites, and compared with the levels of seismic activity recorded by mine-wide networks over three-month periods. It emerges 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'. The term 'remnant' refers to reef that has not been mined, owing 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 current project aims to evaluate the design criteria of regularly spaced dip pillars 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 with elastic and inelastic results, obtained by modelling using MINF.
7) SIM 050302: 'Minimizing the Rockburst Risk' is a 5-year research programme that began in April 2005. Collaborators include the CSIR, ISSI and the CGS. The programme encompasses both fundamental research on topics such as seismic source mechanisms, the dynamics of fault zones and rock

Fig. 5. Damage in Stilfontein caused by the $M_L = 5.3$ tremor on 9 March 2005.

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 that are 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 the CSIR in consultation with the coal mining industry. GoafWarn can monitor micro-seismicity 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; 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 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), specially designed for recording strong ground motions underground, was used to create a large database of peak particle velocities measured on stope hangingwalls. The project monitored a total of 58 sites, located in stopes mining the Carbon Leader Reef, Ventersdorp Contact Reef, Vaal Reef and Basal Reef. 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 with those measured by the mine's seismic networks to determine the site response. The peak ground velocity measured on the skin of the excavations was found on average to be 9 ± 3 times greater than the peak ground velocity derived from the mine seismic data.[22]

Another unique and recently established research field is that of in-stope micro-seismic monitoring. This encapsulates a wide range of research, such as regional and local support behaviour, the mechanism of pillar failure,[23] quasi-static 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 regarded as 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 on mining-induced seismicity in the RaSiM proceedings.

The sixth RaSiM symposium, held in Perth, Australia, in 2005, included a wide range of papers from South Africa, on such topics as: 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] Overall, 23 out of a total of 80 papers in RaSiM6 were written by South Africans as first or sole author. Most of the South African papers were on seismicity or rockbursts in deep-level gold mines, although four articles were related to other types of mining, namely underground platinum[23,28] and copper[29] as well as open-pit mining.[30]

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

This congress was held in South Africa in September 2003. Although the focus was mostly on rock mechanics, nine papers by South Africans on mining seismology research and case studies were presented on a wide variety of topics. These were 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] the dynamic failure of pillar remnants;[37] and dynamic numerical modelling.[38]

Second International Seminar on Deep and High Stress Mining

The aim of the seminar, which was held in Johannesburg in 2004, 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 M_L, 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 (Fig. 5). Two mineworkers were killed and 3200 others had to be evacuated. It was the largest mining-related seismic event ever to occur in South Africa.

The Chief Inspector of Mines appointed a team of experts, led by the CSIR's R.J. Durrheim, 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 event of 9 March could be ascribed to past mining. The possibility that the event and its aftershocks were solely due to natural forces was considered to be extremely small. Seismic events will continue to occur as long as there is mining, and for some time after mining ceases, as earthquakes 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 to date. Nevertheless, the recommendation is 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 new buildings are designed. Municipalities 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 hard rock 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 motivated additional work in other fields. Recent research has demonstrated the value of seismically determined crustal thickness values, for assessing the isostatic response 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. The platinum resources of southern Africa would greatly increase if the Bushveld Complex can be shown to have economic horizons at shallow depth in its centre. Surprisingly little research has been conducted on the 3D geometry of the Bushveld Complex, for such an economically important resource. Research Vibroseis lines should ideally be collected across the entire extent of the complex, to delineate fully 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. The contribution to the gravity signal from the seismic velocity variations in the mantle is, surprisingly, 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,[20] which proposes that Archean cratons are underlain by thick, depleted mantle keels with relatively high magnesium content.

Conclusions

The SANSN has been upgraded, enabling data to be retrieved in quasi-real-time. The location accuracy of data recorded by the network 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 the 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 accuracy of locating mine tremors.

An investigation into the $M_L = 5.3$ event near Stilfontein concluded that it 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, as a result of flooding. The unusually large earthquake of $M_L = 7.3$ that occurred in Mozambique was related to the 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, and new methods for quantifying the hazards association with remnant extraction. Devices to detect seismic events have been developed to give prior warnings of goafing in coal mines and falls of ground in platinum mines. The site response has been evaluated from measurements of peak ground velocity of the skin of excavations, which was found to be on average nine times higher than the velocity in the rock mass, as inferred from the in-mine networks.

New models of the structure of the Bushveld Complex have used seismically determined values of the crustal thickness to assess the isostatic response to the load of the complex in the crust, and postulate the existence of economic horizons in the centre of the complex. The consequences of this research have the potential to increase greatly the platinum resources of southern Africa.

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