Recent research in earth structure, earthquake and mine seismology, and seismic hazard evaluation in South Africa

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Research in earth structure, earthquake and mine seismology, and seismic hazard evaluation in South Africa is summarized for the last four years. Improvements to the South African National Seismograph Network (SANSN) include the gradual replacement of short-period by broad-band instruments. New regional travel-time curves for P and S waves, and models of the structure of the crust and mantle beneath southern Africa to depths of 800 km, have been constructed by South African seismologists using earthquake data recorded by the temporary Kaapvaal broad-band seismic network and SANSN. A significant increase in crustal thickness of about 10 km was also identified between the southern part of the Kaapvaal craton and the northern region affected by the Bushveld magmatism. The Kaapvaal network has also been used to relocate mine tremors and tectonic earthquakes in South Africa to compare its location capability with SANSN. In mine seismology, research has focused on the understanding of rock behaviour in response to deep mining activities, assessment of seismic risk, prediction of seismicity, and controlling rockburst damage. A major emphasis has been on the integration of numerical modelling and seismicity. Developments in probabilistic seismic hazard analysis have emphasized improved estimates of the maximum regional magnitude, of peak ground acceleration attenuation values, and on providing uncertainties in model parameters.

Introduction

The routine monitoring of earthquakes in South Africa is undertaken by the Council for Geoscience (CGS) using the South African National Seismograph Network (SANSN), which publishes quarterly earthquake bulletins. The events in the bulletins are predominantly mining-induced tremors associated with deep gold mining on the margins of the Witwatersrand basin, which have local magnitudes in the range 1–5, of which recent examples can be found in ref. 1. Research in South Africa on the use of earthquakes to determine earth structure, over the last four years, has made use of the data recorded by the Kaapvaal broad-band seismic network of 84 stations deployed across southern Africa between April 1997 and April 1999 (Fig. 1), and a telemetered array of 32 broad-band instruments deployed around Kimberley between December 1998 and June 1999. The network and array formed part of the international Kaapvaal craton project involving geologists and geophysicists from Botswana, South Africa, the U.S.A. and Zimbabwe.[2] Research contributions involving seismology have been made at the University of Cape Town and the University of the Witwatersrand.

Seismicity in deep gold mines is monitored by regional networks in the Klerksdorp and Welkom areas, and by networks in individual mines in the Far West Rand and West Rand regions (Fig. 2). In the East Rand, networks have been sporadically operated in the East Rand Proprietary Mine. Networks of seismometers have also been installed to monitor induced seismicity in platinum mines. Research on mine seismicity and associated hazard to underground workers is conducted mainly by the CSIR Mining Technology (Miningtek), Integrated Seismic Systems (ISS) International, and seismologists employed in the individual mines or mining areas. The importance of research into seismic activity in South African mines is now recognized internationally, as teams of earthquake seismologists and experts in other areas of geophysics from Japan, the United States and other countries become involved in monitoring of seismic activity in South African mines, with the aim of better understanding the physics of seismic sources. Over the last four years, a large number of projects in the field of mine seismology, the area in which most of South Africa's seismologists are employed, have been completed. This report briefly summarizes some of the relevant SIMRAC (Safety in Mines Research Advisory Committee), DEEPMINE and internal CSIR Miningtek projects. This is not a complete listing, since work undertaken by universities and various consulting groups has not been included. Seismic hazard analysis for tectonic earthquakes is undertaken by the CGS and some other organizations are involved in palaeoseismic and neotectonic studies.

This article provides a summary of the most important developments in South African seismology over the last four years. These comprise changes in SANSN, the use of earthquakes to determine earth structure, the study of mining-induced seismicity and associated hazard evaluation in mines, tectonic seismicity and probabilistic hazard evaluation. A major concern is the shortage of young seismologists completing higher degrees in South African universities. A short history of earlier studies of earthquakes, earthquake hazard and earth structure in South Africa was prepared for the centennial handbook of the International Association of Seismology and the Physics of the Earth's Interior (IASPEI).[3] References to theses completed in the last four years that are relevant to the material described in this report are also given.

Changes to the South African National Seismograph Network

SANSN has throughout the years comprised approximately 25 seismological stations scattered around the country (Fig. 1). Since most of these stations were installed in the 1970s and early 1980s, there has been a recent move towards upgrading and restructuring the entire network. This process encompasses the upgrading of the seismometers, recorders and the vaults of the stations, and should result in fewer (ultimately about 20), but better quality stations.

This has, however, been quite a long process since it requires sufficient funding, and, in a bid to reduce the costs involved in

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the upgrading process, in-house designed and constructed seismograph systems (EARS, short for Event Acquisition Recording Systems) have been installed and will continue to be installed in the future. The first EARS systems were introduced in the late 1980s and early 1990s and have been upgraded through the years to EARS Alpha, EARS Delta, EARS Omega, EARS Sigma and EARS Delta Plus. The main changes were in the motherboards and in the digitizers (16 bit to 24 bit).

To reduce the risk involved in investing in just one type of technology, the Council for Geoscience will, over time, split the network and use EARS systems for one half of the network and commercially available, Stand Alone Quake Systems (SAQS) manufactured in South Africa by ISS International, for the second half.

Most of the stations of the SANSN had single short-period, vertical-component seismometers, and only a few had three-component, short-period seismometers. Thus a move has been initiated to incorporate 15 broad-band seismometers into the network to improve the detection capability of the SANSN. However, to be able to deploy these seismometers effectively, better vaults have to be constructed.

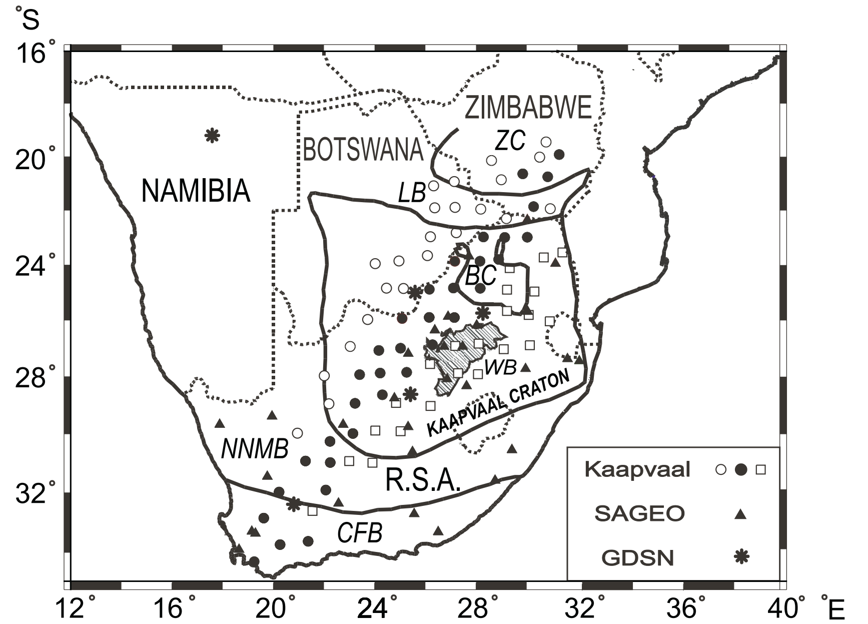

Fig. 1. Map of southern Africa showing distribution of seismic stations and main tectonic elements. BC, Outer boundary of surface outcrops of Bushveld Complex; CFB, Cape Fold belt; LB, Limpopo belt; NNMB, Namaqua Natal mobile belt; WB, Witwatersrand basin; ZC, Zimbabwe craton. Open and closed circles and squares denote stations of the Kaapvaal broad-band network that operated in the periods April 1997 – April 1998, April 1997 – April 1999 and April 1998 – April 1999, respectively. Triangles denote stations of the South African network as it was in 1999, and asterisks represent broad-band stations of the Global Digital Seismic Network or permanent long-period stations.

Accompanying all these advances in the instrumentation, the CGS has also moved to using SeisLog on their latest EARS (Omega and Delta) systems. This move will eliminate the need for converting the seismic data to Nordic format, and will allow for instant incorporation into the SEISAN analysis software utilized by the analysts.[4]

Studies of earth structure

Recent research in South Africa on the application of seismograms of earthquakes to the study of earth structure beneath southern Africa has made use of the data recorded by temporary installations: the Kaapvaal craton broad-band seismic network and the Kimberley broad-band array. The development of regional P and S wave travel-time curves[5,6] from regional, local and mining-induced earthquakes using data from both the Kaapvaal and South African seismic networks has been useful in relocating earthquakes and mine tremors listed in the bulletins published by the CGS. Average P and S wavespeed models starting from the surface were constructed from earthquake records for the first time for southern Africa to depths of 800 km.[7–9] Major features are prominent discontinuities at depths of 420 km and 660 km, and a low wavespeed zone for S waves between depths of 210 km and 350 km off the margin of the Kaapvaal craton. The discontinuity for S waves at 660 km depth is more prominent than for P waves, suggesting that the phase transformation from the spinel form of olivine to denser structures is not a complete explanation of the discontinuity (Fig. 3).[8] Estimates of crustal thicknesses from receiver functions have average values of about 38 km below the southern part of the Kaapvaal craton that has remained undisturbed by any tectonic events since the end of the Archaean, with similar average values for the Zimbabwe craton.[10] In contrast, a larger average of 44 km occurs for the northern regions of the Kaapvaal craton that were influenced by the Bushveld magmatic event at 2.05 Gyr, which is comparable with the thicknesses estimated below the surrounding Proterozoic mobile belts. The estimates of crustal thicknesses from *Pn* and *Sn* arrivals also have average values of about 38 km in the southern part of the Kaapvaal craton, with higher values of 40–42 km below the Witwatersrand basin, in excellent agreement with the results from receiver functions.[11] Below the northern parts of the Kaapvaal craton, however, estimates of average crustal thickness from *Pn* and *Sn* arrivals are greater than those calculated from receiver functions by about 7 km (51 km compared with 44 km).[6,11] This strange result suggests that the receiver functions for the northern regions are more strongly influenced by a boundary between intermediate granulites and plagioclase-poor mafic granulites that form an underplated lowermost crust, whereas the *Pn* and *Sn* arrivals define the petrological crust–mantle boundary

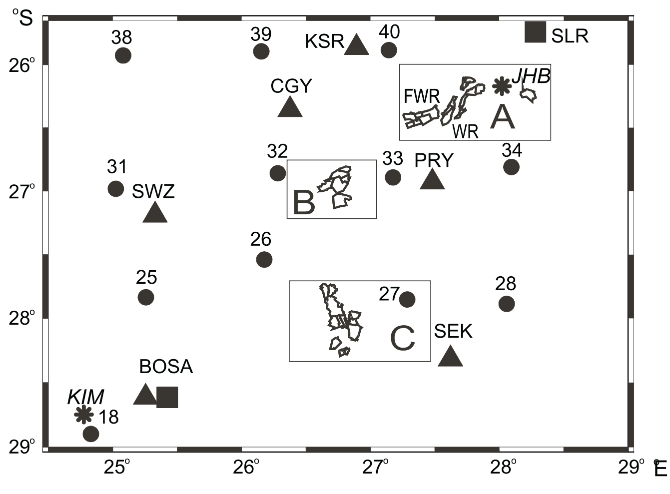

Fig. 2. Map of gold-mining areas on the margin of the Witwatersrand basin. A, Far West Rand, West Rand and Central and East Rand from west to east; B, Klerksdorp; C, Welkom; KIM, Kimberley; JHB, Johannesburg; FWR, Far West Rand; WR, West Rand. Numbers and circles denote stations of the Kaapvaal network. Three- or four-letter codes and triangles denote stations of SANSN. Permanent long-period or broad-band stations are shown as squares.

between mafic granulites and peridotites.[6] Average *Pn* and *Sn* wavespeeds are relatively uniform and high across the central and eastern regions of the Kaapvaal craton (8.35 km/s and 4.76 km/s, respectively), suggesting that the uppermost mantle is comprised of highly depleted magnesium-rich peridotites, though these wavespeeds decrease to the west and across the southern margin of the craton.[5,6,11] An analysis of crustal thicknesses from receiver functions in the Namaqua-Natal mobile belt and Cape Fold belt (Fig. 1) was provided by Harvey *et al.*[12]

The telemetered array of broadband instruments deployed around Kimberley was used to estimate the depths and sharpness of mantle discontinuities below the southern part of the Kaapvaal craton using signals converted from P to SV at the discontinuities.[13,14] Above the 410 km discontinuity, the average wavespeeds were found to be up to 5% higher than the global average, in agreement with the results of Simon *et al.*[7,8]

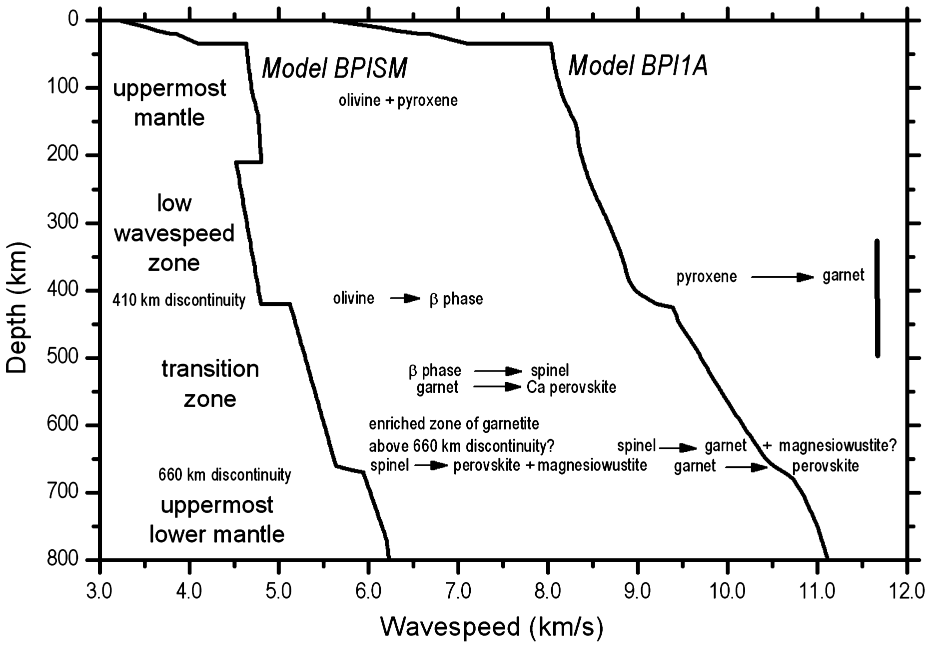

Fig. 3. Possible phase transformations occurring in the mantle superimposed on models BPISM (S waves) and BPI1A (P waves) for southern Africa (from Simon *et al.*[8]).

Seismicity studies

The Kaapvaal network provided a unique opportunity to study the seismicity of South Africa between April 1997 and April 1999. Work on the relocation of earthquakes listed in the CGS bulletins[1] and to locate additional earthquakes that do not appear in any catalogues is in progress. An important reason for undertaking the study of seismicity was to collect sufficient data to derive models of the crust and uppermost mantle using tomography to build on the preliminary work of Kwadiba *et al.*[11] Mining-induced tremors are generally located by the networks operated by the mining industry with errors no more than 400 m,[15] so that locations published in the CGS bulletins can be compared with those from the more extensive Kaapvaal network, assuming that the errors in the epicentres determined from the mine networks are small compared with the locations from the two other networks. In total, 429 such events of local magnitude greater than 2.5 were relocated using the software package HYPOELLIPSE.[16] The relocations made using data from the Kaapvaal network showed major improvements in accuracy compared with those made using SANSN.[15,17] Average errors of 1.56 ± 0.10 km and 9.50 ± 0.36 km were derived for the Kaapvaal network and SANSN, respectively. These results demonstrate the need for improved location capability of SANSN, so that location accuracies comparable with those obtained from the Kaapvaal network are routinely available. Relocations of tectonic earthquakes located by the SANSN using seismograms from the Kaapvaal network indicate larger mislocation errors than for the mine tremors.

The induced seismicity (maximum $M_L = 3$) associated with the impoundment of the Katse Dam in Lesotho, constructed as part of the Lesotho Highlands Water Project to provide water to South Africa, was analysed over the period November 1995 to March 1999 by Brandt.[18] Observed shear-wave splitting showed that the maximum horizontal stress in the upper crust around the dam lies parallel to the regional tectonic stress.

Developments in mine seismology

SIMRAC projects

Numerous SIMRAC projects in the areas of seismicity and rockbursts in gold and platinum mines were undertaken by various research agencies under the direction of SIMGAP (Safety in Mines, Gold and Platinum, SIMRAC's gold and platinum sub-committee).

The SIMRAC research is divided into four research areas: 1, understanding rock behaviour and assessment of the seismic risk; 2, prevention of seismicity; 3, controlling rockburst damage; and 4, technology transfer.

The following list highlights some of the most important findings of the first two research areas during the last four years. GAP is short for 'Gold and Platinum'.

GAP517 'Qualification of seismic hazard from seismic events in mines'.[19] The primary output of this project was a computer program called 'SeisHazM'. This program calculated and displayed the probability of occurrence of future seismic events in space and time on the mine plan.

GAP610 'Risk to personnel during continuous mining operations'.[20] The objective was to determine whether a difference in the seismic response of the rockmass between the traditional 11-day fortnight mining cycle and 'full calendar operations', namely, 'FULLCO'. The concept of 'seismic exposure' (SE) was developed to describe risk and the hazard was described by the 'potential damage area' (PDA).

GAP622 'Identifying rock mass discontinuities in a cloud of seismic event foci'.[21] A technique to interpret a cluster of seismic events in terms of causative structures was developed. The process consisted of moving the located hypocentres of events within their confidence ellipsoids until a simplified pattern of the seismic event cluster was obtained. The simplified pattern was then interpreted in terms of a fault, system of faults, or as a rock mass discontinuity.

GAP711 'Preliminary assessment of seismic risk in the Bushveld Complex platinum mines'.[22] The aim of this project was to identify conditions that constitute seismic hazards and to assess the risk associated with such hazards in the platinum mines of the Bushveld Igneous Complex.

In GAP303 'Mine layout, geological features and geological hazard',[23] several unique observations were made that contributed towards the development of a proposed improved mine layout design method and new interpretation of seismic data to confirm the design as mining progresses.

GAP524 'A study of rockburst source mechanism'.[24] This project involved detailed examination of a group of three rockburst structures or burst-fractures discovered in a VCR (Ventersdorp Contact Reef) stope panel on a peninsular remnant on Mponeng Mine at a depth of 2550 m below surface.

GAP603 'Fundamental aspects of the integration of seismic monitoring and numerical modelling'.[25] A major focus of recent research has been an integration of numerical modelling and seismicity. Integration is essential to improve the assessment of seismic hazards and the understanding of large-scale rock-mass deformation. In this project, special attention was paid to the ability of different models to emulate the basic patterns of mining-induced seismicity.

GAP604 'Routine moment tensor inversion for design of stabilizing pillars'.[26] During this project, a 'hybrid' moment tensor inversion method was developed. The theory, implementation and case studies are discussed in Andersen[27] and to a lesser extent in Andersen and Spottiswoode[28] and applied to clusters of events. The techniques attempted to compensate for various types of systematic error (or noise) that influence seismograms recorded in the underground environment in order to achieve an accurate and robust measure of the seismic moment tensor.

SIM (Safety in Mines) 02 03 04 'Improved seismic locations and location techniques' is a project currently being undertaken by S.M. Spottiswoode and L.M. Linzer. A hybrid location program 'MLOC' has been developed. The program uses both absolute and double-difference arrival-times,[30,31] to provide much improved absolute and relative locations by reducing the effect of the errors in the wave velocity of ray paths between each event and each geophone. Further improvements are obtained by using known locations, such as blasts.

Fifth International Symposium on Rockbursts and Seismicity in Mines

This symposium was held in South Africa in 2001. Because of the long history of dependence on 'local knowledge' in the mining industry around the world at the expense of reviewed research articles, papers in the symposium proceedings of this symposium arguably contain the best synthesis of the current state of knowledge in the field of mining-induced seismicity. Of particular interest was a series of 16 papers on the topic of 'Integration of modelling and (mostly seismic) monitoring'. Half of these papers were written or co-authored by South Africans and were summarized by Spottiswoode.[32]

DEEPMINE Programme

The DEEPMINE Programme was launched in July 1998 to create a technological and human resources platform which would make it possible to mine gold safely and profitably at depths of 3000 to 5000 m. One of the DEEPMINE projects focused on 'seismic management'. This project was divided into a number of tasks (sub-projects), in which the sub-tasks listed in Table 1 were investigated.

CSIR Miningtek internal projects

Several internal projects have also been undertaken by CSIR Miningtek. One project formed the basis of a Ph.D. thesis by Kataka,[33] who showed that an empirical Green's function and cross-correlation coefficients could be used as an indicator of the fracture plane for mining-induced earthquakes. He also extended the scaling laws found among natural earthquakes to mining-induced earthquakes and acoustic emissions. Some of the data used were from the I.A.S.P.E.I.-sponsored semi-controlled experiment conducted in the Western Deep Levels gold mine aimed at better understanding the physics of seismic sources. The experiment was a joint Japanese–South African project with the South African component organized by R.W.E. Green, formerly of the Bernard Price Institute of Geophysical Research, and A. Cichowicz, formerly of the Department of Geophysics, University of the Witwatersrand.

Table 1. Summary of DEEPMINE projects associated with mine seismicity.

Task 5.1	**Environmental definition/systems criteria**
Sub-task 5.1.1	The relationship between depth and seismicity
Sub-task 5.1.2	The relative effects on seismicity of mining by blasting or by continuous non-explosive. processes
Sub-task 5.1.3	The effect of rate of mining on seismicity
Task 5.2	**Prevention**
Sub-task 5.2.1	Integration of seismic monitoring and numerical modelling
Task 5.3	**Protection**
Task 5.4	**Prediction**
Sub-task 5.4.1	Review of current seismic prediction and hazard assessment practice and capability

Developments in probabilistic seismic hazard analysis

The recent developments in the Probabilistic Seismic Hazard Analysis (PSHA) procedure used by the CGS extend the earlier work of Kijko and Graham[34,35] and include 1, the development of a probabilistic procedure for the assessment of the maximum regional magnitude m_{max}; 2, the construction of a more realistic peak ground acceleration attenuation relationship which can be applied over very short distances, and 3, the incorporation of uncertainties in the model parameters.

Assessment of m_{max}

The value of the maximum magnitude considered in the PSHA approach is the same as that used by many earthquake engineers,[36] and complies with the meaning of this parameter as used, for example, by the Working Group on California Earthquake Probabilities,[37] Stein and Hanks[38], and Field *et al.*[39] This terminology assumes a sharp cut-off magnitude at a maximum magnitude m_{max}, so that, by definition, no earthquakes are to be expected with magnitude exceeding m_{max}.

The approach provides an evaluation of m_{max}, which is free from subjective assumptions and dependent only on seismic data. The procedure is generic and is capable of generating solutions in different forms, depending on the assumptions about the statistical distribution model and/or the information available on past seismicity. The procedure can also be applied in the extreme case when no information about the nature of the earthquake magnitude distribution is available, that is, the procedure is capable of generating an equation for m_{max}, which is independent of the particular frequency–magnitude distribution assumed. The procedure can also be used when the earthquake catalogue is incomplete, that is, when only a limited number of the largest magnitudes are available.

The normal PSHA approach is parametric and applicable when the empirical log-frequency-magnitude graph for the seismic series exhibits apparent linearity, starting from a certain minimum magnitude value. However, when (i) the empirical distributions of earthquake magnitudes are of bi- or multi-modal character, (ii) the log-frequency-magnitude relation has a strong non-linear component or (iii) the presence of 'characteristic' events (Schwartz and Coppersmith[40]) is evident, the analytical (parametric) models of the frequency-magnitude distributions are replaced by a non-parametric counterpart.

Attenuation relationships for short distances

Many attenuation relationships have a significant limitation in that they give unrealistic values for the ground motion parameter at short distances. The Council for Geoscience has developed an approach that will prohibit the saturation of the value of the ground motion parameter. It is based on the limited accuracy with which the coordinates of the earthquake hypocentre can be determined.

Uncertainty in model parameters

The Council for Geoscience developed a procedure for the assessment of the uncertainties in the model parameters, as part of the PSHA These include uncertainty in the attenuation relation and its parameters, namely earthquake magnitude and location. If the variability of the attenuation function is also included, one can determine the probability of exceedance for any selected value of acceleration. In addition, the maximum acceleration can be determined with a confidence level of 84%.

Other studies of seismic hazard

Hartnady[41] outlined briefly the seismic moment conservation idea[42] to calculate a maximum earthquake size as an alternative to PHSA, arguing that PHSA underestimates the probability of the rare large events. He also discussed this concept in relation to the Nubia–Somalia plate with its recurrence period of large earthquakes exceeding 1000 years, and its proximity to the South African cities of Durban and Pietermaritzburg.

Conclusions

Upgrades planned for SANSN include the gradual replacement of short-period instruments by broad-band instruments, thereby improving the location capability of the network. Records of earthquakes from the Kaapvaal broad-band network have allowed researchers in South Africa to make valuable contributions to the understanding of the structure of the crust, upper mantle and transition zone beneath southern Africa that has complemented work undertaken by American researchers. There is a relatively sharp boundary between the southern part of the Kaapvaal craton and the northern region influenced by the Bushveld magmatism in which there is an increase in crustal thickness due to underplating. The first continuous P and S wavespeed models from the surface to depths of 800 km have been derived for southern Africa. Mine tremors relocated using the Kaapvaal network are closer to the epicentres determined from mine seismic networks than those located by SANSN, indicating the need for a denser station distribution for SANSN.

Important advances in mine seismology and seismic hazard evaluation in gold and platinum mines sponsored by SIMRAC include the preliminary assessment of seismic risk in the platinum mines of the Bushveld Complex, the development of a new 'hybrid' moment tensor inversion method, and the integration of numerical modelling and seismicity. Studies of the influence of mining activities on seismicity, the prevention of induced seismicity, and the development of new approaches to rockburst prediction were also part of the DEEPMINE programme. Improvements have been made to the approach to estimating the maximum magnitudes of earthquakes to be expected in South Africa. Other advances include the construction of better peak ground acceleration attenuation relationships for short distances, and the estimation of uncertainties in the probabilistic model parameters.

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