IUGG QUADRENNIAL REPORT 2000 to 2003

South African Committee for the International Association of Hydrological Sciences

1. MEMBERS OF THE COMMITTEE

The current committee was elected through a postal vote during 1999 and finalized at the 9th South African National Hydrology Symposium held at the University of the Western Cape during November 1999. The members are as follows:

Chairman and National Representative
Prof Denis Hughes, Institute for Water Research, Rhodes University
Dr Peter Ashton, CSIR
Prof Gerrit Basson, Dept. of Civil Engineering, University of Stellenbosch
Mr Jean Boroto, Global Water Partnership, Harare
Prof Andre Görgens, Ninham Shand Inc., Cape Town
Dr Phillip Hobbs, Consultant Geohydrologist
Dr Graham Jewitt, School of Bioreseources Eng. & Environmental Hydrology, University of Natal, Pietermaritzburg
Prof Geoffrey Pegram, Dept. of Civil Engineering, University of Natal, Durban
Prof Roland Schulze, School of Bioreseources Eng. & Environmental Hydrology, University of Natal, Pietermaritzburg
Mr Renias Dube, Water Research Commission

Mr Dube replaced Mr Hugo Maaren who was a valued member of SANCIAHS since its inception but who unfortunately passed away during 2002. Prof Hughes and Dr Simon Lorentz (School of Bioreseources Eng. & Environmental Hydrology, University of Natal, Pietermaritzburg) have been elected as vice-presidents (unopposed) to the ICSW and ICT, respectively, while Prof Görgens has been nominated as a vice-president of ICWRS.

2. RESEARCH CONTRIBUTIONS

Since 1998 a great deal of the research in hydrology and water resources in South Africa has focused on supporting the National Water Act (NWA, 1998) of 1998, which involves a totally revised approach to water resource management within the country and places the emphasis on equity of water distribution, as well as environmental sustainability. This change in emphasis is reflected in the topics funded by the Water Research Commission over the period 1981 to 2000 (see Fig. 1). New areas of funding in 2000 include IWRM, water policy and water services, while conservation of water ecosystems also enjoyed a high priority. The Water Research Commission has recently restructured its support programme and funding now operates under five Key Strategic Areas; Water Resource Management (KSA 1), Water-Linked Ecosystems, (KSA 2) Water Use and Waste Management (KSA 3), Water Utilisation in Agriculture (KSA 4) and Water Centred Knowledge (KSA 5 – knowledge dissemination and information systems). In addition, four cross-cutting domains (Water and Society, Water and the Economy, Water and the Environment, Water and Health) have been established to draw together projects and programmes that are under way within each KSA.

Hughes (2002) reviewed some of the contemporary issues in hydrology and points out that a high proportion of hydrological research programmes in South Africa over the last few decades have been orientated towards the solution of practical water resource problems. While this may be seen as a criticism of the development of hydrology as a science, where the supply-side has dominated

at the expense of the demand-side, it was almost inevitable in a country with pressing water supply problems. One measure of the success of such programmes could be the extent to which they have prepared the country to respond to new challenges. The speed with which the hydrological community (in cooperation with other disciplines) has responded to the challenges of the new Water Act suggests that these programmes have been successful.

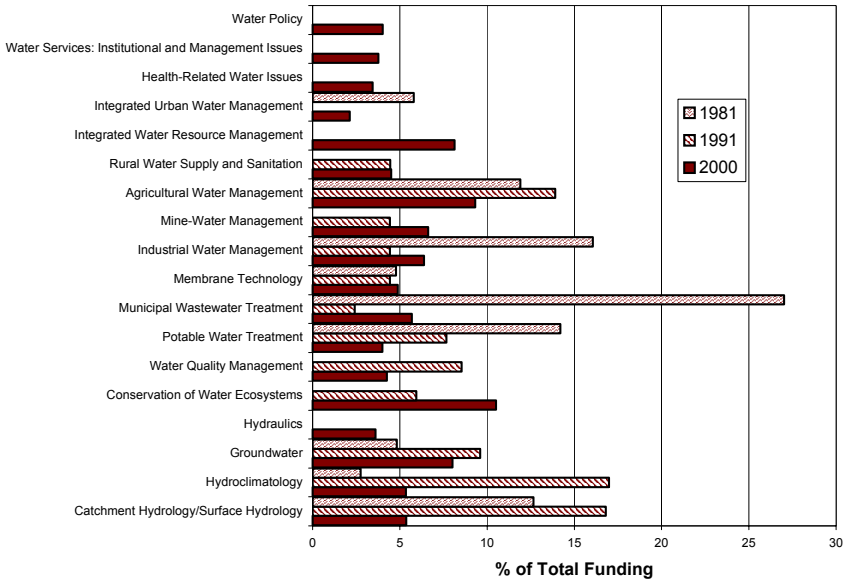

Figure 1 Water Research Commission funding: proportion of total funding divided amongst the sectors identified in the Annual Report for 2000

As models and any other hydrological tools become more and more sophisticated it becomes increasingly important for them to be supported by training and technical support programmes. This is especially true in a country such as South Africa that has a limited number of individuals or organisations undertaking development work, but a much larger group that needs to apply the methods. As South Africa moves toward a regionalised system of water resource management (through the establishment of Catchment Management Agencies- CMAs), the training requirements in the application of hydrological estimation methods will significantly increase. Unfortunately, the country appears to be experiencing shrinkage in technical capacity and the average age of practicing hydrologists is increasing, a situation that needs to be reversed as soon as possible.

The following sections highlight some of the research directions that have been dominant in the hydrological sciences within South Africa during the reporting period, while the 'Selected References' section illustrates some recent outputs in international journals and other sources. A great deal of the research undertaken in the hydrological sciences in South Africa is documented in Water Research Commission reports. Further information about past, current and future research programmes supported by the WRC can be found at their web site, which also includes lists of publications (http://www.wrc.org.za).

2.1 Hydrology and the ecological Reserve

The ecological Reserve is the quantity and quality of the flow regime of a river (or estuary, ground water or wetland) that is 'reserved' under the NWA for the purposes of sustaining the environment in a pre-determined condition. The determination of the Reserve has become a relatively complex multi-disciplinary process that also involves the stakeholders living near the resource. From a hydrological point of view, the introduction of the Reserve concept into South African water resource management provided a number of research challenges. It was soon discovered that the hydrological analysis tools to support the Reserve determination process were not available and had to be developed for practical application as a matter of some urgency. This problem has now largely been addressed and there are several well-developed model packages available to assist the ecological scientists in the process (Hughes, 2001; Hughes and Hannart, 2002). There remain several challenges related to the implementation of the Reserve by regional water management authorities. Some of the problems are of a technical nature and relate to the real-time determination of reservoir releases or abstraction curtailment, while others are of an institutional nature. Many of these are currently being investigated by various groups in cooperation with the Department of Water Affairs and Forestry.

2.2 Ground and surface water interactions

Traditionally within South Africa there has been a quite substantial divide between the two disciplines of ground and surface water hydrology. While this has been recognized as a not very satisfactory situation, it has proved difficult to resolve. The NWA calls for an integrated approach to water resource development and this has generated renewed interest in resolving issues related to surface-ground water interactions. One of the research programmes supported by the WRC over the last few years has been an investigation of the contribution that ground water discharge makes to low flows in rivers. One of the main purposes of this research is to determine the level of development of ground water resources that can be permitted without adversely impacting on the surface water resources. This has always been difficult to quantify in South Africa where the majority of the ground water is stored in fractured rock aquifers. Some progress is being made through an improvement in the understanding of the associated hydrological processes by scientists from both disciplines.

2.3 Rainfall-runoff modelling

South Africa has a long history of developing and, more specifically, the practical application of rainfall-runoff models for water resource estimation purposes. Recent initiatives in this field have involved the use of such models for the assessment of water use by managed forest plantations, the role that commercialisation can play in sustaining the development and support of models and associated software and the selection of the most appropriate models for use by the Catchment Management Agencies of the future. The Water Research Commission are also currently reviewing the available existing approaches with the intention of developing a strategy for future funding support. Once again the emphasis is on the practical use of scientific research in the field of water resource planning and management. During the 1990s the well-known Pitman monthly model was used to generate natural time series for 1946 so-called quaternary catchments covering the whole of South Africa, Lesotho and Swaziland. While not without problems, these data have provided the baseline information for a wide range of water resource assessments. Terms of reference are currently being developed to update this information and to extend the simulations to incorporate interactions between ground and surface water to enhance the countries ability to undertake integrated water resource planning. A similar project has been envisaged for the whole of southern Africa and terms of reference for such a study have already been accepted by the Southern African Development Community (SADC), Water Sector Coordination Unit (SADC, 2001). Financial support for this large and ambitious project is still being sought. From a research perspective, both the South African update and the SADC wide projects have the potential to promote improvements in a model that has been available and widely used

for about 30 years. Such improvements are likely to include the incorporation of a better understanding of natural processes, as well as artificial influences, and how to incorporate these into practical water resource management tools. The projects also offer an opportunity for improving the format of the model software and the way in which it links to existing databases.

Models (notably the ACRU model) have also been used to investigate issues such as the impact of land use changes on water resource availability (see section 2.5), as well as the possible effects of climate change.

2.4 Management of transboundary (shared) water resource systems

The last few years has seen a dramatic increase in the interest and concern expressed with regard to the importance of effective management of shared aquatic systems (both surface waters and ground water aquifers) throughout the world. These concerns are most acute in the more arid regions of the globe. Shared or transboundary aquatic systems in southern African have also attracted their share of attention and there is growing awareness amongst SADC water resource managers of the need to work collaboratively with their neighbours to ensure that shared water resources are used in an equitable and sustainable way. In southern Africa, most attention has been focussed on key river systems that span the territories of several countries that currently experience water stress or water shortages. Particular attention has been focussed on the Cunene, Incomati, Limpopo, Okavango, Orange and Zambezi systems. There is considerable international interest in the Okavango system, driven by a variety of local, national and international agendas. Specific concerns have been voiced around perceptions that basin states might undertake unilateral and/or "unfair" abstraction of water from the system with the possibility that this may give rise to disputes between basin states. As a result, considerable attention is being focussed on the development of a management plan for the entire Okavango basin. A selection of recent publications dealing with the management of transboundary (shared) river systems in southern Africa and options that can be considered to prevent conflict over access to water are listed at the end of this report.

2.5 Research related to streamflow reduction activities in South Africa

Land-uses that cause significant diffuse reductions in streamflows are currently controllable under the NWA (1998). While the only streamflow reduction (SFR) activity so far declared under the Act is commercial afforestation, other impacts such as sugar-cane cultivation and wide-spread catchment invasions by alien plants are also being investigated for this purpose. These have been important, yet not very well quantified, issues in South African water resource management for many years. The country is spending a great deal of time and money on the clearance of invasive alien plants which are known to use more water than indigenous species, but the effects of clearing have yet to be adequately quantified.

Recent published South African research in this field focused on three themes:

- Improved field-scale and catchment-scale experiments and high-tech monitoring of actual consumptive use of the relevant plants or plant categories, or of the downstream changes in streamflow or groundwater availability.
- Improvements to catchment or profile models to represent the impacts of the SFR activities at various spatial and temporal scales
- Evaluation of the relative magnitudes of SFRs in terms of utilisable yields from dams and complex river systems.

The ACRU model has played a major role in some of the studies related to streamflow reduction activities and has been enhanced through the development of new algorithms to handle such as tillage practices and the impacts of afforestation.

A number of publications on this topic were generated during the reporting period. Some of these are listed in the Selected Publications section below, while there are additional reports available from the Water Research Commission.

2.6 Design rainfall and flood estimation

Engineering project designs rely heavily on estimates of design floods and poor estimates have resulted in major loses to the economy, environment and human and animal life. Reliable estimates of floods, their peaks and the frequency of such peak flows and volumes have continued to challenge the hydrological practitioners. A recently completed study linked the techniques developed in previous project which concerned short and long duration design rainfall estimates. The techniques from these studies were further developed to give regionalised and actual hyetographs for South Africa and to produce a computer package for design rainfall estimation. The design rainfall estimation techniques were linked to the regionalised index-flood based design storm estimation methodology using L-moments at selected catchments. A Java based programme developed in this study implements the procedures developed in this study to enable users to estimate design rainfall at any location in South Africa for return periods of 2 to 100 years and for durations of 5 minutes to seven days.

There has been a long-term research programme (under Prof Pegram's leadership at the University of Natal, Durban) to look at various aspects of estimating spatial rainfall fields from radar data and combining this with information from ground based observations (raingauges) and satellites to generate improved estimates of spatial rainfall variations over the whole country.

2.7 Operational hydrology research

As the water requirements in the Orange River catchment continue to grow, the water is becoming ever more valuable. It is therefore becoming increasingly important to optimise the releases from impoundments, in order to supply the downstream demands whilst minimising any excess releases, so as to conserve the valuable resource. The major difficulty in optimising reservoir releases is that it can take several weeks for water released from upstream to reach the river mouth where the domestic, industrial and environmental demands must be satisfied. The time taken for the releases to reach the mouth depends on the prevailing conditions in the river in relation to the amount of water released. Releases during low flow conditions may take up to 6 weeks to reach the mouth. It is evident that there can be no quick relief from any shortages that might be experienced along the lower Orange River through additional releases. Due to the nature of these demands any water shortages would have a major impact, both economic and environmental. A project has recently been completed that has developed a decision support tool to be used by the reservoir operators. The strategy determined in this study will provide a rational basis for the operators of upstream dams to determine a discharge release pattern to ensure that the various demands downstream are satisfied. As the model is based on sound hydraulic principles rather than simplified routing methods the users can be confident in the simulated results, provided that the real time data are accurate and available. The use of real time data further improves the simulation because unmodelled events such as localised inflows can be taken into account.

Issues related to the incorporation of the Reserve and an allowance for environmental flow requirements in real time water resource management also fall within this section. Research on such issues has lagged behind research on the methods of determining the requirements from an ecological point of view, but the pressure to implement is such that there is an urgency to solve the problems. Many of the problems are not of a technical nature, but more related to the institutional issues surrounding a change in the procedures used to manage water resources.

3. CONFERENCES and SYMPOSIA

The ***Fourth International Conference on FRIEND*** (Flow Regimes from International Experimental and Network Data) with the theme 'Bridging the gap between research and practice' was held in Cape Town during March 2002. The conference was financially supported by UNESCO, IAHS, WMO, UK DFID, the IHP National Committees of Germany, the Netherlands and Japan, the French Ministry of Foreign Affairs and IRD (Institut de Recherche pour le Dévelopment), while the Institute for Water Research were responsible for the local organization. A large part of the financial sponsorship contributed towards the costs of attending the conference by some 60 delegates from developing countries throughout the world. A total of 130 delegates attended the conference from more than 35 countries. A wide variety of papers were offered covering issues of water scarcity, managing hydrological risks, regional water resource problems and sustaining ecological functioning. All the papers were refereed and pre-published in an IAHS red book (No. 274), which was edited by Henny van Lanen and Siegfried Demuth. A workshop on Hydrology and Poverty Alleviation was held during the conference.

The ***2nd International Symposium on Integrated Water Resources Management*** was held in Stellenbosch during January 2003. This conference was well attended with delegates from several European Countries, USA and Australia apart from many 'local' delegates from Southern Africa and some from East Africa. The papers presented covered a wide range of topics from the technical aspects of managing water resources, through information systems and decision support tools to the more social aspects of community involvement in water management.

The ***10th National Hydrology Symposium*** was held at the University of Natal, Pietermaritzburg during September 2001 and this saw the inauguration of the Des Midgley Memorial Lecture (given by Prof. Hughes on Practical problems associated with the implementation of the ecological reserve for rivers). Prof Des Midgley has been considered as the 'father' of South African Engineering Hydrology and many of the senior hydrologists in the country today were students of his at one time. During the conference dinner, Hugo Maaren and Eberhard Braune (past Chairman of SANCIAHS) were honored for their contributions to the development of SANCIAHS and maintaining links between the South African hydrological community and the international community during the years of isolation.

The ***11th National Hydrology Symposium*** is scheduled to be held in Port Elizabeth during September 2003 and will be structured with a series of very focused workshops together with more general plenary sessions. Some of the workshop sessions that are planned include discussions of the potential for commercialization of model and software developments, interactions between surface and ground water and the shrinking technical capacity being experienced by some South African organizations.

4. SELECTED PUBLICATIONS

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

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Abstract

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 focussed 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 thrust has been towards the integration of numerical modelling and seismicity. Developments in probabilistic seismic hazard analysis have emphasised the better 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 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 Graham.[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 broadband seismic network of 84 stations deployed across southern Africa between April 1997 and April 1999 (Figure 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 in 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 (Figure 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 Council for Scientific and Industrial Research (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 USA 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 summarises some of the relevant SIMRAC (Safety in Mines Research Advisory Committee), DEEPMINE and internal CSIR (Council for Scientific and Industrial Research) 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 Council for Geoscience and some other organizations are involved in palaeoseismic and neotectonic studies.

The objective of this article is to provide 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 have also been given.

Changes to South African National Seismograph Network

SANSN has throughout the years been comprised of approximately 25 seismological stations which are scattered around the country (Figure 1). Since the majority of these stations were installed in the '70's and early '80's, there has been a recent move towards upgrading and restructuring the entire SANSN. 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 as it requires sufficient funding, and, in a bid to reduce the costs involved in the upgrading process, in-house designed and constructed seismograph systems (EARS, short for Event Acquisition Recording System) have been installed and will continue to be installed in the future. The first EARS systems were installed in the late '80's and early '90's 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 digitisers (16 bit to 24 bit).

To reduce the risk involved in investing in just one type of technology, the Council for Geoscience (CGS) 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.

The majority 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 a number of broad-band seismometers (15) 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.

Accompanying all these advances in the instrumentation, the Council for Geoscience 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 utilised 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 Council for Geoscience. 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.[7,8,9] 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 (Figure 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 2.05Ga, 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 estimated 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 boundary between the petrological crust-mantle boundary 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 (Figure 1) was provided by Harvey et al..[12]

The telemetered array of broad-band 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]

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 Council for Geoscience 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 Council for Geoscience 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 other two networks. 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.

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.

SIMRAC projects

Numerous SIMRAC projects in the areas of seismicity and rockbursts in gold and platinum mines were undertaken by a number of different 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, *viz*.

1. Understanding rock behaviour and assessment of the seismic risk.

2. Prevention of seismicity.

3. Controlling rockburst damage.

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' *viz*. '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 methodology 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 3 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 2550m below surface.

GAP603 ‘Fundamental aspects of the integration of seismic monitoring and numerical modelling’.[25] A major thrust of recent research has been towards the 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 for 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 in progress 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.

Deleted: ¶

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 papers, papers in the proceedings of this symposium arguably contains 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 the data used was 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 Prof R.W.E. Green, formerly BPI Geophysics, and Dr. A. Cichowicz, formerly Department of Geophysics, University of the Witwatersrand.

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:

(i) The development of a probabilistic procedure for the assessment of the maximum regional magnitude $m_{\max}$,

(ii) The construction of a more realistic peak ground acceleration attenuation relationship which can be applied over very short distances and,

(iii) 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 (WGCEP, 1995),[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 which is 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, i.e. 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, i.e. 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 **C**ouncil for Geoscience developed a procedure for the assessment of the uncertainties in the model parameters, as part of the probabilistic seismic hazard analysis. 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] dicussed 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 discusses 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.

Acknowledgments

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Figure Captions

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 from 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 broad-band stations of the Global Digital Seismic Network.

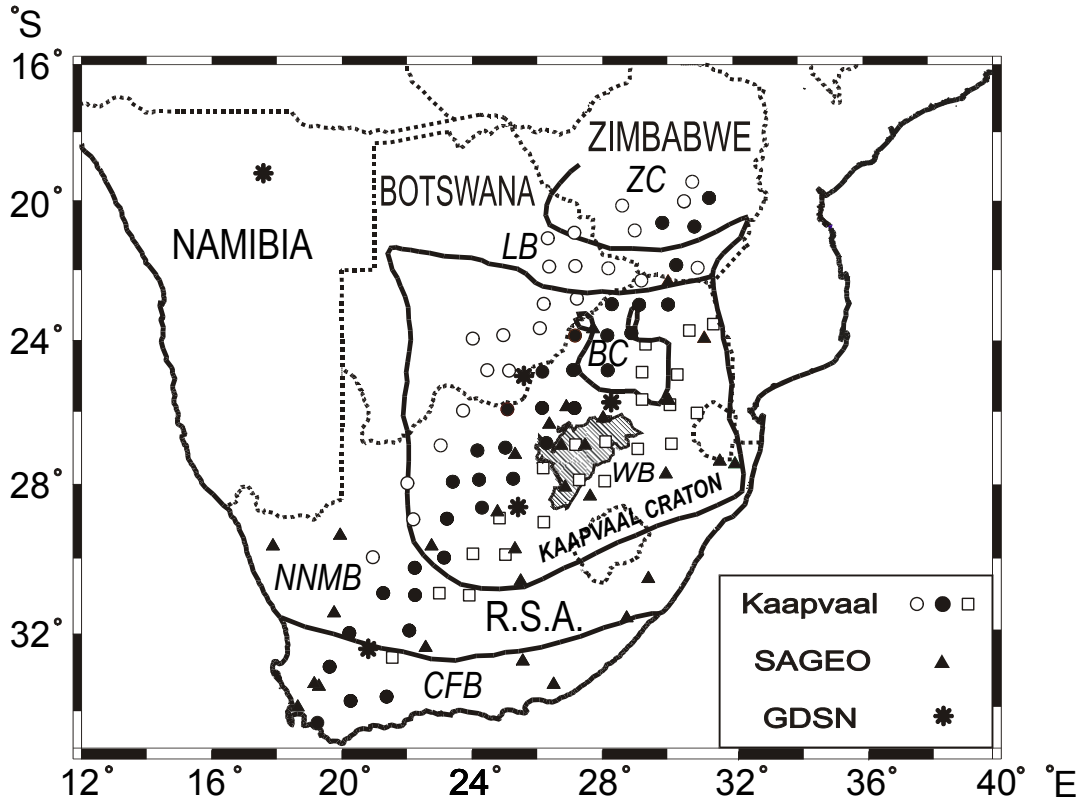
Fig. 2. Map of gold-mining areas on the margin of the Witwatersrand basin. A: Far West Rand, West Rand and Central and East Rand from west to east. B: Klerksdorp. C: Welkom. KIM: Kimberley. JHB: Johannesburg. FWR: Far West Rand. WR: West Rand. Numbers and circles denote stations of the Kaapvaal network.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

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

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:	current seismic prediction and hazard assessment practice and capability.

Figure 1


°S
16°
20°
24°
28°
32°
ZIMBABWE
ZC
BOTSWANA
NAMIBIA
LB
BC
WB
KAAPVAAL CRATON
NNMB
R.S.A.
CFB
Kaapvaal
SAGEO
GDSN
12°
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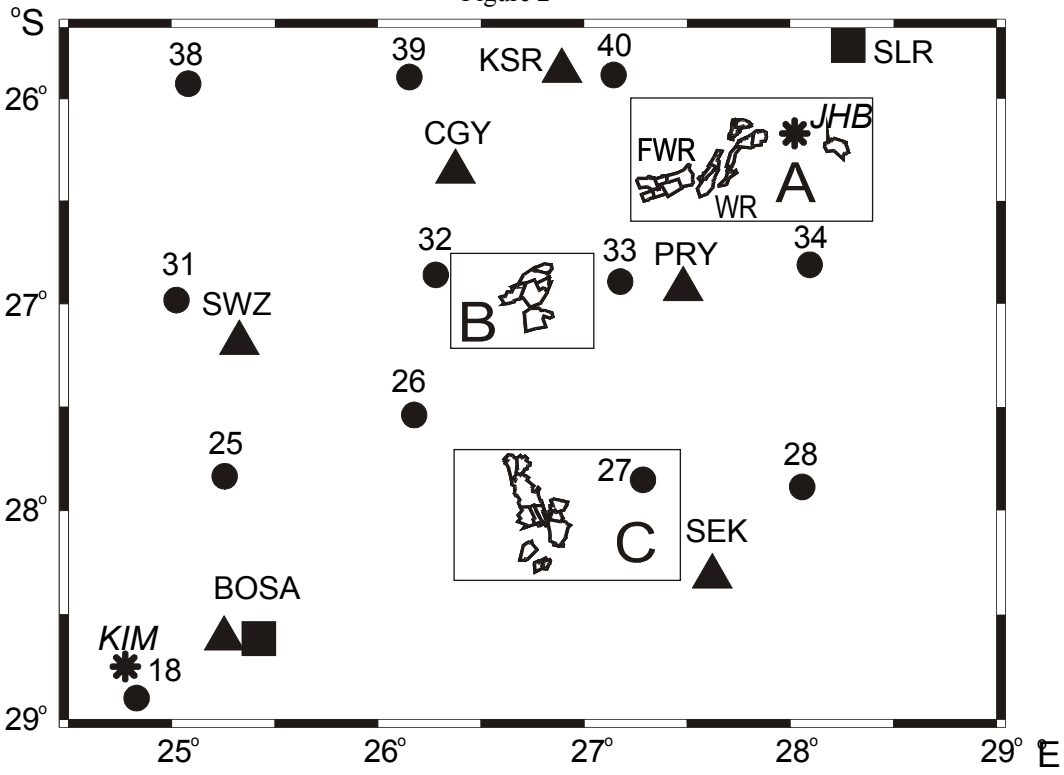
28°
32°
36°
40°
°E

Figure 2


°S
38
39
KSR
40
SLR
26°
CGY
JHB
FWR
WR
A
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26
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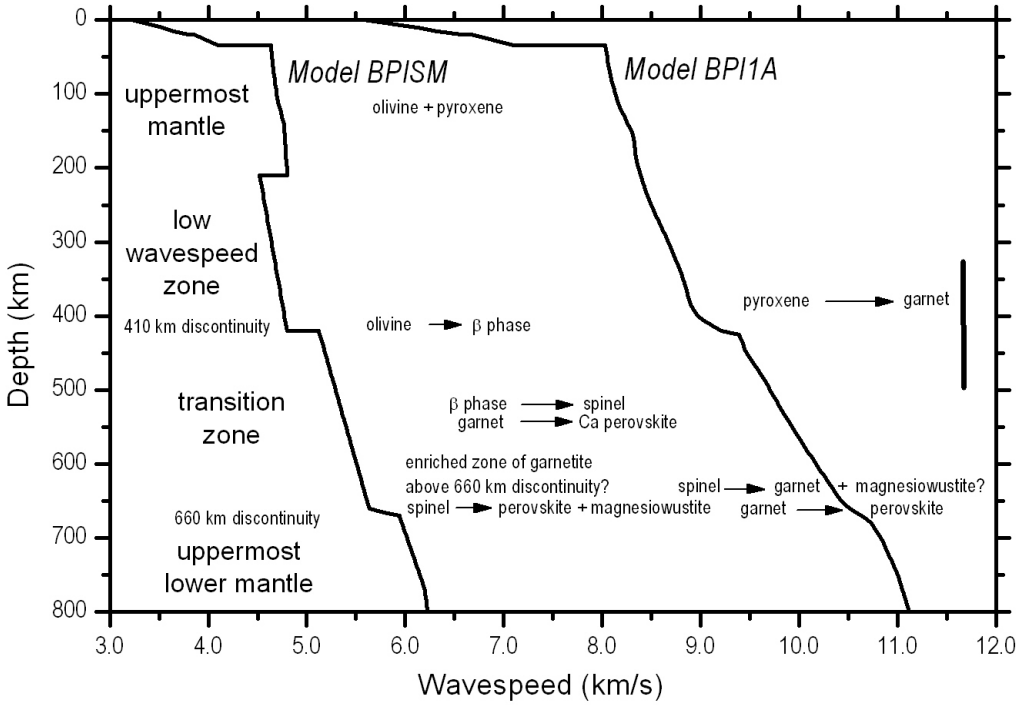
Figure 3


Model BPISM
Model BPI1A
uppermost mantle
olivine + pyroxene
low wavespeed zone
410 km discontinuity
olivine → β phase
pyroxene → garnet
transition zone
β phase → spinel
garnet → Ca perovskite
enriched zone of garnetite
above 660 km discontinuity?
spinel → perovskite + magnesiowustite
spinel → garnet + magnesiowustite?
garnet → perovskite
660 km discontinuity
uppermost lower mantle
Depth (km)
Wavespeed (km/s)
0
100
200
300
400
500
600
700
800
3.0
4.0
5.0
6.0
7.0
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10.0
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Review of South African research on volcanic and related rocks and mantle-derived materials: 1999-2002

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This report reviews South African research relating to the scientific interests of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and which was published between in 1999 through 2002. The focus is on published research and does not include conference presentations and abstract volumes or other informal documents. As a previous National Correspondent[1] has noted it is not easy to determine what precisely is covered by "South African research" and the "scientific interests of IAVCEI". In compiling this report, one approach I could have adopted would be to include all research of any igneous or volcanic flavour. Another is to aim at comprehensive coverage but to select on the basis of research results which I perceive to be of interest to the broader IAVCEI membership. As an example, consider an Archaean pyroclastic deposit. A paper focused on the description and emplacement of the deposit would clearly fall within the interests of IAVCEI. If the deposit has been tectonized and metamorphosed and is mentioned briefly in a paper whose main focus is the dating of zircons recovered from the unit, then it is legitimate to consider the paper to have little relevance to global IAVCEI membership. However, the timing of volcanism and associated igneous activity in relation to tectonism is of considerable interest to our understanding of temporal trends in global volcanism and tectonics, a topic falling within the broad interests of IAVCEI members and, on balance, might be included in the report to IAVCEI. In this context this review does report on papers concerned with dating of volcanic and igneous rocks.

Apart from research on volcanic rocks and associated intrusions this review also reports on inclusions of deep origin contained in kimberlite and other rare alkaline rocks as they are a rich source of information on the chemistry of the Earth's interior. Work carried out by South African-based scientists in contiguous countries as well as in the oceanic environment surrounding South Africa is also covered. I have not reported research on South African rocks carried out exclusively by scientists based in other countries, as this work is expected to be reflected by the reports from the National Correspondent of those countries. Much of such work is, however, published in collaboration with South African scientists and is included here.

Most of the material in the report is organized according to geological time periods starting with the Archaean. The exceptions are carbonatitic and kimberlitic rocks and associated materials which are discussed together regardless of age. Some published research has probably been inadvertently omitted, but for some the omission is on the basis of a judgement of relevance. Such omissions are minor and do not detract from the overall impact of this review as a statement of the research achievements of South African scientists from 1999 to 2000.

Archaean Greenstones, Komatiites, and Granitoid rocks

These are complex entities involving volcanism and plutonism and allied structural deformation and metamorphism. Much of the research carried out is by necessity of a multidisciplinary nature, including age dating.

The 3.48 Ga Komati Formation Barberton was mapped by Dann[2] on a scale of 1:5 000 with special attention to detailed mapping of chill-bounded cooling units and to defining volcanic, intrusive and tectonic contacts. This mapping

allowed the magmatic architecture of the Komati Formation to be established. The formation consists of a lower sequence of komatiitic sheet flows emplaced in a lava-plain setting, followed by pillowed komatiites emplaced in a more irregular topographic environment, possibly caused by faulting. The sequence is intruded by pyroxene-spinifex-textured sills, but the wherlite dykes are younger than the Komati and overlying Hoogenoeg Formations. Thus the komatiites do not have a feeder dyke system analogous to post-Archaean ophiolites. Cloete [3] also gives a detailed account of the volcanology and geochemistry of the komatiitic eruptives and concluded that they have attributes akin to modern oceanic plateaux rather than typical mid ocean ridge crust. His work is also concerned with primary sea floor alteration of the komatiites.

Anhaeuser [4] argues that the more metamorphosed komatiites and komatiitic basalts of the Nelshoogte Schist Belt and associated intrusions represent a younger (ca 3250 Ma) ultramafic volcanic event and he also rejects previous proposals that these rocks are similar to Phanerozoic ophiolites.

A number of studies report single zircon ages for a variety of granitic rocks in the greenstone belts. These ages are important in providing a temporal framework for the evolution of the belts. Hence Poujol and Robb[5] demonstrate that the granitic magmatism was contemporaneous with the deposition of the 3-09-2.97 Ga Murchison greenstone belt and extended to younger ages of 2.85 Ga. This was subsequently extended to an even younger age of 2680 Ma[6] . In the Pietersburg greenstone terrane felsic volcanism is dated at 2949.7 +/- 0.2 Ma[7] indicating that it is coeval with felsic volcanism in the Murchison Belt to the east. A granite intruding the greenstone is dated at 2853 +/- 18 Ma. In addition, the associated Turfloop Batholith was emplaced at about 2.78 Ga on the basis of U-Pb, Sm-Nd and Rb-Sr dating [8] and has an origin in the lower Archaean crust. In the Amalia-Kraaipan greenstone belt in the western Kaapvaal craton, the earliest tonalites and trondhjemites as varying in age from 3162+/-8 to 3070+/-7 Ma and the youngest pluton , the Mosita adamellite, is dated at 2749+/-3 Ma[9] . In the same area, Poujol et al.[10] have dated granite magmatism varying from ca 3008 Ma (trondhjemitic) to 2791 Ma (granodioritic). These new results suggest a temporal correlation of the youngest granitoid activity with the emplacement of the Gaborone Granite Complex in Botswana. In the Giyani greenstone belt meta andesites have yielded an age of 3203.3+/-0.2 Ma and younger intrusive quartz porphyries have an age of 2874.1+/- 0.2 Ma [7]. In the Johannesburg Dome a variety of trondhjemitic and granitic rocks yield single zircon U/Pb ages from 3340+/-3 Ma in the north to 3114+/-2.3 Ma in the S[11]. Similar age ranges were obtained using a variety of dating techniques by Barton et al [12].

Archaean Supracrustal Sequences

The oldest supracrustal sequence in the Kaapvaal craton is the Pongola Supergroup with a lower Nsuze Group of volcanic and sedimentary rocks and an overlying siliclastic Mozaan Group. Gutzmer et al.[13] report an age of 2837+/- 5 Ma for quartz porphyry sill intruded into these sediments and deformed with them.

The Late Archaean Ventersdorp Supergroup continues to attract attention. It consists of basal formations of mafic lava overlain by a clastic wedge deposit, the Kameeldoorns Formation, which formed in grabens. Intermediate to felsic ash-flow deposits of the Makwassie and Goedgenoeg Formations overlie these sediments. Large spherical structures and clasts have been described at the base of the Makwassie Formation at T'kuip in the Northern Cape Province[14] and are ascribed to eruption of the hot ash-flow onto water-saturated sediments. De Bruiyn et al. [15] also report on the geochemistry of alteration of andesitic and basaltic andesite lavas of the uppermost Allanridge Formation. Such studies are important for effective use of geochemistry in petrogenetic studies on these old sequences. Hall and Els[16] report on lava - soft sediment interactions at the base of the Ventersdorp Supergroup. Features such as sediment injection into lava, "ball and pillow" structures in lava, and soft sediment deformation are described. These features developed during dewatering of the sediments in response to differential loading of the sediments by the

overlying lava.

Palaeoproterozoic

Oberholzer and Eriksson[17] describe the volcanic sequence in the Palaeoproterozoic Hekpoort Formation of the Transvaal Supergroup as consisting of equal volumes of basaltic-andesite lava flows and intercalated with volcaniclastic rocks emplaced in a subaerial intracratonic setting. The volcaniclastic rocks are thought to represent a variety of pyroclastic flow and laharic deposits. In a paper which is significant for correlation of the Kheis and Magondi mobile belts as components of a extensive Palaeoproterozoic orogen in southern Africa, McCourt et al.[18] report an age of 1997.5 +/-2.6 Ma for the syn kinematic Hurungwe granite, Zimbabwe. This age invalidates the Kheis-Magondi correlation.

The Bushveld Magmatic Province

The Bushveld Complex is purported to be the largest continental layered mafic-ultramafic intrusion (Rustenberg Layered Suite) and is associated with coeval mafic and silicic volcanic suites (the Rooiberg Group) and intrusive granites (Lebowa Granite Suite). Collectively these suites form the Bushveld Magmatic Province. The enormous metal reserves (platinum group elements (PGEs), Cr, Ti, Fe) in the complex has ensured that it is the target of much research. The South African Journal of Geology published two Special Issues largely relating to the Bushveld Complex. The first, edited by Cawthorn[19] , commemorated the 75th anniversary of the discovery of the Merensky Reef, and the second, edited by Maier [20] , was directed at Platinum group minerals and elements. Not all of the papers in these two volumes fall within the interests of IAVCEI

Bushveld magmatism was initiated by eruption of basaltic andesites and felsic volcanic rocks of the Dullstroom Formation, the lowest formation of the Rooiberg Group. Buchanan *et al.* [21] demonstrate that the mafic rocks can be divided into a high- and low-Ti lineage with strong compositional similarities to the Mesozoic Karoo flood basalt geochemical types. They suggest that a mantle plume was responsible for the mafic volcanism and present petrogenetic models involving magma mixing and assimilation to account for the compositional variability. Associated high-Mg felsic rocks in the Dullstroom Formation, as well as siliceous to intermediate rocks in the upper part of the Rooiberg Group, are derived from the low-Ti mafic magmas by assimilation of crustal material and fractional crystallization (AFC) in shallow magma chambers [22].

Maier *et al.* [23] use the PGE geochemistry of the ultramafic Pyroxenite Marker within the mafic Main Zone of the Bushveld complex to constrain a model for the formation of this zone. In a study using mineral composition reversal and whole-rock compositional trends within the vicinity of the Pyroxenite Marker, Nex *et al.* [24] examine the processes of magma addition to the Main Zone. The transition from the Critical to Main Zones is believed to exist in the vicinity of the Giant Mottled Anorthosite but has not been pinpointed precisely. Mitchell and Manthree [25] investigate this problem and develop a model for the emplacement of the Main Zone.

The Merensky Reef in the top of the Critical Zone is arguably the most famous horizon within the Bushveld Complex. A number of papers [26,27,28,29,30,31,32] address problems of geology, mineralogy, and geochemistry of the reef and discuss implications for its origin. The development of cyclic units in the Critical Zone below the Merensky Reef is ascribed by Cawthorn [33] to crystal sorting during settling.

In broader studies, Maier and Barnes [34] analyzed for PGEs in a wide range of silicate rocks through the complex in an attempt to constrain ore forming processes within the intrusion. Eales [35] examined the Cr budget in the western Bushveld and demonstrated that the amount of chromite in the rocks exceeds the Cr solubility of mafic magmas and suggests that the magmas emplaced into the Bushveld chamber were carrying up to 3% chromite as microphenocrysts. Willmore *et al.* [36,37] have investigated halogen geochemistry of the Bushveld and identify correlations of Cl/F ratio with a number of geochemical and mineralogical trends through the complex. Bushveld magmas appear to have been unusually enriched in Cl, and all evidence points to the halogens being a primary magmatic component and not derived by assimilation of,

or infiltration from, country rocks. Separation of Cl-rich fluids have played a role in mineralization in the Lower and Critical Zones. This is supported by chlorine isotopes . Maier *et al.* [38] report on a wide ranging Nd-isotope study of the Bushveld complex which supports older Sr-isotope data indicating a large crustal component in the upper part of the intrusion. The isotopic data are decoupled from highly incompatible element concentrations. This is interpreted in terms of changes in the nature of the crustal assimilant with evolution of the complex. Contamination by crust, including unusual compositions such as dolomite, are also indicated in the work of Harris and Chaumba [39] on the Platreef in the Northern Limb of the Bushveld Complex.

A structural study relating to mechanisms of intrusion of the Rustenberg Layered Suite along its southwestern margin (Spruitfontein Inlier) was documented by Clarke *et al.* [40] .

Discordant ultramafic iron-rich pegmatoidal bodies are common in the Rustenberg Layered Suite and their origin and petrogenesis is controversial. A detailed study [41] on the Tweefontein pipe indicates that it was magmatically intruded when the layered rocks were still extremely hot and that it is a magmatic as opposed to metasomatic feature. The pipe magmas are not residual liquids derived from adjacent layered rock, but distinct magma batches in their own right. Reid and Basson [42] focused on similar bodies replacing the Merensky Reef at Northam Platinum Mine. They conclude that the pegmatoid bodies result from replacement of pre-existing rocks by residual melts migrating from the upper Critical Zone. Scoon and Eales [43] showed that spinels in the pegmatoids can be divided into three types and that there is a relationship between spinel type and stratigraphic height. The composition of the Fe-Ti-Cr spinels is not duplicated by cumulus spinels in the layered rocks but the disseminated Ti-magnetites are very similar to that found in the Upper Zone.

Minor intrusions associated with the Bushveld Complex include the Uitkomst Complex and numerous mafic-ultramafic sills in the footwall of the Bushveld Complex. Using olivine compositions and sulphur isotopes Li *et al.* [44] present a model for multiple intrusion emplacement of the Uitkomst complex which is consistent with it being a conduit to the Bushveld Complex as proposed by Gauert [45] . Age and geochemical similarities between the Uitkomst complex and a diorite intrusive into the Marble Hall fragment suggest that there is a genetic link between the two and has led De Waal and Armstrong [46] to define a new magma type (Bu-type) which preceded the emplacement of the Bushveld B1-type magma and which may also have been significant in a number of sub-Rustenberg Layered Suite intrusions such as the Lindequesdrift, Roodekraal, and Rietfontein complexes. The nature of the Bushveld magmas is also discussed by Eales [47]. Maier *et al.*[48] discuss PGE mineralization of ultramafic footwall sills exposed around the eastern margin of the complex.

Maier and Barnes [49] investigate the origin of the Cu-sulphide deposits associated with mafic-ultramafic intrusive bodies, 2.0-2.3 Ga in age, in the Curaçá Valley, Brazil. These intrusions have been emplaced in a high-grade metamorphic terrane and as such resemble the O'okiep deposits in western South Africa.

Although strictly an Archaean intrusion, research on the Great Dyke of Zimbabwe is reported here because of its similarities to the Bushveld Complex. Wilson and Prendergast [50] have reviewed the magma evolution and magma chamber structure of the Great Dyke with emphasis on implications for PGE mineralization. In more detail Wilson [51] and Wilson *et al.* [52] report on geology, mineralogy and geochemistry of the Selukwe subchamber of the Great Dyke, Zimbabwe. The zone of PGE enrichment is associated with sharp compositional changes in orthopyroxene, and the layered subzones, characterized by different PGE contents, may reflect original liquid layering in the chamber.

Mesoproterozoic

Research results are of two types - petrogenetic studies on igneous intrusions and volcanic sequences and dating of intrusive and extrusive rocks with the aim to constrain correlations and the tectonic and metamorphic evolution of mobile belts. In the latter category fall the work

of Gutzmer *et al.*[53] on the Koras bimodal volcanic suite and Mendonidis *et al.*[54] on the Glenmore granite, Kwazulu-Natal South Coast. Petrogenetic studies include that of Kruger *et al.*[55] who describe the petrology and geochemistry of the 1.1 Ga Oranjekom Complex of layered gabbronorites and anorthosite. The Oranjekom magmas were derived from a depleted mantle source and were Al-rich. Differentiation took place by sorting of mafic phases with plagioclase remaining largely suspended. Evans *et al.* [56] investigated the petrogenesis of the 1.0 Ga Tete complex in NW Mozambique. Magmas forming this complex were also derived from depleted mantle sources with little evidence of crustal contamination and were emplaced at shallow levels in the upper crust with differentiation to form gabbroic, pyroxenitic and anorthositic rocks. Maier *et al.* [57] repot on PGE-mineralization in this complex

South African-based scientists have also been involved in research related to the 1.33 Ga Voisey's Bay troctolite-gabbro intrusion and associated Ni-Cu-Co sulphide deposits in Canada. These involve Nd-Sr-Pb isotopes and crustal assimilation [58] , melting of gneiss inclusions in the ore-associated breccia [59] , comparison of Voisey's Bay and the Mushuau intrusion [60] , the oxygen isotope geochemistry of Voisey's Bay intrusion [61], the oxygen fugacity during sulphide segregation [62], and the Re-Os isotope systematics of the intrusion with implications for parental magma chemistry and ore genesis [63] .

Neoproterozoic.

Research on Neoproterozoic rocks essentially concerns granite magmatism, especially the precise dating of magmatic activity. In South Africa Frimmel *et al.* [64] report ages ranging from 833+/-2 Ma through to 741+/-6Ma for various components of the felsic extrusive and intrusive Richtersveld Igneous Complex, northwestern South Africa. This magmatism developed in accordance with crustal thinning over a mantle plume. Also in this area are the post-orogenic alkaline granites of the Kuboos-Bremen line of intrusions trending NE from northwest South Africa into southern Namibia. One of the largest plutons is the Kuboos pluton which intrudes the Pan-African Gariep belt whose main phase of deformation occurred at 545+/-2 Ma. Frimmel *et al.*[65] reports a U/Pb age of 507+/-6 Ma for the youngest intrusive phase of this pluton. Scheepers and co-workers have focused on the 515-552 Ma Cape granite suite intrusive into the Pan-African mobile belt in the south western part of the Western Cape Province. They report broadly synchronous SHRIMP ages of 547+/-6 Ma for the early syntectonic Darling granite and 536+/-5 Ma for the post-tectonic Robertson granite [66]. Nd isotopes suggest that both granites were derived form Mesoproterozoic crustal sources. This range of ages for granite activity was extended by subsequent SHRIMP age determinations on 3 granites comprising the Saldanha batholith, believed to be amongst the oldest of the Cape Granite Suite [67]. Ages obtained range from 552+/-4 Ma to 539+/-4 Ma . Scheepers and Nortje [68] describe rhyolitic ignimbrites at Postberg, associated with the Saldanha batholith and Scheepers and Pojoul [69] discuss their geochemistry and petrogenesis and demonstrate by a single zircon age of 515+/- 3 Ma that they represent the final phase of Cape Granite suite magmatism. A detailed petrogenetic study of the Malmesbury batholith was published by Siegfried[70] . He showed that the batholith is built of seven granitoid intrusions derived largely from a mafic igneous source by fractional crystallization with crustal assimilation.

Further afield, Handke *et al.* [71] report U-Pb zircon and baddeleyite ages of 804-779 Ma for 11 coeval gabbroic and granitoid intrusions of along a 450 km belt in Madagascar. Yibas *et al.* [72] report U-Pb ages of 880-526 Ma granitoids in Ethiopia. In a petrogenetic study Harris and Ashwal [73] report results of an O-isotope study on the 750 Ma Seychelles granites indicating that the Mahé types was derived from juvenile mafic to intermediate crust, whereas the Praslin type was derived from a source which was a mixture of this crust and older crust which acquired its low $*^{18}O$ significantly before granite genesis.

Mesozoic Volcanism

Karoo Flood Basalt Province

Most publications focus on the intrusive element of this classic continental flood basalt province (CFB). Chevallier and Woddford [74] analyzed a large amount of field data for 3 sill-ring complexes in the western Karoo basin, South Africa. They show that these structures are complex and built of stacked saucer-like intrusions (inclined sheets) interlinked with flat inner and outer sills and arcuate dykes. Their work shows that emplacement of these complexes is initiated from dykes which feed the inclined sheets. These then propagate into the outer sill and then into the inner sill. The implications are that the sheets are an integral part of the feeding system to the subaerial lavas.

In an analysis of magma flow directions at the mineralized Insizwa intrusion using the AMS technique, Ferre *et al*. [75] show that magnetic and mineral lineations coincide and represent magma flow directions. Furthermore, the intrusion is built by multiple injection events from a lower level located to the SE of the Insizwa massif. In a paper focused on the Ni-Cu-PGE potential of Insizwa, Maier *et al*. [76] show that the magmas feeding the intrusion were depleted in PGE before emplacement and contained no entrained sulphide. They indicate little potential for an economic deposit associated with Insizwa. Expanding this work to the lavas of the Karoo province and other CFB sequence of all ages in southern Africa, these authors [77] find that all the flood basalts are depleted in PGE relative to Cu, except the oldest (Dominion, Ventersdorp). They conclude that the data are consistent with minor sulphide segregation during ascent and that these CFBs have to be considered poor exploration targets.

The behaviour of lava flows is addressed by De Bruiyn *et al.*[78] who present evidence of flow concentration of olivine phenocrysts in a basalt flows high in the sequence in Lesotho to produce a picritic core to the flow. Such evidence is important in accounting for olivine-rich layers within large differentiated intrusions such as Insizwa. In the Sabie River Formation in the northern Lebombo the occurrence of peperite in the upper margin of a basalt sheet is interpreted as a shallow sheet that has burrowed into unconsolidated water-saturated sediment [79] . It is suggested that sediment-impregnated blocky flow tops that occur elsewhere in the Karoo volcanic sequence might have a similar origin. Weinert and Dunlevey [80] report the first recorded occurrence of the zeolite yugawaralite in Karoo basalts of the southern Lebombo.

Etendeka Igneous Province

Marsh *et al*. [81] reviewed decades of research on the Etendeka Group, Namibia, which is equivalent to the Paraná Province in South America. On the basis of geochemistry they define eight mafic and seventeen silicic magma types and describe their areal and stratigraphic distribution. There is a marked but not exclusive geochemical provinciality within the Etendeka Province with incompatible element enriched (high-Ti) mafic and silicic rocks having a close geographic association as do the low-Ti mafic and silicic rocks. The Doros complex is shown to the eruptive site of the early Tafelkop basalts which have affinities to the Tristan Plume. Comparisons with the Paraná indicate that all the important silicic types in the Paraná have geochemical equivalents in the Etendeka, hence extending the previous the trans-Atlantic correlations of the two provinces. These correlations indicate that volumetrically giant silicic systems developed with pronounced lithospheric thinning and rifting in continental flood basalt provinces.

Associated with the Etendeka flood volcanism are a large number of cental volcanic complexes. One of these, Messum, has been subjected to detailed studies. Ewart *et al.* [82] showed that the complex igneous geology at Messum is best interpreted as a downsag cauldron subsidence which is distinctly different to the classic cauldron subsidence structures found in the western USA. Focusing on the alkaline rocks in the core of the complex, Harris et al. [83] show that trends towards silica oversaturated syenites reflect crustal contamination of nepheline-bearing parental magmas. Basanite dykes are isotopically similar to the modern Tristan lavas and may reflect an input from the Tristan plume into the complex.

Other Mesozoic igneous suites.

As part of the South African Earth Sciences

Research Programme in Antarctica, Harris et al. [84] discuss the petrogenesis of he largest Mesozoic intrusion in Dronning Maud Land, Antarctic - the Sistefjell Syenite which is associated with the 'Karoo' CFB igneous event in that continent. Major, trace, radiogenic and stable isotope data indicate that the composition variation in the syenite is consistent with fractional crystallization with some contamination by the metamorphic basement and the low $*^{18}O$ Sistenup lavas of unknown age. Harris also contributed to the understanding of the large-volume rhyolitic volcanism in Patagonia and the Antarctic Peninsula [85] which parallels the palaeo-Pacific margin of Gondwana.

Cenozoic to Recent Volcanism

Ocean Island volcanism

Harris *et al*. [86] discuss oxygen isotopes measured on phenocryst in lavas from those Tristan Da Cunha and Gough Island basalts which have enriched isotopic signatures. For Gough Island the phenocrysts are in isotopic equilibrium and suggest that the least evolved magmas had the same O isotopic composition as MORB and that more evolved lavas evolved by closed system fractional crystallization. At Tristan, O-isotopes ratios are lower suggesting that material from the volcanic edifice contaminated the parental mafic magmas. The most primitive lavas evolved by AFC involving crystal accumulation, but the evolved lavas evolved by closed system fractional crystallization.

Mid-Ocean Ridge volcanism

In a series of papers, Le Roux *et al*. [87,88,89] describe the geochemistry and petrogenesis of MORB erupted along the southern Mid Atlantic Ridge (MAR) 40 - 55 degrees . This part of the MAR is moderately slow-spreading and lies in the vicinity of the Discovery and Shona mantle plumes. There are systematic distribution of E-MORB and N-MORB on the ridge with the former related to the proximity of the mantle plumes. The basalts also exhibit mild geochemical signatures of subduction. A model involving interaction in the melting regime of the mantle plumes, delaminated continental lithosphere from Gondwana break-up, and subduction contaminated asthenospheric mantle is proposed. Along this segment the source in the vicinity of the Discovery plume has greater proportions of clinopyroxene. Partial melting (15-17%) at 18 Kb produces N-MORB whereas slightly higher degrees of melting at slightly higher pressures characterize melting in the vicinity of the plumes. Subsequent evolution of melts involve crystallization of olivine, plagioclase and clinopyroxene. Crystallization of N-MORB occurred at pressures of 3-6 Kb whereas that in the plume-influenced melts occurred over a greater pressure range (1 atm - 7Kb, but predominantly at 1 atm -3Kb). These differences are ascribed to higher temperatures, more constant magma fluxes and increased longevity of subaxial magma chambers in the vicinity of mantle plumes.

Continental Rift Volcanism

Spath *et al.* [90,91] and Le Roex *et al*. [92] report on geochemical studies of volcanoes on the flanks of the southern Kenya rift (Chyulu Hills 10 km E of the rift) and from the rift walls and floor (Lake Magadie area). The Chyulu Hills volcanoes range in composition from nepheline-normative nephelinites, basanite, and hawaiites to orthopyroxene-normative subalkali basalts. Compositions are consistent with olivine-dominated differentiation. Spatial and temporal variations in degree of silica-undersaturation is explained in terms of variation in depth and degree of melting. The striking geochemical feature in these lavas is their depletion in K in mantle-normalized trace element plots; this is explained in terms of residual amphibole in the melting regime. This is turn implies a source in the lithosphere which is metasomatized by a rising mantle plume to be followed later by melting. Similarly the mildly nepheline-normative within-rift alkali basalts and basanite are generated by variable amounts of melting to depths extending into the garnet stability field and in the presence of residual amphibole, again suggesting melting in the sub-continental lithosphere rather than in the asthenosphere or rising mantle plume. The lithosphere must extend to depths of 75 km beneath the Magadie area.

Anorogenic alkaline volcanism

Using the South Western Cape melilitite-alkali basalt province (76-58 Ma) Janney *et al.* [93] demonstrate that strong trace element and isotopic variations correlate with lithospheric thickness. Eruptives on the continental shelf have strong HIMU affinities whereas those on thick Proterozoic lithosphere have EM 1 isotopic features and kimberlite-like trace element patterns. A complex two-stage mixing process is used to account for the data and it is proposed that unlike oceanic areas where the HIMU component is supplied from a conventional mantle plume, under Africa the HIMU component is in pods of recycled oceanic crust incorporated in a laterally broad, long-lived upwelling.

Carbonatites

Reviewing Sr and Nd-isotope composition of carbonatites, Harmer [94] compares these to kimberlites and argues that CO_2-rich residues forming from ponded kimberlites rise from the base of the lithosphere and are trapped at the peridotite-CO_2 thermal maximum at 2 GPa and enrich the lithospheric peridotite there. This enriched peridotite forms the source for subsequent carbonatitic magmas. Ionov and Harmer [95] report results of laser-ablation ICPMS trace element determinations in calcite-dolomite carbonatites with well-preserved igneous textures from Spitskop. Calcite phenocrysts have low REE and flat patterns in comparison with interstitial late-crystallizing calcite which is strongly enriched in LREE . This suggests that REE are incompatible during fractional crystallization of carbonatite liquids. The phenocryst abundances are similar to carbonates in mantle xenoliths indicating that the latter are crystal cumulates rather than quenched carbonatite liquids. In a paper focusing on potassic trachytes, the only significant silicate rock of the Dicker Willem carbonatite, Namibia, Cooper and Reid [96] show that the trachytes are isotopically similar to the highest grade of potassic fenites associated with the carbonatite. They propose that the trachytes are partially melted fenites.

Kimberlites and mantle materials

In 1998 the 7th International Kimberlite conference took place in Cape Town and a two volume set of papers relating to that meeting was published in 1999 [97] . Other publications on this topic have appeared in numerous journals.

Kimberlites

Field and Scott-Smith [98] present a comprehensive review of the geology of kimberlite pipes, reviewing the standard model which was established from observations on South African pipes and comparing it to others in southern Africa and the newly-discovered pipes in Canada. They review and redefine terminology and demonstrate the variability of pipes in terms of pipe shape and internal geology. They demonstrate relationship between pipe type and the nature of the country rocks and discuss implications for emplacement mechanisms. Emplacement mechanism is also a concern of Rice [99] who has applied engineering studies on blasting to understanding kimberlite eruption mechanisms.

Skinner *et al.* [100] address the controversial topic of the presence of melilite in kimberlite and shows that it is present in most Group II kimberlites and in some phlogopite-rich Group I kimberlites. Crystallization is favoured in the diatreme facies as a consequence of CO_2 loss. Recognition of late-crystallizing phases which formed subsequent to melt degassing is important for Ar-Ar dating of kimberlite as shown by Phillips *et al.* [101] who success fully applied laser probe step-heating analysis to single groundmass phlogopite and K-richterite grains in eleven kimberlites in South Africa.

In more general studies on the origin of kimberlite magma, Sweeney and Winter [102] integrate results from high pressure experimental petrology and major element composition of kimberlite to constrain the depth of melting and the residual mineralogy of the source. Nowell *et al.* [103] adopts and isotopic approach offering an Hf -isotope perspective on components contributing to both Group I and II kimberlite magmas. They recognize a negative),Hf component which they propose derives from a deep sub-lithospheric source. Kimberlite magmas are generated in a plume derived from this deep source and attain additional isotopic variability by assimilating variably enriched

lithospheric mantle.

Several descriptions of individual kimberlite pipes in southern Africa [104,105] and Australia [106,107] are also reported.

Xenocrysts

Xenocrysts, including diamond and its inclusions, have proved to be fertile sources for information about the Earth's interior. The 240 Ma Jwaneng pipe in Botswana is one of the few where diamonds with an eclogitic inclusion assemblage (eclogitic diamonds) occur[108]. These inclusions yield a Mesoproterozoic (1580 Ma) Sm-Nd isotope age, similar to that obtained from Finsch eclogitic diamonds, and initial Nd-isotopic composition indicative of derivation from a depleted mantle source. The Jwaneng and Finsch results point to a regional eclogitic diamond formation event in the Mesoproterozoic Proterozoic related to interaction between subducted lithosphere with the stable Archaean lithosphere.

Viljoen *et al*. [109] and Aulbach *et al.* [110] reviewed the inclusions in diamonds from the Venetia pipes which are important as they have an unusual and somewhat anomalous location in the Limpopo Mobile Belt at the junction of the Kaapvaal and Zimbabwe cratons. The most common inclusion type is sulphide with peridotitic oxide and silicate inclusions and minor eclogitic and websteritic types. Mineral chemistry suggests diamond crystallized at 900°-1400°C at 55-70 Kb in a thick ancient cratonic root dominated by highly-depleted magnesian peridotite. Results for websteritic and eclogitic inclusions are consistent with eclogite representing subducted ocean crust whereas the websterites represent the product of reaction of slab-derived melts with mantle peridotite. Viljoen [111] reports on infrared studies on diamonds from the Venetia kimberlite. Nitrogen contents and nitrogen aggregation states are highly variable with unusually high aggregation in the majority of diamonds - making it unusual when compared to the cratonic kimberlite localities in southern Africa. High aggregation is a feature of other craton margin localities world-wide. Deformation in the mantle is thought to accelerate nitrogen aggregation in the diamonds.

Descriptions of inclusions in diamond from a craton-margin kimberlite, Dokolwayo, Swaziland, are reported by Daniels and Gurney [112]. They report a variety of inclusions (peridotitic assemblages predominating) with variable composition recording macro- and micro-scale geochemical heterogeneity in the mantle where the diamonds formed. Among the inclusions is staurolite which has implications for the high-P stability of this mineral. They also discuss the carbon isotopic composition of a suite of 88 diamonds from Dokolwayo [113], the majority of which lie with the normal range, regardless of their eclogitic or peridotitic character. The carbon source is considered to be methane which degassed from the lower mantle or core. Grutter *et al.* [114] have surveyed the composition of xenocrystic peridotitic garnets occurring on a regional scale on the Slave craton, Canada. Using the Cr_2O_3-CaO relationships as an indicator of depletion, they show that there are marked differences across at least three distinct northeast-trending lithospheric domains which are not reflected in isotopic compositions of Archaean crustal rock, suggesting isotopic decoupling between crust and mantle. For South Africa these authors demonstrate significant compositional differences in the lithospheric mantle on either side of the wrench-fault system that defines the the SW margin of the Kaapvaal craton. Towards the centre of the craton lithospheric thickness is correlated with geochemical signatures of melt depletion in peridotite which imparts stability to thickened cratonic roots.

Xenoliths

Xenolith studies encompass thermobarometry, whole rock major and trace element geochemistry, and isotope geochemistry. Girnis *et al.* [115] carried out experiments in the FMASCr system to derive internally consistent thermobarometers for spinel and garnet harzburgites and apply the results to touching and non-touching inclusions in diamond. Tainton *et al.* [116] applied garnet thermobarometry to garnets recovered from a number of intrusions in the Central Tanzanian Craton and define heatflow patterns within this craton. In a detailed description of the xenolith suite from Venetia, South Africa, Stiefenhofer

et al. [117] show that the suite is dominated by peridotites with pyroxenite and demonstrate that they have been affected by melt-metasomatism. Thermobarometry reveals the presence of a high-temperature inflection in the Venetia geotherm. In Namibia non-kimberlitic mantle xenoliths have been recovered from a ca 75 Ma nephelinite[118] at Swakopmund and from a lamprophyre pipe at Okenyenya[119] both sited on the Damara Mobile belt between the Congo and Kaapvaal cratons. Refractory and fertile peridotite xenoliths are present, the latter representing a variety of mantle not previously documented in southern Africa. They define a hot geotherm which probably relates to regional Cretaceous magmatism associated with the opening of the south Atlantic ocean.

Van Achterbergh *et al.* [120] have estimated the element fluxes during metasomatism of a suite garnet-bearing mantle xenoliths from the Letlhakane kimberlite, Botswana. They show that modally metasomatized rocks become enriched in Sr, Na, K, LREE. And Ti, Zr, and Nb, with the removal of Al, Cr, and Fe and garnet-compatible trace elements are removed. The proposed depletion in Al challenges a previous view that the metasomatic environment was merely Al-poor.

Gregoire *et al.*[121] re-examine the occurrence of the two phlogopite-bearing xenolith suites, MARID and PIC, and demonstrates that the two are clearly distinguished in terms of major and trace element compositions of common minerals and Sr and Nd-isotopes. Moreover geochemical data indicate a genetic relationship of the xenolith types to Group I kimberlites (PIC) and Group II kimberlites (MARID). In a detailed textural compositional and oxygen isotope study Zhang *et al.*[122] interpret the ilmenite-rich ploymict mantle xenoliths from Bultfontein as precipitates from a Fe-Ti-Cr-rich melt which in turn could have separated through immiscibility of a migrating high-Ti silicate melt. Carlson *et al.*[123] present new and review previously published Re-Os isotopic data for peridotite xenoliths in southern Africa. Menzies *et al.* [124] report additional data for the Newlands peridotites. Overall the Kaapvaal craton peridotites Re-depletion ages in the early Proterozoic to late Archaean, and they have the lowest $^{187}Os/^{186}Os$ of any terrestrial rock.

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