Seismotectonic Models for South Africa: Synthesis of Geoscientific Information, Problems, and the Way Forward

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INTRODUCTION

In South Africa the demand for energy resources, water, and infrastructure has grown significantly in recent years. Furthermore, many coal reserves that are currently being exploited will be depleted within the next 20 years. Consequently, plans to provide alternative sources of energy are underway. Energy providers are slowly moving away from traditional coal-fired stations to gas-powered facilities, nuclear power plants, and portable pebble bed modular reactor (PBMR) units. Several dams within the country have also been constructed to accommodate the growing demand for water. In South Africa, no regulatory guidelines for seismic design of such critical facilities exist; hence engineers make use of international guidelines such as Regulatory Guide 1.208, published by the U.S. Nuclear Regulatory Commission (U.S. Nuclear Regulatory Commission 2007). Engineers also need to assess the seismic risk to formulate emergency evacuation procedures and for insurance assessment purposes.

The first step in assessing the seismic hazard and risk for any site is to develop a seismotectonic model. The area under investigation is divided into smaller zones/regions of similar tectonic setting and similar seismic potential (Cornell 1968). These zones are then used in a seismic hazard assessment model to determine return periods of certain levels of ground motion at a given site in the area in question. For example, U.S. Nuclear Regulatory Guide 1.208 (U.S. Nuclear Regulatory Commission 2007) states that regional seismological and geological investigations should be undertaken to identify seismic sources and describe the Quaternary tectonic regime. The investigations should include a comprehensive literature review (including topographic, geologic, aeromagnetic, and gravity maps, as well as aerial photos), plus focused geological reconnaissance based on the results of the literature study. Once the regions of active faults have been identified, more detailed explorations such as geologic mapping, geophysical surveying, borings, and trenching should be undertaken. Finally, the Quaternary history should be reviewed; surface and subsurface investigations of the orientation, geometry, sense of displacement, and length of ruptures should be conducted; and the possibility of multiple ruptures ought to be assessed.

Seismotectonic models have not yet been developed for South Africa. The delineation of seismotectonic zones of Africa as part of the Global Seismic Hazard Assessment Program (GSHAP) in 1999 was based on an analysis of the main tectonic structures and a correlation with present-day seismicity. Because of the large scale of the GSHAP project, only regional structures were accounted for in the preparation of the source zones. Our study was initiated to remedy this knowledge gap. We have completed four steps, which are described in this paper.

1. Compilation of a catalog of earthquake activity that has been documented in historical records or instrumentally recorded.
2. Synthesis of geological mapping, magnetic, and gravity surveys, and evidence of neotectonic activity.
3. Correlation of the seismicity data with the geological, geophysical, and neotectonic data.
4. Identification of any other data that could help to better define the boundaries of seismotectonic provinces.

EARTHQUAKE CATALOG

South African National Seismological Database

We used earthquake records from the South African National Seismological Database (SANSD) to map seismicity. The SANSD is a compilation of seismological data from the South African National Seismograph Network (SANSN), operated by the Council for Geoscience (CGS). Historical data originates largely from the work of Fernandez and Guzman (1979) and De Klerk and Read (1988), updated recently by Brandt *et al.* (2005). Instrumental data recorded by the SANSN has been published in regular seismological bulletins since 1977.

Figure 1 shows the distribution of earthquakes above magnitude 3 in the SANSN database to June 2008. Note that earthquakes in the database are limited to South Africa and Lesotho. There are in excess of 27,000 earthquakes in the database from 1620 to June 2008, ranging from M_L 0.2 to M_L 6.3, with vary-

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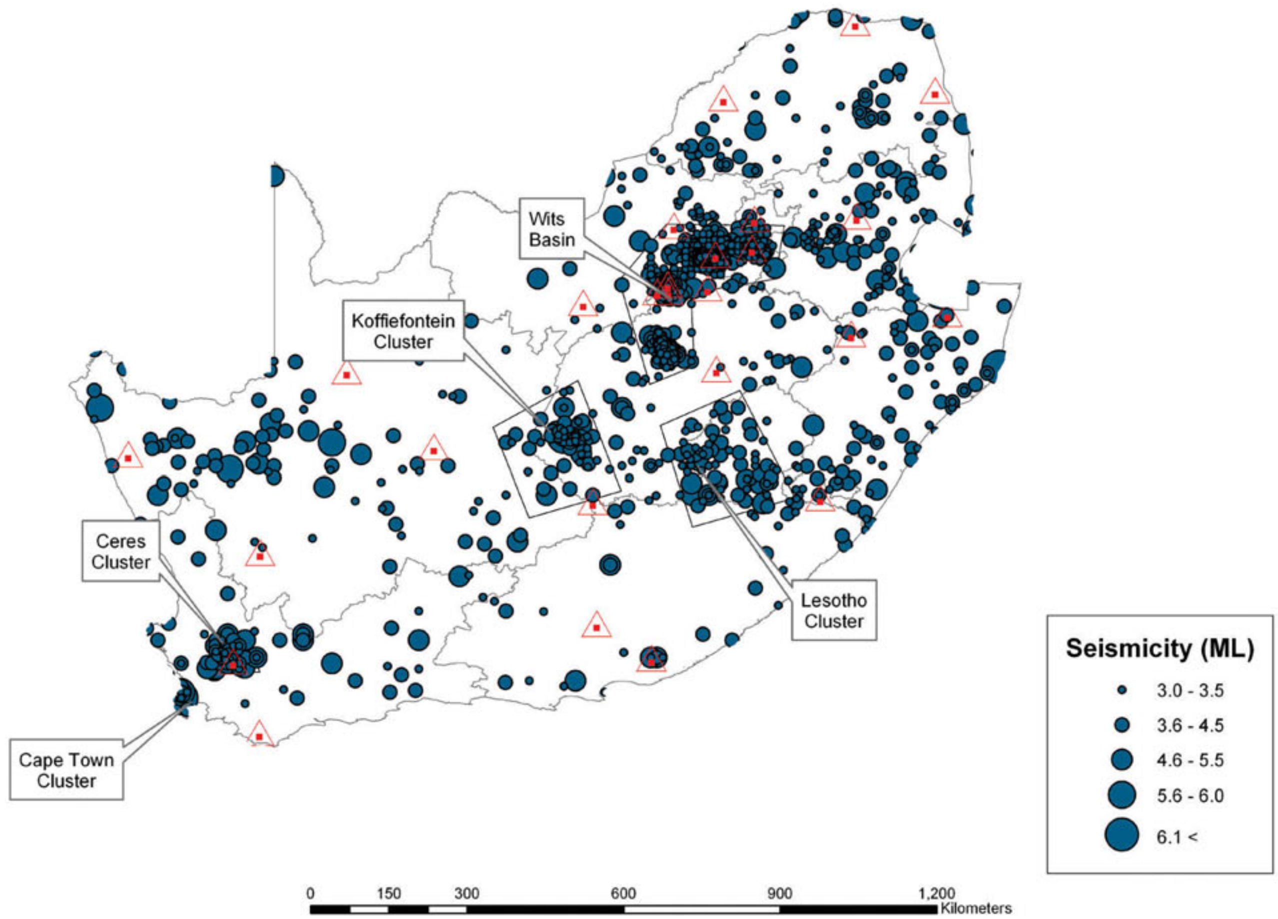


▲ **Figure 1.** Map of Earthquakes 1620–2008 contained in the South African National Seismological Database (SANSD). Known clusters relating to natural and mining-induced seismicity are highlighted. The seismic recording stations are represented by triangles.

ing levels of completeness relating to the different stages of development and detection capabilities of the network.

Seismicity Clusters

Fernandez and Guzman (1979) first identified seismicity patterns in South Africa. The most prominent clusters are:

- *Historical Earthquakes in the Cape Town area*—Earthquakes in this cluster were compiled from diaries, journals, and newspapers written from 1620 to 1902. The locations are given as Cape Town because this is where the effects were felt, but the actual epicenter could be 100 km away or more (Brandt *et al.* 2005). No earthquakes have been located in the Cape Town area since instrumental recording began in 1972.
- *Ceres Cluster*—Earthquakes of M_L 1–3 are recorded in this region six times per month, on average. The well-known 1969 Ceres earthquake (M_L 6.3) occurred on the western termination of the Kango-Bavianskloof fault (KBF). Ongoing research in this area has shown that it is possible that an *Mw* 7.0 earthquake occurred some 10,000 years ago in this region.
- *Koffiefontein Cluster*—An M_L 6.2 earthquake occurred here in 1912. Paleoseismic studies show that a large earthquake (*Mw* 8) occurred here some 50,000 years ago (Visser and Joubert 1990; Joubert *et al.* 1991). Thermal springs are found here.
- *Lesotho Cluster*—The rate of seismicity toward the north of Lesotho increased significantly after the impoundment of the Katse Dam (Brandt 2000). Toward the west and south of Lesotho the seismicity is of natural origin.
- *Witwatersrand Basin Cluster*—South Africa has a number of mining regions located in and around the country. Probably one of the most difficult tasks in monitoring earthquakes in South Africa is to distinguish between earthquakes of natural origin and tremors and blasts from the gold, manganese, platinum, diamond, and coal mines. Most seismicity originates from the gold mining districts of the Witwatersrand basin. Within the basin, the clusters can further be classified into the Welkom, Klerksdorp, Carletonville, West Rand, Central Rand, East Rand, and Evander gold fields. Seismicity in these areas differs due to the different tectonic faults affecting the regions and differences in mining activities (Singh and Pule 2007; Gay *et al.* 1995).

To better understand earthquakes of tectonic origin, one needs to know to what extent the earthquakes recorded in the SANSN are mining related. In site-specific hazard investigations, care should be taken to carefully analyze the earthquake database. The history of mining in the area should be documented, and possible correlations made with mining-related tremors. One needs to research the active mining areas, obtain blasting schedules and records of mining tremors encountered, and correlate them with the database. Similar studies were done by Kgaswane (2002) for the mining regions. This is beyond the scope of this study and is merely stated as a precautionary measure to be noted before drawing conclusions on the tectonic origins of earthquakes.

Largest Earthquakes

The earliest recorded large earthquake in South Africa occurred on 4 December 1809 (Von Buchenröder 1830). Many houses in Cape Town suffered minor damage, and liquefaction features and fissures in the ground were observed in nearby Blauweberg Valley. An M_L 6.2 earthquake that occurred near Koffiefontein on 20 February 1912 was felt all over South Africa. The M_L 6 Cape St. Lucia event of 31 December 1932 (Krige and Venter 1933) was located in the sea offshore the Zululand coast. Shocks were reported in Port Shepstone, Kokstad, Koster, and Johannesburg (some 500 km away). The nearest point on land to the epicenter was Cape St. Lucia, where Modified Mercalli Intensity (MMI) of IX was assigned on the evidence of sand boils and cracks in the surface, but the damage in this area was small because it was uninhabited. The MMI in Pretoria and in Pietermaritzburg was III and V, respectively. In the severely shaken areas, poor-quality houses (built of unburned or half-burnt bricks or other low-quality materials) were severely damaged. In well-built houses, small cracks were occasionally seen but the structures did not suffer major damage. The phenomenon of site effects was clearly displayed in the observations of the after effects of this event. Structures built on thick sand were undamaged, while those built on alluvial sands suffered severe damage. Changing rock types in the area also had a strong influence on the attenuation of the seismic wave. From evidence of its effects, Krige and Venter (1933) argue that this earthquake was probably caused by slip along a fault in the sea striking in a SSW-NNE direction parallel to the coast.

The strongest and most devastating earthquake to occur in the 20th century was the Tulbagh earthquake of 29 September 1969, with M_L 6.3. This earthquake was widely felt over the Western Cape, especially in Ceres, Tulbagh, and Wolseley. Serious damage occurred to certain buildings in the area (amounting to a total of U.S. $24 million). The damage varied from almost total destruction of old and poorly constructed buildings to large cracks in the better-built ones. Nine people were killed and many more were injured. Green and Bloch (1971) studied the event's aftershocks, which formed a linear plane that had little correlation with mapped faults in the area. No surface expression of the fault was found. The Groenhof fault, originally suspected to be the locus of the earthquake, showed no evidence of recent displacement. Therefore it is probable that the fault associated with the earthquake did not intersect the surface.

An *Mw* 7.0 earthquake occurred on 23 February 2006 in the western province of Manica in Mozambique. Fenton and Bommer (2006) provide a detailed description of this earthquake and its associated effects. The earthquake was felt throughout Mozambique, as well as in parts of the neighboring countries of Swaziland, Zambia, Zimbabwe, and South Africa, but caused surprisingly little damage and a very small number of casualties. This is partly because the area immediately affected by the earthquake is sparsely inhabited. The earthquake was felt as far as Durban, where people were evacuated from high-rise buildings.

Earthquakes with magnitudes exceeding 5 are listed in Table 1. The most striking feature of this list is that no earthquake exceeding magnitude 6.3 has been recorded since 1969, the start of the instrumental network. This could be due to a number of different reasons: 1) the magnitudes of historical earthquakes have been overestimated; 2) the M_L scale of the network is underestimating earthquake magnitude (note that M_L saturates at larger magnitudes, and other magnitude scales like *Ms* or *Mw* should be used); 3) crustal stress might have been released in the historical period; or 4) because South Africa is in a stable continental region (SCR) setting, the return period for earthquakes of $M_L > 6$ is longer than the approximately 50 years of observation, and stresses need to accumulate before the onset of another large earthquake. None of these possibilities have been explored in this study, but an understanding of this issue is crucial in determining the seismic hazard potential for the country.

Mining-related Events

A large seismic event occurred in the Welkom region in 1976, causing damage to surface and mine infrastructure, most notably the collapse of a six-story block of apartments. In 1989, a second earthquake caused widespread damage on the surface. Observed and documented displacements on the President Brand fault in a nearby mine demonstrated that the origin of this event was local. On 7 March 1992 an event of M_L 4.7 occurred near Carletonville in the Far West Rand area. Damage to structures was observed as far as Johannesburg and Pretoria. Newspapers reported that high-rise buildings in Johannesburg swayed a few times. It was strange that this event caused so much damage, because an M_L 4.8 event occurred in this region in 1972, and a review of the press coverage showed no reports of damage on that occasion. It would seem that the attenuation for this M_L 4.8 event was much more rapid than other mine-induced seismic events.

Another notable event that caused significant damage to buildings and mine infrastructure occurred in 1999 in the Free State district, known as the Matjabeng earthquake. It was associated with the Dagbreek fault, which extends across kilometers of active mining (Durrheim *et al.* 2007). Dor *et al.* (2001) observed total displacement of 44 cm on the Dagbreek fault. Dor *et al.* (2001) list large earthquakes in the Welkom region since 1972. These earthquakes occurred on faults like the Erfdeel, President Brand, and Saaiplaas, with M_L in the range of 4.7–5.2 and observed displacements of 150–440 mm. The largest earthquake that occurred in the mining areas was the Stillfontein M_L 5.3 event of 9 March 2005 (Saunders *et al.* 2007), which caused significant damage to surface buildings and mine infrastructure.

TABLE 1
List of Earthquakes in the National Database above Magnitude 5

Year	Month	Day	M	Region
1809	12	4	6.3	Cape Town Region
1811	6	2	5.7	Cape Town
1811	6	19	5	Cape Town
1850	5	21	5	Grahamstown
1857	8	14	5	Western Cape
1870	8	3	5	Harrismith
1899	9	13	5	Cape Town
1908	9	26	5	Bloemfontein
1910	10	21	5	Philipstown
1911	11	8	5	Windhoek
1912	2	20	6.2	Koffiefontein
1919	10	31	6.3	Swaziland
1921	10	9	5	Tulbagh
1922	6	23	5	Panbult Siding—Transvaal
1922	8		5	Panbult Siding—Tansvaal
1925	10	10	5	Leutwein Siding—Nambia
1932	8	9	5	Grahamstown
1932	12	31	6.3	Off Cape St. Lucia
1936	1	12	5	Mooihoek-Swaziland
1936	1	16	5	Fauresmith (Free State)
1940	11	10	5	Tzaneen (Transvaal)
1942	11	1	5.5	Port Shepstone
1950	9	14	6	Mozambique Channel
1950	9	30	5.5	Namaqualand
1952	1	27	5	Sutherland
1952	1	27	5.3	Sutherland
1952	1	28	5	Sutherland
1952	1	28	5.4	Sutherland
1952	6	9	5.5	Keetmanshoop District (Namibia)
1952	9	4	5	SWA (Namibia)
1952	11	8	5.2	SWA (Namibia)—Botswana Border

TABLE 1 (continued)
List of Earthquakes in the National Database above Magnitude 5

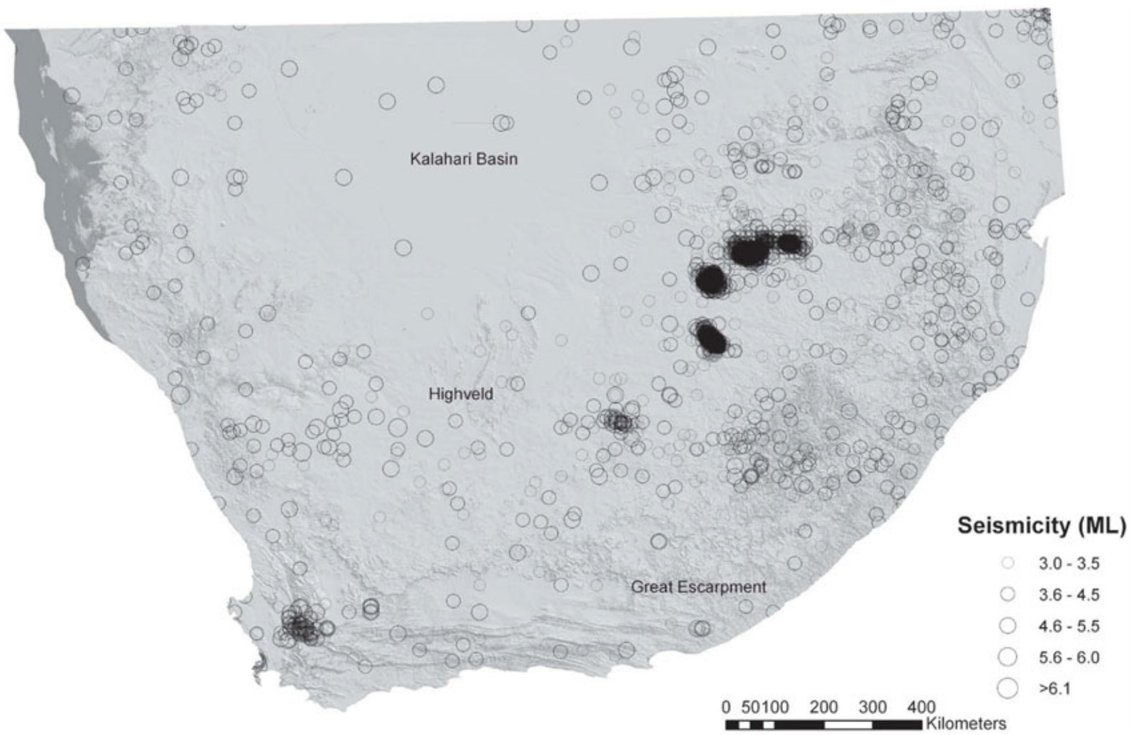
Year	Month	Day	M	Region
1953	5	1	5.8	Namaqualand
1954	2	17	5.5	Mozambique
1955	1	20	5.5	Offshore Mozambique
1955	5	20	5.1	Fauresmith District (Free State)
1957	4	13	5.5	Zastron District (Free State)
1963	8	27	5	Worcester-Ceres
1964	6	9	5	Luckhoff (Free State)
1966	6	18	5	Mokhotlong (Lesotho)
1968	1	12	5.5	Uitenhage
1968	1	14	5	Sul Do Save Prov (Mozambique)
1969	9	11	5.2	Heidelberg
1969	9	29	6.3	Tulbagh
1976	12	8	5.1	Welkom gold mines
1977	3	2	5.3	S.W. Cape Province
1977	4	7	5.2	Klerksdorp gold mines
1979	2	21	5.8	N. Cape Province SA.
1984	1	28	5.01	Klerksdorp gold mines
1985	5	8	5.22	Koffiefontein Region (Free State)
1986	10	5	5.15	Transkei
1987	9	30	5.04	Klerksdorp gold mines
1989	9	29	5	Mandileni Region (Transkei)
1991	10	31	5	Ceres Area Cape Province
1992	12	23	5.1	Namibia
1994	8	20	5	Southern Namibia
1994	10	30	5.1	Free State gold mines
1994	12	31	5.1	Brandvlei Region—Northern Cape
1996	9	15	5.1	Loeriefontein Region
1999	4	22	5.1	Free State gold mines
2001	4	6	5.2	Boesmanland Area—N. Cape
2001	7	31	5	Klerksdorp gold mines
2005	3	9	5.3	Klerksdorp gold mines
2005	10	12	5.1	Klerksdorp gold mines

Assessment of the Earthquake Catalog

We repeatedly encountered the following fundamental problems when looking at the data provided by the SANSN for the purpose of better understanding the seismotectonic origins of earthquakes in the region:

- The current number of stations and their configuration allows for a very limited detection capability of the network. As a result the location of events can be poor, and the ability to detect micro-earthquakes on active structures is rather limited.
- A comprehensive study is required to distinguish mining-related earthquakes from earthquakes of natural tectonic origin in the database. Furthermore, analytical techniques should be adopted in the SANSN to distinguish these events as they are reported.
- An accurate assessment of the depth of earthquakes should be made.
- Focal mechanisms of earthquakes should be obtained.

A denser monitoring network is required to better understand earthquake occurrence. This network should be concentrated in areas with active seismicity such as Ceres and Koffiefontein.



▲ **Figure 2.** Topography of South Africa together with the recorded seismicity.

GEOLOGICAL PROVINCES AND GEOPHYSICAL OBSERVATIONS

Topography and Major Geological Provinces

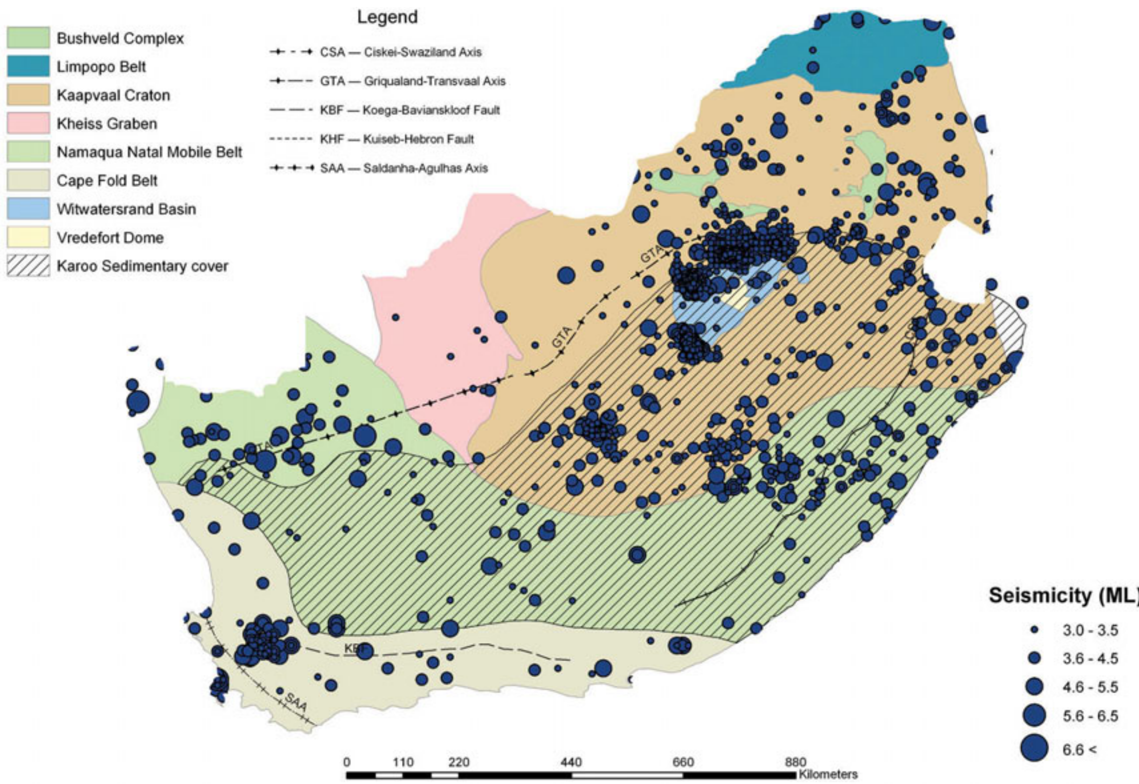
As the relief map shows (Figure 2), the South African interior is surrounded in the west, south, and east by a cornice of mountains. This chain, consisting of many individual mountain ranges, is known as the Great Escarpment. In the east, in the area of the Drakensberg of KwaZulu-Natal and in the Kingdom of Lesotho, it reaches heights of almost 4,000 m. In the south and west, the highest peaks reach 2,000 m. In front of the escarpment is a mostly narrow coastal strip. Inland of the escarpment, the central high plateau of South Africa reaches elevations of 1,000–1,700 m. The plateau slopes slowly toward the Kalahari basin in the north. There is a relatively greater concentration of seismicity along the Great Escarpment.

A brief description of the geologic units is provided below; refer to Johnson *et al.* (2006) for more detail. A schematic representation of the geological provinces superimposed on the seismicity recorded for the country is shown in Figure 3. The Kaapvaal craton (KC) is of Archean age. It is the foundation upon which the geological formations of South Africa have subsequently developed. A zone of metamorphic sediments on the northern marginal zone of the KC separates the KC from the Zimbabwe craton (ZC), which is of similar age and composition. It is thought that this zone, referred to as the Limpopo belt, was formed as a result of a collision between the KC and the ZC. The oblique nature of this collision is believed to have initiated or re-activated major transcurrent fault systems, resulting in important structures such as the Thabazimbi-Murchison lineament, which prepared the craton for the development (2,600–2,100 million years ago) of the Transvaal and Griqualand West basins. The Bushveld igneous complex intruded the KC at about 2,000 million years ago. Tectonic activity on the KC ceased about 1,800 million years ago. Proterozoic fold and thrust belts up to 400 km wide were added to the KC on the south (Namaqua-Natal mobile belt, NNMB) and west (Gariep-Kaoko). A complex tectonic history 1,750–1,200 million years ago of rifting, basin development, oceanic basin development, subduction, and plate collision is recorded in the rocks of this period (Wilson 2005). The Pilanesberg alkaline complex and the Premier diamond pipe intruded around 1,300 million years ago.

The rocks in the Cape fold belt (CFB) were laid down as sediments in a coastal delta environment upon the Malmesbury unconformity in the Ordovician (450 million years ago) period, with the folding subsequently occurring in the Carboniferous and Permian periods during the merging of the supercontinent Pangaea.

The Karoo supergroup is the largest geological feature in southern Africa, covering almost two thirds of the present land surface, including some parts of Western and Eastern Cape provinces, almost all of Free State, western KwaZulu-Natal, much of southeast Gauteng Province, Zambia, Zimbabwe, and Malawi. Its strata, mostly shales and sandstones, record an almost continuous sequence of marine glacial to terrestrial deposition from the Late Carboniferous to the Early Jurassic, a period of about 100 million years. Extensive basic and acid lavas of the Lebombo and Drakensberg groups cap the Karoo supergroup, and their extrusion preceded the fragmentation of Gondwana.

South Africa began breaking away from Australia in the northeast around 200 million years ago, and this breakup pro-



▲ **Figure 3.** Major geological provinces and neotectonic features/faults of South Africa superimposed with the seismicity recorded by the SANSN (adapted from Nguuri *et al.* 2001).

ceeded southward and then westward until the proto-Atlantic was formed about 120 million years ago. This was accompanied and followed by widespread anorogenic alkaline magmatism of the kimberlitic, carbonatitic, and ring-complex types (Wilson 2005).

Geologically younger deposits, ranging in age from Cretaceous to recent times, include the Kalahari group sediments; coastal, shallow marine and lagoonal sediments; and present and ancient river terraces (Schlüter 2006).

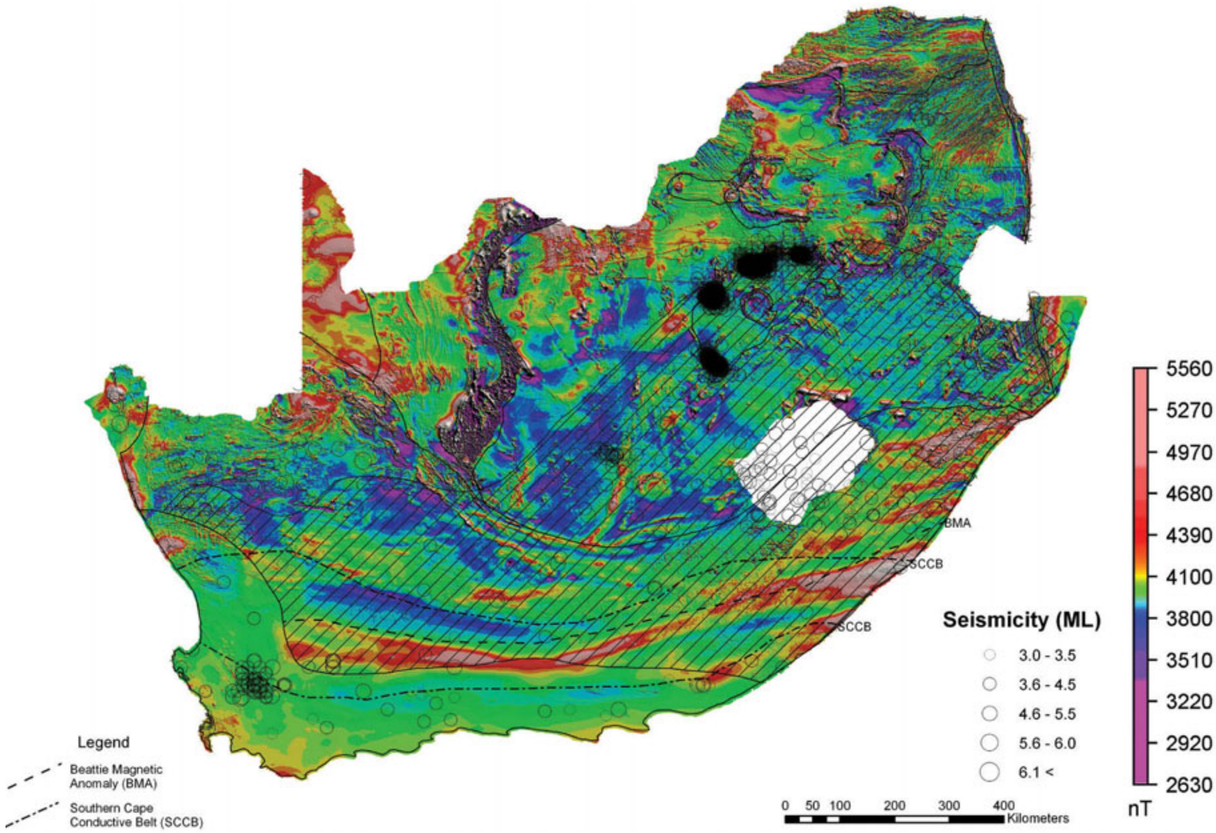
Figure 3 shows that mining-related seismicity is prevalent in and around the Witwatersrand basin. Given that the Karoo supergroup covers a large portion of the land surface, it becomes crucial that a depth parameter be included when reporting on earthquake occurrences. This would then provide a better understanding of whether the earthquakes originated from the KC, the NNMB, or the Karoo. With a very regional seismic record and the rather diffuse pattern of seismicity spanning the country, it is rather difficult to ascertain any correlations between recorded seismicity and the respective geological provinces.

Geophysical Observations and Subsurface Geology

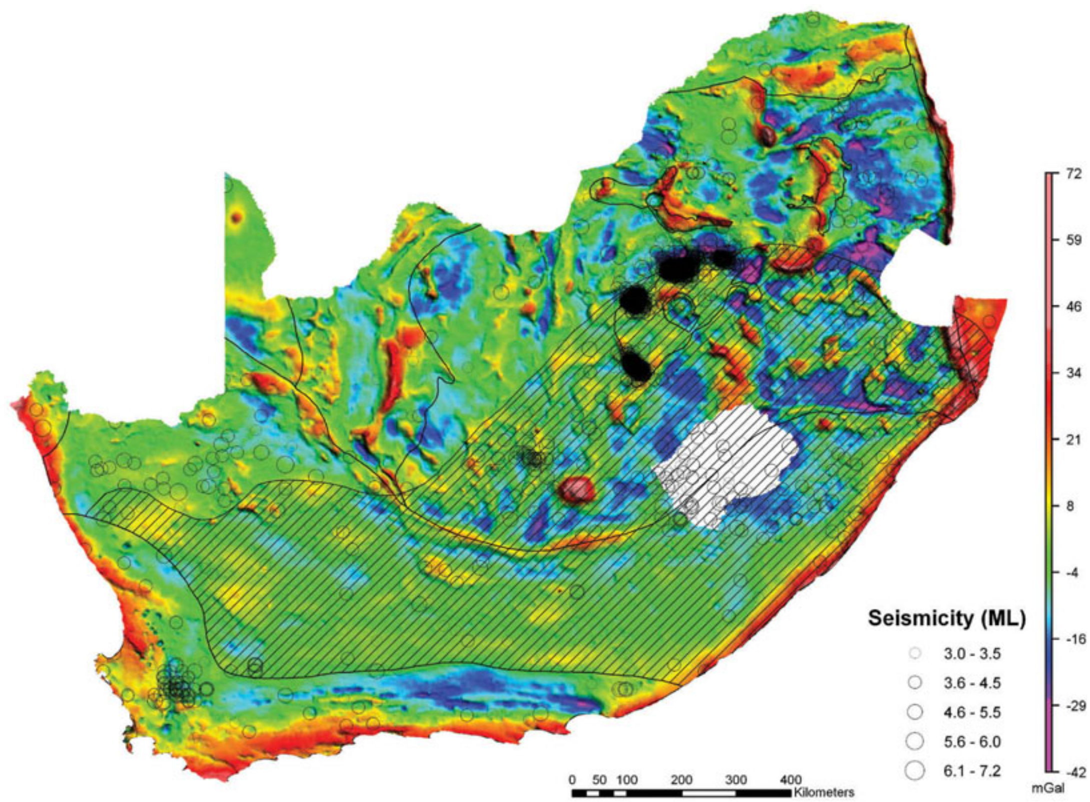
Geophysical investigations (*e.g.*, gravity, magnetics, and seismic anisotropy) provide a better understanding of the subsurface geology of the Earth. Regional aeromagnetic and gravimetric maps of South Africa are shown in Figures 4 and 5. The seismicity data and boundary of major geological provinces are superimposed on these maps. Note that in both these figures the patterns formed by the geophysical signatures correlate to a large extent with the geological provinces beneath the Karoo sediments.

Gravity data provide information about densities of rocks underground. Generally, gravity highs indicate the presence of relatively dense rocks, and magnetic anomalies are caused by rocks with abundant magnetite in them. Very high-intensity anomalies (more than 50 milligals or more than 200 gammas) typify major changes in rock type, usually (but not always) in basement rocks. Most sedimentary rocks (with the exception of banded ironstones) contain little magnetite, so generally we are dealing with igneous and metamorphic rocks (Gibson 2007).

Weckmann *et al.* (2007) used magnetotelluric and seismic imaging to investigate two major geophysical anomalies: the Beattie magnetic anomaly (BA) and the Southern Cape conductive belt (SCCB), which occur in the NNMB and extend across the continent from east to west (refer to Figure 4). The maximum of the Beattie anomaly coincides with a narrow zone of high conductivity at 8–15 km depth and a zone of high seismic reflectivity and high *P*-wave velocity. The results show that the crustal structure of the NNMB is complex, consisting of conductive material in the upper to mid-crustal sections, with the lower crust containing reflectors. The Cape Fold belt is characterized by low electrical conductivities and high *P*-wave velocities. In contrast, the Mesozoic/Cenozoic Kango and Oudtshoorn Basins of the Cape fold belt appear as regions of high electrical conductivity and low *P*-wave velocities. The



▲ **Figure 4.** Regional aeromagnetic map of South Africa superimposed on the major geological boundaries and the seismicity.



▲ **Figure 5.** Regional gravimetric map of South Africa superimposed on the major geological boundaries and the seismicity.

BA and SCCB show no distinct correlation with earthquakes recorded in the region.

A magnetic lineament and a mafic pluton known as the Trompsburg complex (Maré and Cole 2006) can be found within 100 km north of the Koffiefontein cluster. No corresponding magnetic anomalies exist in the vicinity of the Ceres cluster. Toward the west of the country, a cluster of events occurs on a linear magnetic fabric on the NNMB. Similarly, this occurs on the east in KwaZulu-Natal and in the north within a dyke swarm in the Limpopo Province. Earthquakes in the Cape fold belt are diffuse and relatively low in number. No statement can be made about the correlation between earthquakes and magnetic anomalies in Lesotho because of the lack of coverage in this area.

Figure 4 shows that gravity highs delineate the northern boundary of the NNMB, the limbs of the BC, the Kheis graben in the west, and the Trompsburg complex near Koffiefontein. A significant gravity low occurs in the CFB, corresponding with the trace of the reactivated CKBF. No obvious correlations are visible between the seismicity patterns and gravity anomalies. A moderate gravity high is visible within the Ceres cluster area that is worth investigating in detail.

Other geophysical projects aimed to image the deeper earth structure beneath South Africa include the Kaapvaal Project, which was conducted in the late 1990s. Broadband seismic stations were deployed in an array that extended across South Africa. Recordings of teleseismic earthquakes by this array provided an opportunity for scientists to learn more about the deeper earth structures spanning the continent. Nguuri *et al.* (2001) found that the Archean crust (KC, ZC) is typically thin (~35–40 km) in contrast to the Proterozoic belts and post-Archean regions (*e.g.*, Bushveld complex) where the crust tends to be relatively thick (~ 45–50 km). A study of seismic wave anisotropy (Fouch *et al.* 2004), found clear evidence that mantle structures mimic the surface geology. A thick mantle keel (roots) exists underneath the Archean cratons (at 250–300 km), while there is no evidence for similar structures beneath the adjacent, younger Proterozoic mobile belts. Reduced mantle seismic velocities are evident underneath the Bushveld Complex (James *et al.* 2001; Fouch *et al.* 2004).

Current projects that are providing information on geophysical properties in the lithosphere of southern Africa include the SAMTEX project (Hamilton *et al.* 2006) and the AfricaArray project (Shen and Nyblade 2006). These observations can contribute toward better modeling of the seismic structure and the characterization of large structural seismotectonic domains. Only through a denser network of seismic monitoring stations can one better correlate the geophysical investigations with the earthquake record.

Geodynamics: African Plate Motion and Regional Stress Regimes

The motion of the African plate is coupled with intraplate motions. Zoback (1992) showed that large regions in the interiors of plates are characterized by uniform compressive stress orientations, which are produced by forces acting on the plate boundaries (*e.g.*, ridge push). In these areas the maximum principal stresses are horizontal. This stress regime is clearly seen in the southwestern part of South Africa, where an east-west horizontal stress regime prevails, dominated by compressional forces originating in the Mid-Atlantic Ridge. This regime is manifested in strike-slip faulting along major east-west-trending fracture systems (*e.g.*, Worcester and the KBF). A different stress regime prevails in the East African rift system (EARS). Dominant buoyancy forces (swell-push) are generated by the upwelling of the asthenospheric material and the thinning of the lithosphere. The maximum principal stresses are in the vertical direction, resulting in predominant normal faulting. In the area between the above two regions, there is an intermediate zone of elevated topography, extending from eastern and southern Africa into the surrounding oceans, known as the African superswell (Nyblade and Robinson 1994). Here the maximum principal stress remains vertical, and minor principal stress assumes a NW-SE orientation. This feature has been named the "Wegener stress anomaly" (Andreoli *et al.* 1996; Bird *et al.* 2005). This anomaly is best explained in terms of the combined effects of ridge-push and swell-push, with the latter dominant.

Quaternary Faults, Seismotectonic Faults, and Neotectonic Activity

Return periods as long as 10,000 years are considered when assessing the risk posed by large events to critical structures such as nuclear reactors. This is where the field of neotectonics and paleoseismology becomes crucial in determining if and when a large earthquake has occurred in the recent geological past, *i.e.*, 500,000 years ago for intraplate regions. McCalpin (1996) provides guidance on how to identify these features. Many authors, in their quest to understand the relation between seismicity and tectonics, have identified paleoseismic and neotectonic features in South Africa. We briefly review these here, with key features shown in Figure 3.

- A cluster of earthquakes occurs in the vicinity of gravity lows and radial trends of Karoo dolerites in the westernmost past of the NNMB, which can possibly be associated with an ancient impact event. This radial trend can clearly be seen in the aeromagnetic map (Figure 4).
- In the Kaapvaal craton, natural seismicity can be associated in the north with a lineament defined by the Murchison greenstone Belt, the Zebediela fault, and the Thabazimbi fault. The Thabazimbi and Zebediela faults are related to subsidence of the Bushveld basin by as much as 400 m. The Zebediela fault is associated with a number of thermal springs.
- Earthquakes occur seaward of the Great Escarpment, mainly on mountains of the Cape fold belt.
- Earthquakes in the Koffiefontein cluster occur near the Lithani/Matigulu thrust in the amphibolitic Mzumbe terrain. Andreoli *et al.* (1996) discovered a recent fault zone reaching the surface 10 km southwest of Bultfontein. The linear feature appears as a flat-bottomed furrow 30 cm deep and 0.5 m wide, which could represent a belt of ground depressed as a result of extensional faulting.

- Earthquake occurrence in the Lesotho cluster follows the Caledon River.
- Earthquakes in Matatiele cluster in Lesotho occur near the Cedarville fault and Cedarville. Flats alluvial deposits are located on the inland flank of the Ciskei/Swaziland axis of upwarping. Thermal springs in KwaZulu-Natal and Mpumulanga also occur along this axis (Kent 1981)

The Griqualand-Transvaal axis in the continental interior is related to the subsidence of the Kalahari basin (T. Partridge, personal communication 2007). Small movements along this axis led to disruption of drainage networks and development of new drainage lines. The Saldanha-Agulhas axis of warping takes the form of a hinge line over a distance of 300 km in the southwestern Cape. Near Cape Agulhas, fluvial terraces, probably of Neogene age, are uparched across this axis. Andreoli *et al.* (1996) state that neotectonic joints, faults, and breccias cut consolidated and semiconsolidated Late Pliocene to Pleistocene calcarenites near Gansbaai, Quoin Point, Cape Agulhas, and Gouriqua.

The CKBF in the Cape Province has reactivated fault scarps that are, in some places, between 2–4 m high. The Worcester fault lies south of the CKBF, with similar strike and orientation as the CKBF, and extends toward the Ceres cluster. Although there are some correlations with seismicity along the Worcester fault, there is no recorded evidence of reactivation similar to that found on the CKBF.

Andreoli *et al.* (1996) also pointed out widespread reactivation of Precambrian faults from the Wesselesbron panneveld 60 km north of Bultfontein. Late Pleistocene to Holocene faults are well-exposed at Port Durnford near Richards Bay, extending northward through the St. Lucia lakes and the northern KwaZulu-Natal coastal plain into southern Mozambique.

Near Johannesburg, the Rietfontein fault system runs from Edenvale in the east to beyond Krugersdorp in the west. A series of landslides are found that could be related to seismic events along the fault. Other evidence is becoming available that supports the suggestion that this fault system may be the source of localized distress in buildings and may also be the locus of low-level seismic events (Barker 2004).

Although evidence of neotectonic activity is clearly present, systematic recording and mapping is required. The Quaternary sediments need to be mapped. If they are absent, this should be indicated. Similarly, the evidence, or lack thereof, of paleoseismic and neotectonic activity should be recorded spatially. Where there is evidence of such activity, this needs to be investigated using various techniques now available (see McCalpin 1996). A useful seismotectonic model requires: 1) the characteristics of the fault, 2) its earthquake history, and 3) recurrence properties.

CONCLUSIONS

Building a seismotectonic model involves several geoscientific disciplines. Although we have made progress in each discipline, we still need to extend and fine-tune our work to build such a model. Milestones yet to be reached are:

Seismology:

- A denser network of seismic monitoring stations is required to improve the sensitivity and location accuracy of recorded earthquakes.
- The earthquake database needs to be revisited to distinguish between earthquakes of natural origin and those that are mining-related.
- Depths and focal mechanisms of earthquakes need to be determined and routinely published.
- Microseismic monitoring needs to be undertaken of active regions such as the Ceres and Koffiefontein areas and active fault regions in the CFB.

Geology:

Quaternary sediments, especially those providing evidence of neotectonic and paleoseismicity, need to be dated and mapped across the country.

In an intraplate region like South Africa, there may be little correlation between seismicity and faults. Nevertheless, these knowledge gaps need to be addressed.

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