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Seismic Hazard in South Africa

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1 General seismicity

Plate tectonics has been the accepted model for crustal evolution on a continental scale for the past 30 years or more. The primary postulate is that the earth comprises a limited number of continent-sized plates which are being deformed (altered) **only** at their edges by being added to through the process of mid-ocean ridge accretion, or destroyed by subduction, obduction or crustal shortening. The implication is that the kinematics of the world system of plates can be totally resolved if plate geometries are known, as well as rates of crustal addition and destruction.

A model for global plate motions, NUVEL-1, based on 12 major plates bounded by constructive, destructive and transform-fault edges was deduced from topographic and bathymetric data in 1990 (De Mets *et al*., 1990). The crustal accretion was estimated from the spreading rates of constructive plates determined from the separation of magnetic anomalies. Subduction rates were deduced from earthquake slip vectors. The NUVEL-1 model was intended to prove the general validity of plate tectonics; there was hence no reason to "complicate" the model by including slowly evolving plate boundaries. For example, the entire continent of Africa was considered to be part of a single "intraplate area" that included the African Rift System, where the stress field was ascribed to buoyancy forces in anomalously hot lithosphere (Zoback, 1992). The rifting is considered to be "a second-order stress" and therefore, in the global model, only a scheme of convenience.

Plate tectonics is currently refined to also include situations where deformation is not concentrated along narrow, discrete zones like constructive and destructive plate boundaries. Indeed, it is only constructive plate boundaries involving oceanic crust on both plate sides that are narrow, with "deformation occurring only at the plate edge" .Wherever continental crust is involved in the geological process, the boundary zone can be more than 1 000 km wide. This occurs at a plate boundary involving oceanic crust on the one side and continental crust on the other side (e.g. the Nazca/South American plate boundary), or in an area of continental rifting (e.g. the East African Rift), or in an area of continental collision (e.g. at India/Eurasia). These cases are today recognized as **wide plate boundary zones** (Gordon and Stein, 1992). The East African Rift System and Southern Africa are part of a wide plate boundary zone.

A refinement and correction to the NUVEL-1 model was recently produced to accommodate wide plate boundary zones (Jestin *et al*., 1994). This refined model predicts the east-west opening of the East African Rift System between a western, Nubian, and an eastern, Somalian plate with an average divergence of about 3 mm per year over the past 5 Ma. The pole of opening lies towards the south near 55.73° S, 19.76° E in the Southeast Indian Ocean. The model clearly shows that the East African Rift System (EARS) is a divergent wide plate boundary zone between the Nubian and Somalian plate which, theoretically, must continue through the southern part of Africa and into the Indian Ocean. This lends support to hypotheses of its extension based on the increased seismicity in parts of Mozambique, Zimbabwe and northern Botswana. Although a few medium magnitude events have occurred in historic times in the Damara Belt, extension of the EARS through the Caprivi towards Walvis Bay on the Namibian coastline is not as evident from seismicity. A relatively new development is that a review of magnetic anomalies indicates that the Rift extends into the Indian Ocean near the Southwest Indian Ridge southeast of Mozambique (Lemaux *et al*., 2002).

Earthquake magnitude is related to the size of an earthquake. For natural earthquakes, which occur on geological faults or zones of weakness, this can be related to the area of the fault on which slippage occurs. What people are experiencing is the motion of the ground resulting when the waves created by this slippage propagate away from the earthquake source. On average, the strength of the ground motion increases with magnitude and decreases with distance from the source, but there are many other factors that control it as well, such as site conditions (rock or soft soil, being on a slope/hill).

Larger earthquakes are less frequent than small ones – as a rough rule of thumb, if you go up one magnitude unit, the yearly number of earthquakes expected to exceed this magnitude is divided by 10. The number of earthquakes recorded on average per year in a given region (in other words, the activity rate) depends on the tectonic setting of the region.

2 African Regional seismicity

On the small scale of Africa the historic epicentral locations indicate that in the wide plate boundary zone, which is in places as much as 1 600 km wide, there are “belt-like” zones of seismicity (often about 200 km wide) surrounding relatively aseismic “blocks” (See Figure 1). Even though the “seismicity belts” are mainly coincident with rifts not all rifted regions experience strong earthquakes (e.g. the eastern Kenya Rift from south of Afar to near its southern terminus in Tanzania). Notably, seismicity belts sometimes occur where no rift faults are apparent (e.g. the western seismicity belt near to the coast between 10° and 15° S).

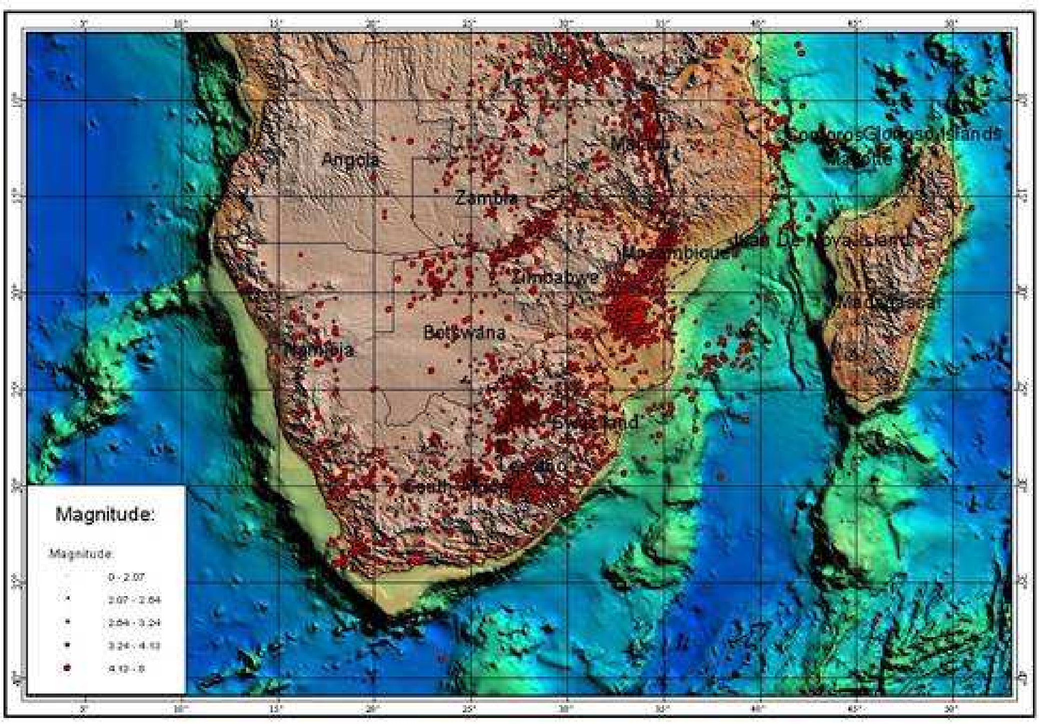

Figure 1: Map of seismicity of southern Africa for the period 1620 to 2010

The occurrence of belt-like zones of seismicity alternating with aseismic blocks continues (with somewhat lesser intensity) into Southern Africa and South Africa. A belt of seismicity extends north-south along the South Africa-Mozambique border, southwards into KwaZulu-

Natal and another trends east-west through southern KwaZulu-Natal, Lesotho and the southern Free State. (See Figure 1).

The seismicity of Africa, especially Southern Africa is, by world standards, very moderate and of shallow character. It is difficult to correlate the seismic foci with geological features in a clear and definite manner. Earthquakes have occurred on the ancient cratons as well as in the mobile belts. The Cape Fold Belt and the adjacent Karoo Basin are equally subject to sporadic activity. Only a few tenuous correlations can be made with the surface geology.

The eastern boundary of a north-south-trending zone of enhanced seismicity along the Mozambique border coincides with the Lebombo Mountains. This zone forms the dividing line between, in the west, the Kaapvaal Craton underlain by Archaean-aged aged basement rocks and in the east, severely subsided, Pan-African reworked crust in Mozambique that is overlain by a major Mesozoic/Cenozoic sedimentary succession. Earthquakes specifically appear to be rare on the Mozambique Plain, immediately east of the Lebombo Mountains. The east-west-trending zone through Lesotho generally coincides with the Meso-Proterozoic (1000-1600 Ma) metamorphic terrain (Namaqua and Natal Metamorphic Provinces), i.e. the zone generally does not trend onto the Kaapvaal Craton. Particularly south of Upington the Kaapvaal Craton exhibits virtually no seismicity and the Namaqua Metamorphic Province, bounding it to the south, displays moderate seismicity. (See Figure 1).

As the historic activity seems to move from one region to another, new explanations are proposed, often contradicting earlier ones. A clear example of is the interpretation in the 1950's that the Cape Fold Belt is not particularly subject to earthquakes. The occurrence from September 1969 of the large Ceres-Tulbagh series of earthquakes completely disproved this opinion. A study by Theron (1974) found that there had indeed been ample evidence for above average seismic activity prior to 1969 (References in Brandt et al., 2005).

Apart from the seismicity recorded in the Lebombo Mountains and the Cape Fold Belt at Ceres, two other areas in the rest of continental Southern Africa have been affected by large earthquakes. One is Cape Town, affected from December 1809 to June 1811 by a series of shocks of which the largest had an intensity VIII on the Modified Mercalli Scale, and the other one occurred at Koffiefontein in the southern Free State, affected in 1912 by a shock of maximum intensity IX on the Rossi-Forel scale. In neither of the two areas are the associated seismogenic structures known. In the case of the Ceres-Tulbagh seismicity, seismicity is clearly associated with a set of WNW striking faults.

Occasional bursts of seismic activity have occurred at numerous other places in South Africa. The earthquake catalogue indicates that the occurrence of earthquake swarms is not infrequent. This is the case for the series of tremors at Sutherland in January 1952 and on the Cape-Lesotho border in 1953. (References in Brandt et al., 2005).

The scatter of seismic foci in Southern Africa is quite similar to the diffuse seismic pattern of intraplate regions elsewhere in the world, such as the central and eastern United States, central China and Australia. For China, maps covering almost 3 000 years of seismicity show intermittent large earthquakes. Earthquakes of magnitude 8 and above are reported for almost every region, with some migration of the seismic activity with time. A similar situation exists in continental United States, with isolated large shocks in New Madrid (1810-1811) and Charleston (1886) in the interior of the North American Plate. The 1966

Koynanagan earthquake of magnitude 7.0 in the Deccan Plateau of India is another example of an isolated intraplate event. Investigations in the latter area revealed periodicities of about 200 years for such earthquakes. Whilst the seismic histories of Southern Africa and the United States are too short to accurately establish the spatial and temporal patterns of seismicity, the Chinese record clearly shows that large earthquakes cannot be ruled out in intraplate areas.

The historical record of seismicity in Southern Africa is not only restricted in time, but is also affected by the uneven distribution of population. As more instrumental records are obtained and seismic tomography, magnetic, gravity and magnetotelluric investigations reveal more geological information, better associations between seismicity and geology will be obtained.

3 Seismic Hazard Maps for Southern Africa by Fernandez and Du Plessis

Fernandez and Du Plessis (1992) described seismic hazard (SHA) using a direct method of estimating the apparent probability of exceeding a certain horizontal peak ground acceleration. They used earthquake records from the South African National Seismological Database (SANSD) to map the seismicity. The SANSD is a compilation of seismological data from the South African National Seismograph Network (SANSN), operated by the Council for Geoscience, and historical data recently updated by Brandt *et al.* (2005). Instrumental data recorded by the SANSN has been published in regular seismological bulletins since 1977. Figure 2 shows the distribution of earthquakes above intensity II in the SANSN database to 1992.

Figure 3 and Figure 4 (taken from Fernandez and Du Plessis, 1992) are maps showing respectively seismic intensity (Modified Mercalli Scale, MMS) and peak horizontal ground acceleration (PGA) levels that have a 10 percent probability of being exceeded, at least once a year, in a period of 50 years. The maps represent data from 1620 to 1989. Both maps depict natural as well as mining-related seismicity. In respect of the latter, the maps are relevant only if mining activities continue. It is notable that the areas of greatest seismic hazard in South Africa occur in three regions namely (1) in the southwestern Cape in a 100 x 50 km sector extending northeastward from Cape Town; (2) in a 200 x 100 km sector in the southern Free State and Lesotho; and (3) in Swaziland (Fernandez and Du Plessis, 1992).

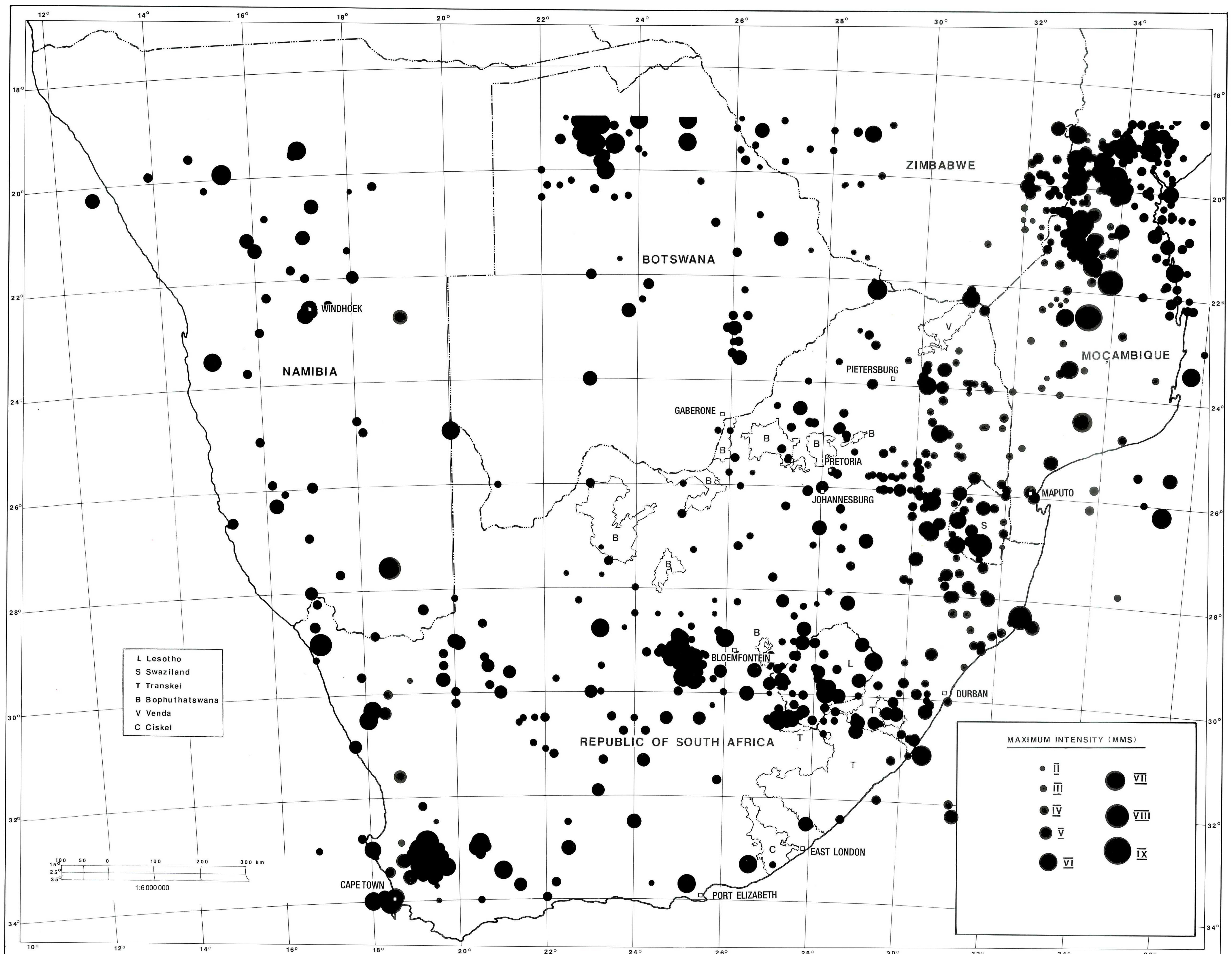

Figure 2: Maximum reported intensities (Modified Mercalli Scale) from 1620 to 1988

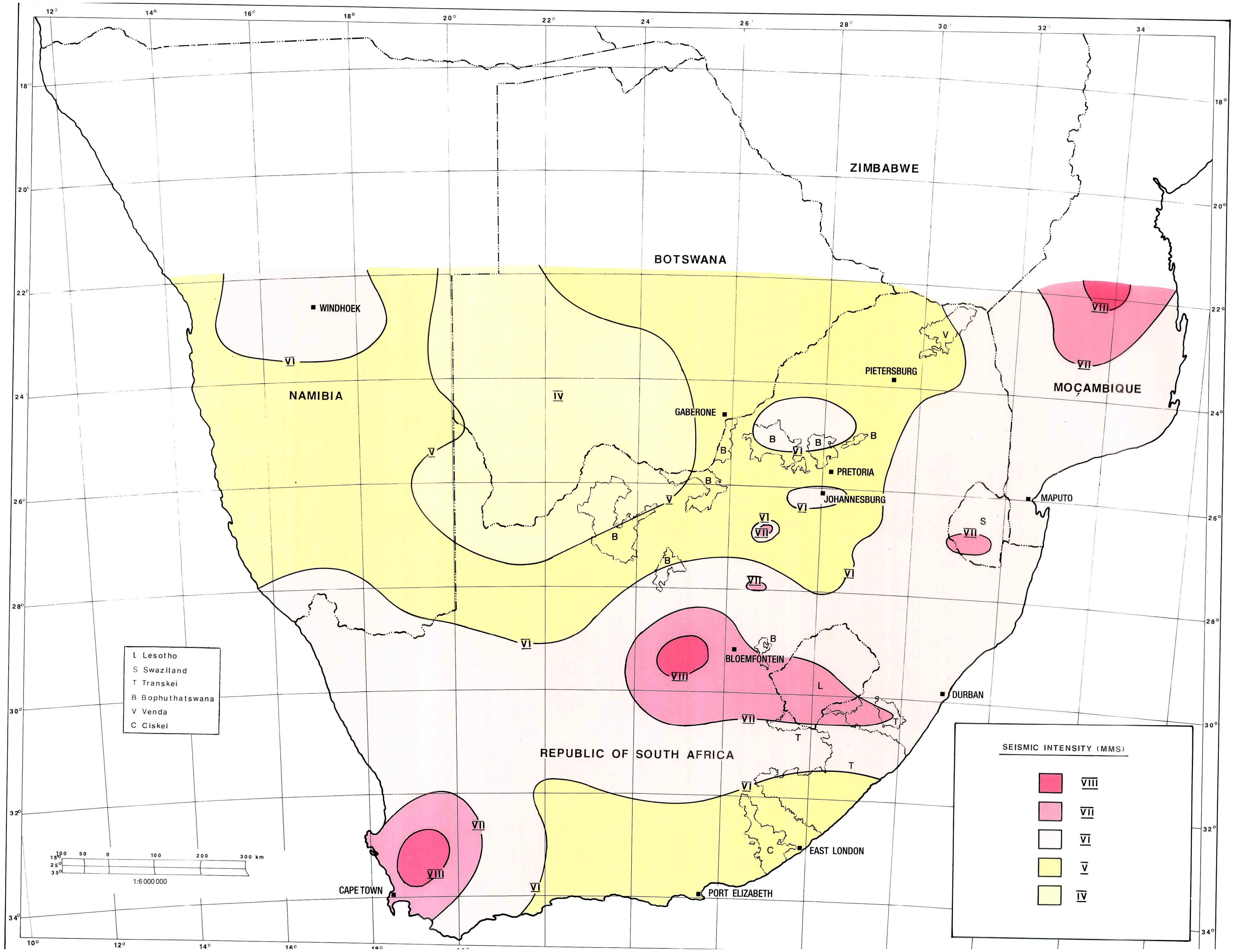

Figure 3: Seismic intensities (Modified Mercalli Scale) with a 10% probability of being exceeded at least once in a period of 50 years

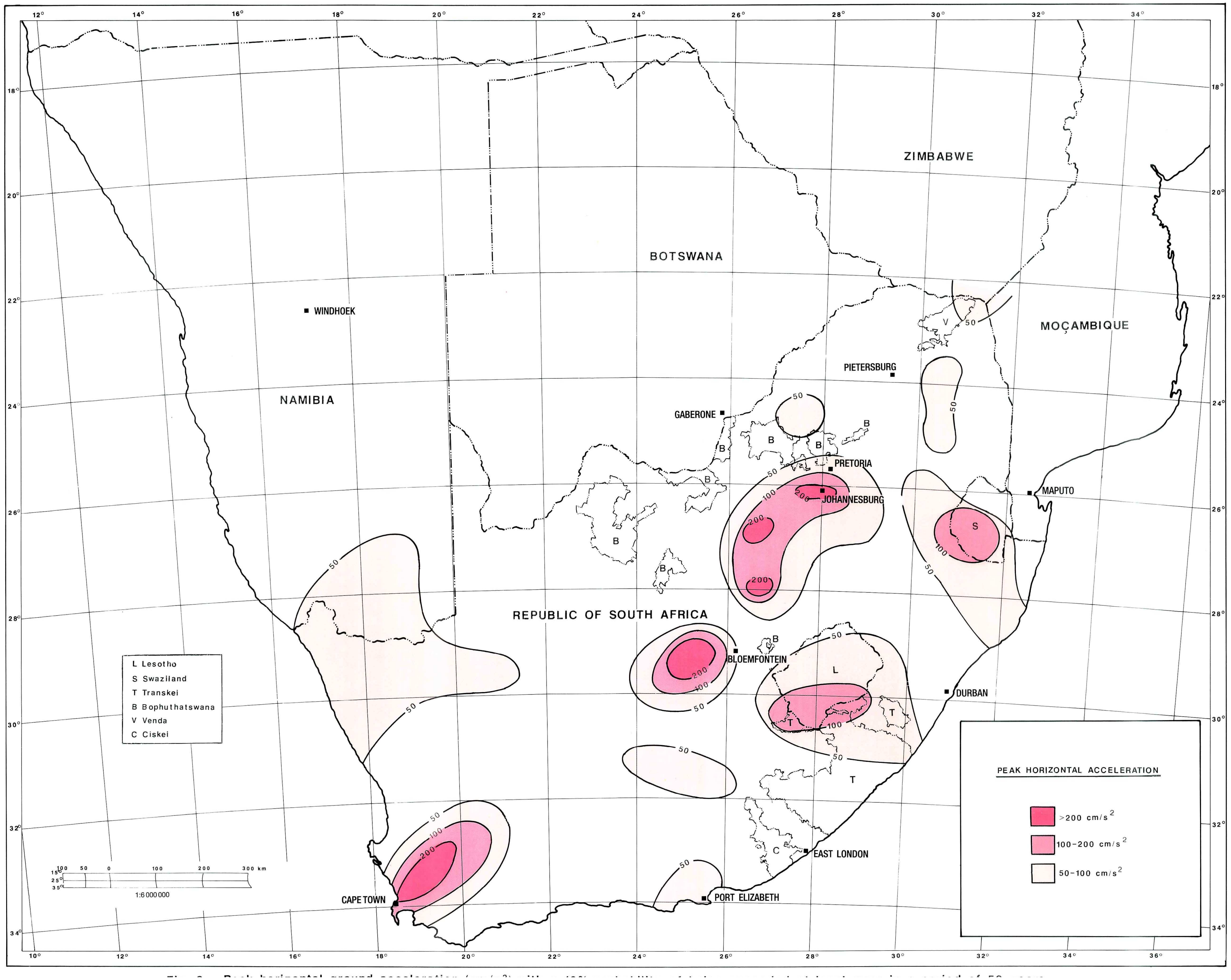

Figure 4: Peak horizontal acceleration (cm/s^2) with a 10% probability of being exceeded at least once in a period of 50 years

4 South African Seismograph Network and Database

The South African National Seismograph Network (SANSN) was established to monitor the seismicity in and around South Africa. It underwent significant changes in 2005 to 2006. This was the result of three earthquakes that were felt in South Africa, namely: M=9.1 near Indonesia on 26 December 2004 that caused an Indian Ocean tsunami; M=7 in southern Mozambique on 23 February 2006 that was felt all over northeastern- and eastern South Africa; and M=5.3 mine-related event on 9 March 2005 in the Klerksdorp gold-mining area that caused some damage to buildings and the mine itself. These events prompted upgrading to extended short-period and broad band seismometers that record continuously as opposed to only triggered events before (Saunders et al., 2008).

4.1 Limitations and the need for updating the SHA maps

The Seismic Hazard maps for Southern Africa do not fulfill the requirements of advanced industry stakeholders in liquid gas - and nuclear construction.

Specifically, there are four shortcomings that originate from the SANSD namely:

(1) Location uncertainty;
(2) Magnitude calibration;
(3) Hypocentral depth uncertainty; and
(4) Limited knowledge about earthquake mechanisms.

In addition, modern Seismic Hazard Maps are derived with probabilistic methods and advanced statistical methods to incorporate uncertainty with logic trees and expert opinion. Once a seismological database that fulfills international standards has been assembled, stakeholders may use it to derive updated seismic hazard maps and/or seismic hazard studies for their specific areas.

In order to address some of the shortcomings of the SANSD the National Research Foundation has made funding available via its Technology and Human Resources for Industry Programme for project TP2010061400012: “Seismological data base for nuclear power plants”. This project aims to make progress towards improving the location uncertainty of all recorded tectonic earthquakes using the program HYPOCENTER (Lienert and Havskov, 1995) for the period 2003 to 2009 starting with the previous network and adding increasingly more new waveform data until the end of 2006 when the upgrade was complete. Relocations are being completed with modern procedures (Havskov and Ottemöller, 2010) and using additional data from stations of the global network not used until then.

The first step to prepare the updated SANSD for hazard studies is to identify and remove quarry blasts. Literature was consulted about mining activities in South Africa (e.g. Wilson and Anhaeusser, 1998; Gold & coal mines, 1999), followed by an investigation with Google Earth (http://earth.google.com) to identify open cast mines and structures such as shafts and mine dumps on maps and images. South Africa is blessed with large coal-, diamond- and mineral resources that are mined over large areas. Hence, this method was preferred above an automatic procedure which assumes that most blasts occur during the daytime and thus mapping out the daytime to nighttime event ratio. The re-located earthquake catalog for 2006 has been completed and published (Saunders *et al*., 2010). Figure 5 taken from Saunders *et al*. (2010) show the re-located tectonic earthquakes in comparison to the seismograph stations. Ultimately all tectonic earthquakes will be re-located.

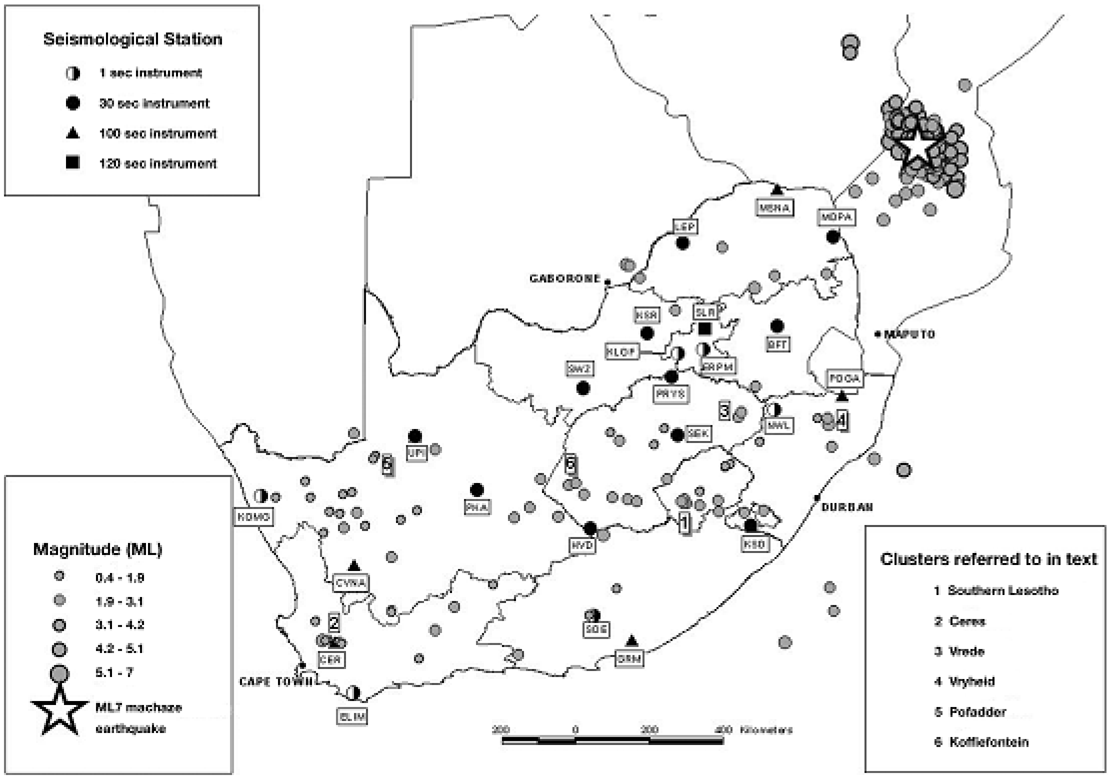

Figure 5: Spatial distribution of seismological stations comprising the SANSN with epicentres of tectonic earthquakes recorded during 2006 (Taken from Saunders et al., 2010).

Another shortcoming is that magnitudes reported by the SANSN are not calibrated against those reported by international agencies such as the International Seismological Centre (of which the South African National Seismograph Network is a member). Three local earthquake magnitudes, as reported by the National Network, were tested against moment magnitude and discrepancies were found between magnitudes (Brandt and Saunders, 2011). Specifically, there were discrepancies of local magnitudes over estimate earthquake size as is shown below in Table 1 taken from Brandt and Saunders (2011).

Table 1: Event parameters of the earthquakes used in Brandt and Saunders' (2011) study and their calculated moment magnitudes. For geographical details, see Figure 6.

	Date	Lat.	Lon.	Depth (km)	Ms ISC	ML PRE	Mw	Remarks
1	97-09-25	-26.37	27.52	2	3.7	4.5	4.1	Mine-related earthquake.
2	98-12-05	-26.36	27.61	2	3.9	4.3	4.1	Mine-related earthquake.
3	99-02-04	-29.76	25.70	5	N/D	4.5	3.8	Compare with event C1 & C2.

ISC = International Seismological Centre

PRE = Council for Geoscience, Pretoria

The discrepancy between local and moment magnitude is not unexpected, because M_L calculations in South Africa are based on the original definition by Richter for southern California. Since the tectonic setting of South Africa differs significantly from southern California, this affects the attenuation of wave energy with distance. Thus, overestimation of M_L with increasing epicentral distance is routinely observed when locating earthquakes with the SANSN.

This overestimation becomes severe with ~1 to 1.5 units for stations at far regional distances beyond 1000 km. M_L standard deviation typically ranges between 0.2 and 0.4 units, and one could not expect a linear M_L–M_w relationship. This has a major impact on seismic-hazard analysis and seismotectonic interpretations in South Africa because both these fields depend on earthquake statistics, specifically the relative and absolute number of small to large earthquakes for a given source area or active fault system. Local- and moment magnitude scales are currently being developed for South Africa to address these shortcomings (Brandt and Saunders, 2011).

The other two shortcomings of the South African dataset are the lack of hypocentral depth information and earthquake focal mechanisms. Both of these are important for hazard analysis as they determine the ground motion characteristics for which an engineer should design.

Brandt and Saunders (2011) determined a depth of 1 km and 2 km for mine-related earthquakes 1 & 2 and a depth between 9 km and 11 km for tectonic earthquake 3 in Figure 6**.** Again, like before, this is only a test for three earthquakes and more research is needed to quantify earthquake depth in South Africa.

Brandt and Saunders (2011) also interpreted the earthquake mechanisms in Figure 6. The stable Kalahari Craton might experience subtle heating and uplift owing to the African superplume and/or lithospheric modification at its base. The interior of southern Africa (except for Mozambique) has approximately 500 m positive residual elevation. The African superplume is a large-scale, low-shear velocity anomaly that extends from the core-mantle boundary to about

1500 km depth under eastern Africa, within which viscous flow from the lower into the upper mantle is thought to lead to surface uplift. The little information that is available suggests that the seismogenic faulting mechanisms in South Africa changes from normal faulting (extension) in the northeast near the east African rift to strike-slip faulting in the southwest.

In northeastern South Africa, fault plane solutions reflect crustal stresses associated with uplift/rifting even though the higher seismicity associated with the east African rift does not extend into the country. Stresses related to deep mining operations modify the normal faulting regime causing local volume closures.

Earthquakes denoted by C prefixes (Figure 6) with conflicting solutions C1 and C2 and different tensor (3) are situated at the change-over area to southwestern South Africa.

In southwestern South Africa, ridge push from the surrounding plate boundaries and/or local crustal thicknesses determines appear to control the stress regime.

Once all of the above research has been completed the updated SANSD will be evaluated for quality and completeness and then made available for seismic hazard analysis to stakeholders in the liquid gas- and nuclear industry. New Seismic Hazard Maps for Southern Africa to replace those by Fernandez and Du Plessis (1989) will also be published.

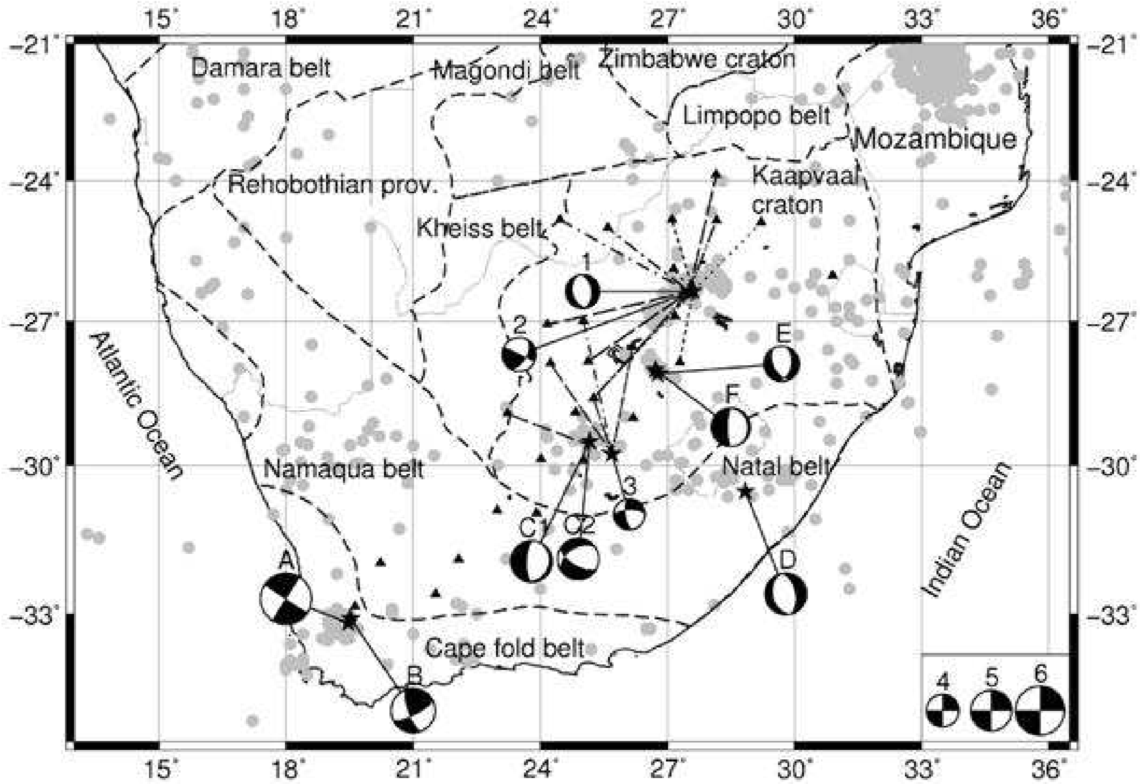

Figure 6: Location map of the seismic stations and earthquakes used in their study. Black stars represent the epicenters and triangles the stations. Moment-tensors/fault-plane solutions are indicated with "beach balls" with sizes proportional to magnitude. Previous solutions are marked with letters A to F and new moment tensors by numbers 1 to 3. Dotted and dash-dot lines show where waves propagate between earthquakes 1 to 3 and the stations used for the moment tensor inversions; other stations were used for the fault plane solution. Major tectonic provinces are separated with thick dashed lines and are labeled. Earthquakes from 1620 to 2009 with local magnitude larger than and equal to 4 are plotted with gray dots. (Taken from Brandt and Saunders, 2011).

5 Identification of zones and hot spots

The first published study to identify seismotectonic zones in South Africa and estimate earthquake catalog completeness was undertaken by Shapira *et al*. (1989). They identified seismic sub-regions A, B, C and D using historical earthquakes from 1620 to 1950 (Figure 7) and instrumentally located earthquakes up to 1985 (Figure 8).

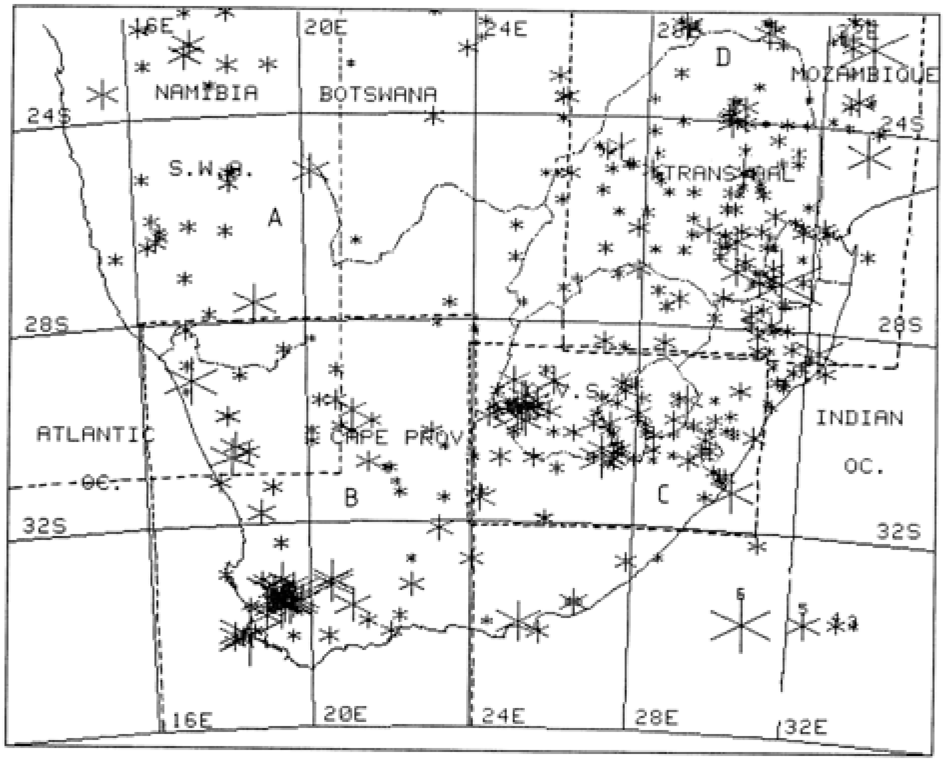

Figure 7: Epicenter location of earthquakes of ML>3 for the period 1620 to July 1950. The size of the location symbol is related to the magnitude of the event. Seismic sub-regions A, B, C and D are outlined (Taken from Shapira et al., 1989).

They estimated the completeness of the SANSD in 1989 to be:

Magnitude ML	Date complete since:	Period T(M) in years
> 3.0	1971	15
> 4.5	1950	38
> 4.8	1910	76
> 5.2	1906	80
> 5.9	1806	180

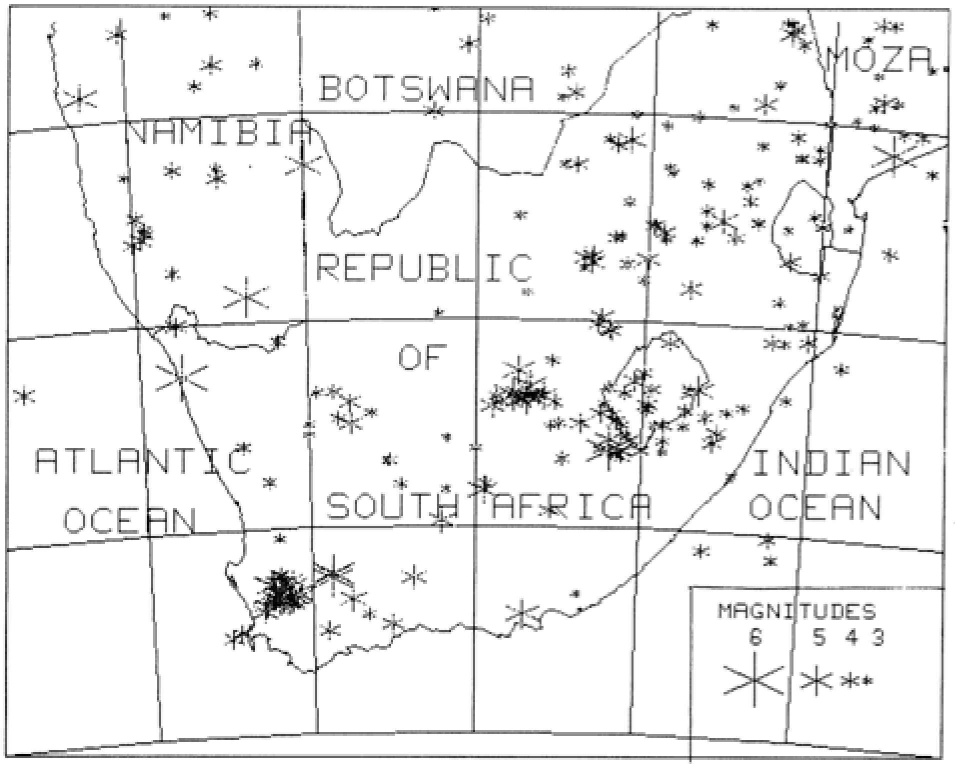

Figure 8: Epicenter locations of tectonic earthquakes of ML>3 for the period 1951 to July 1985 (mostly instrumentally located) (Taken from Shapira et al., 1989).

A more recent study to identify zones and hotspots and hence derive seismotectonic models for South Africa was completed by Singh *et al*. (2009). They identified a number of prominent seismic clusters or "hotspots" in South Africa:

• ***Historical Earthquakes in the Cape Town area*** - Earthquakes in this cluster were compiled from diaries, journals, and newspaper articles written from 1620 to 1902. The locations are given as Cape Town because this is where the effects were felt, but Brandt *et al.* 2005 proposed that actual epicenter could be 100 km away or more. No earthquakes have been located in the Cape Town area since instrumental recording began in 1972.

• ***Ceres Cluster*** - Earthquakes of *ML* 1 to 3 are recorded in this region six times per month, on average. The well-known 1969 Ceres earthquake (M_L 6.3) occurred near the western termination of the Ceres-Kango-Baviaanskloof-Coega fault system, an E-W striking major line of Mesozoic faulting traversing the southern Cape Fold Belt between Ceres in the west and Port Elizabeth in the east.. Ongoing research on this fault system has shown that an M_w 7.0 earthquake may have occurred some 10000 years ago east of Oudtshoorn in the Baviaanskloof.

• ***Koffiefontein Cluster***- A M_L 6.2 earthquake occurred here in 1912. Very preliminary paleoseismic observations suggest that a large earthquake (M_w 8) might have occurred here some 50000 years ago. The abundance of thermal springs in this area lends further support to the interpretation that the area is undergoing active crustal deformation.

• ***Lesotho Cluster*** - The rate of seismicity toward the north of Lesotho increased significantly after the impoundment of the Katse Dam. 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.

Clusters are identified in Figure 9 (from Singh *et al*., 2009).

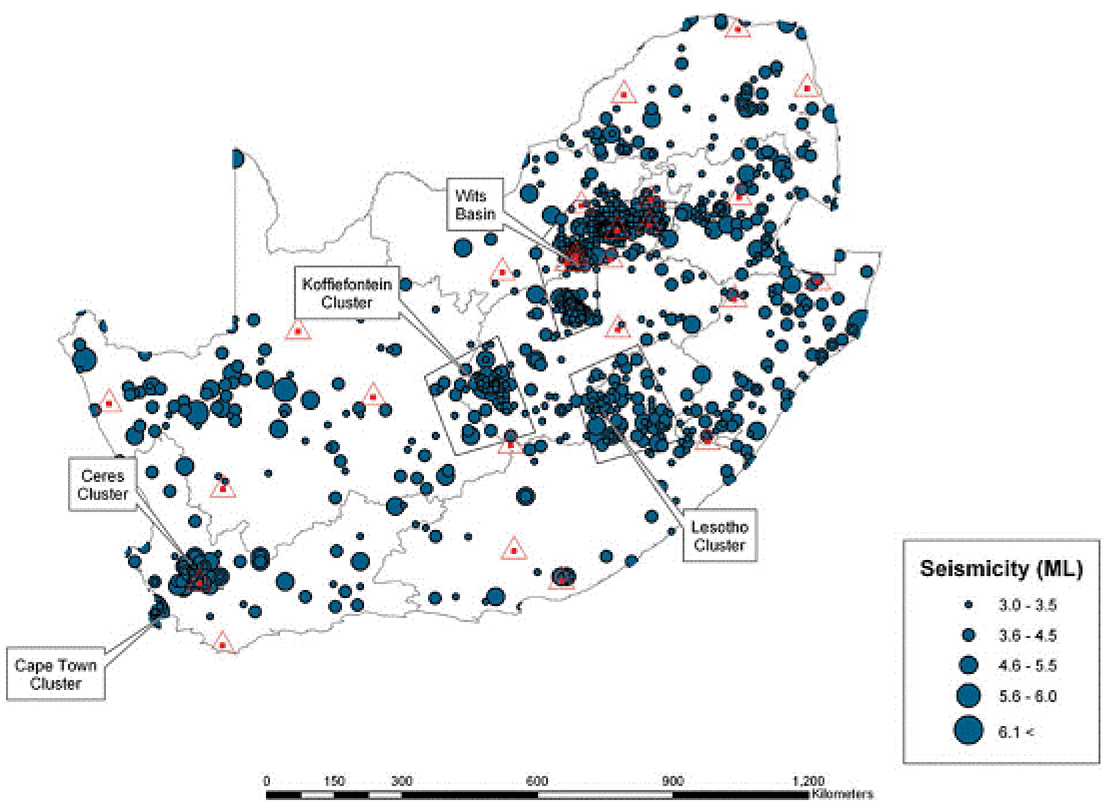

Figure 9: Map of Earthquakes 1620 - 2008 contained in the South African National Seismological Database (SANSD). Known clusters relating to natural and mining-induced seismicity are highlighted. The seismic recording stations are represented by triangles (from Singh et al., 2009).

5.1 Discussion of the Effect on Hotspots by the SANSD Update

It is not foreseen that completion of the NRF funded SANSD update will fundamentally change the location of the above-mentioned clusters. Large earthquakes that occurred in the clusters were felt and reported by the local people and instrumentally determined earthquake size could be estimated independently from effects on people, and damage caused to buildings and infrastructure. However, smaller earthquakes and aftershocks that occurred in the clusters as well as events detected by the SANSN, but not felt and/or reported, may change significantly during the update, both in terms of location and magnitude. Together with research results from studies of hypocenter depth and earthquake focal mechanisms, the updated SANSD will provide a wealth of new information with regard to:

- spatial-temporal seismicity patterns;
- seismotectonic zones;
- fore- and aftershock occurrences in clusters;
- smaller clusters and hotspots unknown before;
- correlation of earthquakes hypocenters with faults, dykes and other geological structures;
- statistical earthquake occurrence patterns;
- earth processes; etc.

All of this information will be used as input data for updated Seismic Hazard Maps for Southern Africa and be made available to stakeholders who require hazard analysis.

6 Local earthquake monitoring

On a global scale, South Africa is considered a stable region, because it is located away from boundaries between tectonic plates. Therefore its activity rate is lower than in seismically active regions like California or Japan. This means that while earthquakes are comparatively rare, they can still happen from time to time, and sometimes this manifests itself as an earthquake swarm.

The area of Augrabies is currently experiencing an earthquake swarm. Earthquake swarms are events where a local area experiences sequences of many earthquakes in a relatively short period of time. The length of time used to define the swarm itself varies, but a swarm may last in the order of days, weeks, or months, but rarely more than two years. They are differentiated from earthquakes succeeded by a series of aftershocks, by the observation that no single earthquake in the sequence is obviously the main shock.

Earthquake swarms occur regularly throughout the world, with recent examples including the swarm that occurred in southern California and Mexicali in February 2008, with over 500 events recorded during that single month. Another swarm began in February 2008 near Reno, Nevada, continued for several months, ending in November 2008. Between February and April this swarm produced more than 1000 quakes of small-to-moderate magnitude. Closer to home, an earthquake swarm occurred in the Sutherland area in early 1952, with no further significant activity recorded since.

As part of its national monitoring programme, the Council for Geoscience has been constantly monitoring the seismic activity in the Augrabies area. The first recorded earthquake of the present swarm occurred during February 2010 but it was only when the population felt an earthquake measuring 3.7 on the local magnitude scale on 26 July 2010, that people became aware of this seismic activity. Since then, at least five earthquakes exceeding magnitude 4 have occurred near Augrabies, the largest to date being magnitudes 4.2 and 4.9, events that occurred on 12 and 25 January, respectively. Historical records include reports of an event being felt near Kakamas in 1918.

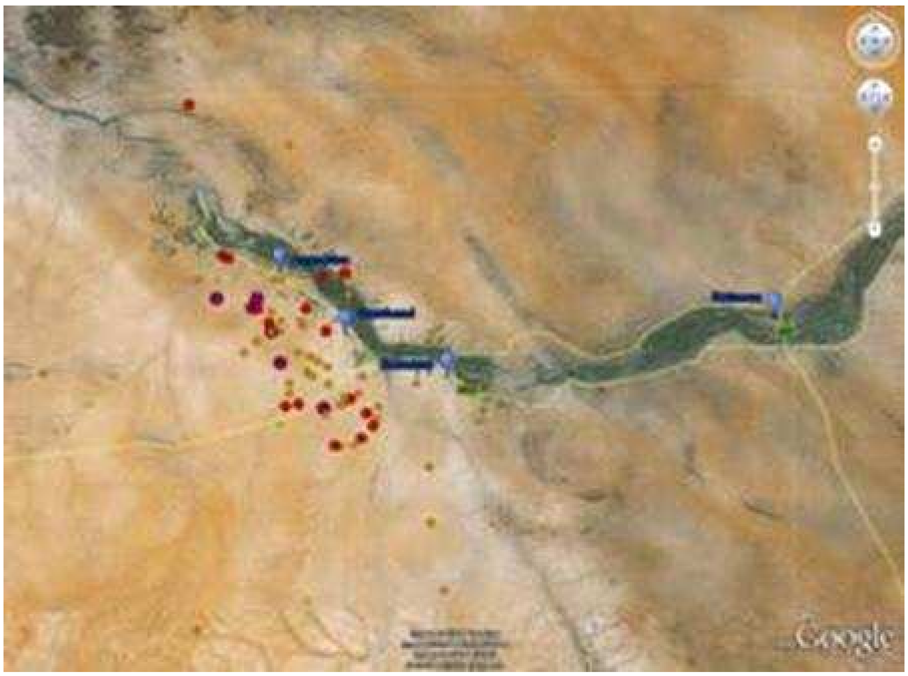

Figure 10: Map of seismicity of the Augrabies area for the period April 2010 to January 2011.

The Augrabies area is situated on the boundary of the Kaapvaal Craton (Archean), the Kheis orogenic belt (1 800 Ma) and the Namaqua-Natal orogenic belt (1000 Ma). This area is highly deformed and there are numerous faults, shear zones, folds and other lineaments, which could provide weak areas in the crust. It also lies on strike of the Hebron fault in Namibia, which is known to have been active during recent times. Earthquake epicentres tend to lie parallel to the Orange river in that area, on both sides of the river, and the structural maps indicate a number of faults striking parallel to this trend all along the river. A possible explanation therefore is that the Orange River follows a weak zone in that area, caused by a relatively wide zone of faults, some of which are being activated by the current strain in the crust.

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