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First-order regional seismotectonic model for South Africa

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Abstract A first-order seismotectonic model was created for South Africa. This was done using four logical steps: geoscientific data collection, characterisation, assimilation and zonation. Through the definition of subunits of concentrations of earthquake foci and large neotectonic and structural domains, seismotectonic structures, systems and domains were created. Relatively larger controls of seismicity exist between the Great Escarpment and the coast. In the south, this region is characterised by large aeromagnetic anomalies and large EW trending faults. In the west, it is characterised by the NW–SE trending Wegener stress anomaly, radial-trending dykes and earthquake clusters. In the east, it is characterised by a large neotectonic domain where several large historical earthquakes occurred. In the centre of South Africa, several clusters of earthquake activity are found, often related to mining activity. Further north, seismicity is related to both mining activity and neotectonic deformation. This work contributes to the development of a seismotectonic model for South Africa by (1) bringing together, digitally, several data sets in a common GIS platform (geology, geophysics, stress, seismicity, neotectonics, topography, crustal and mantle structure and anisotropy), (2) understanding the significance of data sets for seismotectonic zonation and limitations thereof and (3) obtaining a reasonable regional model for use in seismic hazard assessments.

Keywords Seismotectonic model · South Africa · Seismicity · Zonation

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1 Introduction

The seismic hazard and risk associated with potential sites of engineering structures (such as dams and power stations) are derived from a seismotectonic model for the region. To date, there is no published seismotectonic model for South Africa. Furthermore, no standard procedure has been established by the scientific community to produce a seismotectonic model.

As a first step towards the creation of a seismotectonic model for South Africa, Singh et al. (2009) compiled a multidisciplinary geoscientific database. They identified many useful data sets, but found that further seismic monitoring, geological mapping and integrated analysis were required to build an entirely data-driven seismotectonic model. The following recommendations were made by Singh et al. (2009):

1. A denser network of seismic monitoring stations is required in order to improve location accuracy of recorded earthquakes;
2. The earthquake database should be revisited in order to distinguish earthquakes of natural origin from those that are mining related;
3. Depths and focal mechanisms of earthquakes should be recorded and routinely published;
4. Microseismic monitoring should be undertaken of active regions like the Ceres and Koffiefontein areas and active fault regions in the Cape Fold Belt (CFB);
5. Quaternary sediments should be mapped in more detail; and
6. Evidence of palaeoseismicity and neotectonic activity should be documented.

Noting these shortcomings, an attempt is made here to build a first-order regional seismotectonic model using the available information.

2 Review of literature

Different researchers have used different parameters to perform seismotectonic investigations (Erdik et al. (1991); Gonzalez and Skipp (1980); Hicks et al. (2000); Johnston (1996) and Meletti et al. (2000)). This could be due to the wide variety of geological settings, basic assumptions and philosophical approaches [e.g., Gasperini et al. (1998) defined seismotectonic units from historical felt earthquake reports for the central and southern Apennines in Italy. Mohanty and Walling (2008) used a GIS platform for seismic microzonation of Haldia in the Bengal Basin (India)].

Of the many methodologies implemented elsewhere in the world, the one of Terrier et al. (2000) used in France was found to be most appropriate for South Africa, as it allowed one to use an integrated approach by using all available information in a series of logical steps.

The seismotectonic model derived for stable continental regions often does not explain all the observed earthquake activity. This is because structures may exist without recognised surface or subsurface manifestations, and, in some cases, fault displacements may have long recurrence intervals with respect to seismological observation periods. Although attempts should be made to define all the parameters of each element in a seismotectonic model, the construction of the model should be data driven, and any tendency to interpret data only in a manner that supports some preconception should be avoided (IAEA 2002, p. 10, Para. 4.3). One of the main advantages of the methodology used for France (Terrier et al. 2000) is that it is a structured approach and is highly data driven.

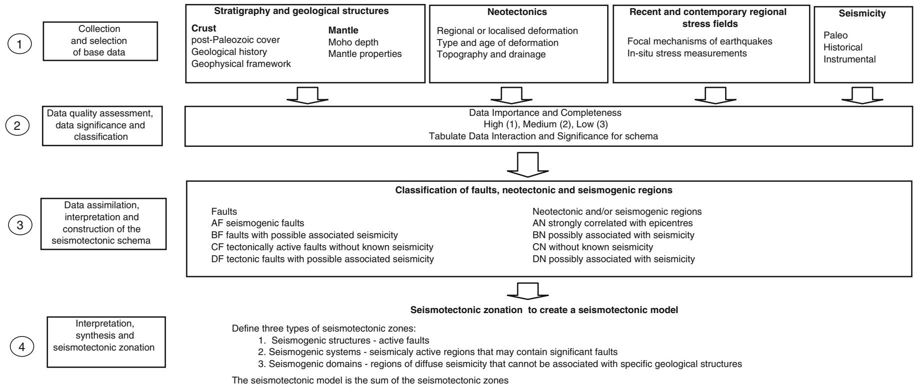

Fig. 1 Schematic representation of stages in the creation of a regional seismotectonic model (adapted from Terrier et al. 2000)

3 Outline of the methodology

Terrier et al. (2000) define *seismotectonic analysis* as the analysis of structural, neotectonic and seismological data to establish links between seismicity and current deformation mechanisms, and their effects on certain tectonic structures, with the ultimate goal of delimiting and characterising various seismotectonic units. *Seismotectonic units* correspond to tectonic structures like faults, or to geological and structural bodies of uniform seismicity. The *seismotectonic model*, otherwise known as a seismotectonic map, will consist of a presentation of all the seismotectonic units identified for the region of interest. An ideal delineation of seismotectonic units requires a complete comprehension of the geology, tectonics, palaeoseismology, historical and instrumental seismicity, and other neotectonic features and phenomena. However, information is incomplete in many parts of the world.

The methodology for the seismotectonic analysis encompasses four stages:

1. Data collection
2. Data quality assessment
3. Data assimilation, interpretation and construction of seismotectonic schema, and
4. Synthesis and compilation of seismotectonic model.

Note that in this study an additional stage was added, (data quality assessment) when compared to the methodology proposed by Terrier et al. (2000) because of the shortcomings noted in the introduction to this chapter. The flowchart summarising the proposed methodology is shown in Fig. 1.

4 Results and discussion

4.1 Stage 1: collection and selection of base data

The data sets collected for this stage include the following:

1. A comprehensive earthquake catalogue of historical and instrumental events from the Seismology Unit, Council for Geoscience (CGS)

2. Isoseismal maps for the country since 1932 (Singh and Hattingh 2009)
3. Regional geological maps
4. Magnetic and gravimetric data (Geophysics Unit, CGS)
5. Map of the depth to Moho (Nguuri et al. 2001)
6. Tectospheric structure (James et al. 2001)
7. Topographical data and
8. Stress data (World Stress Map (WSM) database; Reinecker et al. 2004; Bird et al. 2006)

These data sets are described in detail by Singh et al. (2009). Shortcomings in the data sets have been noted in the introduction to this chapter.

The data sets compiled in Stage 1 are used to define structural and neotectonic domains, and seismic zones. In Stage 2, the usefulness, importance and completeness of each data set is assessed.

Structural domains are regions that display homogeneous mechanical behaviour and contain major faults or structures. *Neotectonic domains* are regions characterised by recent or contemporary tectonic activity. Seismic zones [or *concentrations of earthquake foci* (CEF)] are identified by known historical and instrumental earthquake clusters.

4.2 Stage 2: assessment of data quality and usefulness

First, the usefulness of various data sets for the definition of *structural domains* is described, together with a qualitative assessment of the importance and completeness of each data set (Table 1).

Similarly, the usefulness of various data sets for the definition of *neotectonic domains* and *seismic zones* is assessed (Tables 2, 3, respectively). The neotectonic information generally falls into two categories: descriptions of large well-studied faults and ad hoc accounts of reactivated features.

Table 1 Mapping of structural domains

Type of data (source)	Possible use	Importance High 1 Medium 2 Low 3	Data completeness High 1 Medium 2 Low 3
Geological maps (CGS)	Shallow structure	1	1-Extensive mapping
Crustal thickness (Nguuri et al. 2001)	Deep structure	2	2-Data coverage for large region
Subsurface structure, lithosphere thickness (Fouch et al. 2004)	Deep structure	2	2-Data coverage for large region
Topography (CGS)	Shallow structure	2	1-Good coverage
Aeromagnetic maps (CGS)	Identification of regional anomalies and large structural domains	3	1-Good coverage
Gravimetric maps (CGS)	Identification of regional anomalies and large structural domains	3	1-Good coverage

Table 2 Mapping of neotectonic domains

Type of data	Usefulness for fault characterisation	Importance High 1 Medium 2 Low 3	Data completeness High 1 Medium 2 Low 3
Reactivated fault scarps	Yes	1	3-Sparse data set
Regions of observed neotectonic activity	Yes	1	3-Sparse data set
Thermal springs	Yes	1	3-Sparse data set
Stress indicators	Maybe	1	3-Sparse data set
Seismic anisotropy (Silver et al. 2004; Dr. Matthew Fouch, personal communication)	Not directly	2	2-Data coverage for large region
Axis of warping	Yes	2	3-Interpretation

Table 3 Mapping of concentrations of earthquake foci

Type of data	Usefulness for fault characterisation	Importance High 1 Medium 2 Low 3	Data completeness High 1 Medium 2 Low 3
Earthquake catalogue (1620–2008)	Maybe	1	2-Incomplete data set
Compilation of isoseismal maps (Singh and Hattingh 2009)	Maybe	1	1-Thirty-four maps compiled since 1932

4.3 Stage 3: data assimilation, interpretation and construction of schema

A structured approach is followed in creating the seismotectonic schema that is a schematic plan consisting of a combination of structural and neotectonic domains, and seismic zones. Specific data sets contributing to each classification are highlighted in Tables 1, 2 and 3. From this stage onwards, some interpretation is required. Hence, interpretations vary depending on the experience and background knowledge of the analyst.

4.3.1 Structural domains

Here, we seek to integrate various data sets to define structural domains.

4.3.1.1 Geological and geophysical provinces The major geological provinces are outlined in Fig. 2. The major geological provinces include the Kaapvaal Craton (KC) of Archean age. Some authors (e.g. Eglington and Armstrong 2004) have further divided this province based on the age of lithologies (up to 3 Ga). For our purposes, we are interested in changes in tectonic environments and opted to present this craton as one large province. The Limpopo Belt separates the KC from the Zimbabwe Craton (ZC), which is of similar age and composition. The oblique nature of this collision is believed to have initiated or reactivated major transcurrent fault systems, resulting in important structures such as the Thabazimbi–Murchison Lineament. Rift-related basins like the Witwatersrand Basin developed within the KC. The Bushveld Complex intruded the KC about 2,000 million years ago. Tectonic activity on the KC ceased about 1,800 million years ago. Proterozoic

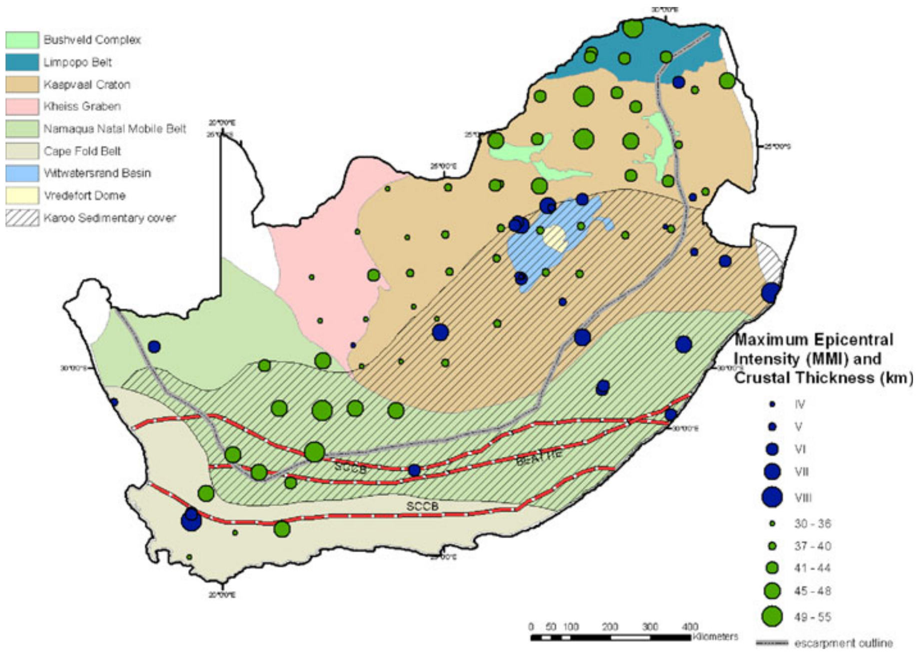

Fig. 2 Geological provinces and crustal thickness results from Nguuri et al. (2001)

fold and thrust belts up to 400 km wide were added to the KC on the south (Namaqua–Natal Mobile Belt, NNMB). The Kheis Province (Cornell et al. 2006), which consists of a passive margin of siliciclastic rocks of the Olifantshoek Supergroup (2–1.7 Ga), separates rocks from the western part of the NNMB from the KC.

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. However, it is relatively thin. Its strata, mostly shales and sandstones, record an almost continuous sequence of marine, glacial and 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 north-east around 200 million years ago. This break-up proceeded 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).

The boundaries of the provinces are often clearly revealed in the geophysical maps. The major geophysical anomalies such as the Beattie Magnetic Anomaly and the Southern Cape Conductivity Belt are also illustrated.

4.3.1.2 Mantle seismic structure The mantle seismic structure beneath the Kaapval Craton (KC) was studied by Fouch et al. (2004). It was found that seismic images provide clear evidence of mantle structures that mimic the surface geology across the craton. Specifically, a thick ($\sim$250 to 300 km) mantle keel exists beneath the KC and a slightly thinner keel ($\sim$225 to 250 km) exists beneath parts of the Limpopo mobile belt. Relatively lower mantle velocities are observed beneath the Bushveld Complex.

4.3.1.3 Crustal structure Nguuri et al. (2001) found that the Limpopo Belt is characterised by a thick crust and complex Moho, while the crust beneath the KC is typically thin ($\sim$35 to 40 km), unlayered and characterised by a strong velocity contrast across a relatively sharp Moho. Across post-Archaean terrains such as the Bushveld Complex and the Namaqua–Natal Mobile Belt (NNMB), the crust tends to be relatively thick ($\sim$45 to 50 km) and the Moho is complex.

4.3.1.4 Topography and drainage Generally the country can be divided into two basic drainage systems: the Orange River as one system and all the other rivers comprising the other. These two systems are divided by the Great Escarpment. The Orange River drains from the interior of the country to the west. All the other rivers drain from the coastal side of the escarpment to the ocean in western, southern and eastern directions. In the north, the tributaries of the Limpopo/Olifants River form a watershed on the Witwatersrand. It is worth noting that regional seismicity, to a large extent, correlates well with the location of the Great Escarpment. This is evident in the north-west, along the Lesotho mountain ranges, and the north-east. Some of the largest earthquakes for which macroseismic data are available occurred along this escarpment.

4.3.1.5 Discussion Based on the above data sets, clearly, the pre-Karoo geological provinces form the main structural domains of the country. The other prominent structure is the Great Escarpment.

4.3.2 Concentrations of earthquake foci

Eighteen earthquake clusters were intuitively identified (Fig. 3, refer to Table 4 for names of clusters and brief description of possible source). The best-known clusters are described in Singh et al. (2009). Along the east coast, at least 10 isoseismal maps collected in Singh and Hattingh (2009) clearly show a high density of large-magnitude earthquakes in these regions, hence linear clusters 4, 5, 14 and 15 were created.

4.3.3 Neotectonic domains

4.3.3.1 Classification Neotectonic faults (F) were classified (see Table 5) using a scheme similar to Terrier et al. (2000):

AF are seismogenic faults with a strong correlation with seismic epicentres.
BF are seismogenic faults with possible associated seismicity as seismic epicentres are known near the faults, but the precision of their locations does not guarantee a reliable link.

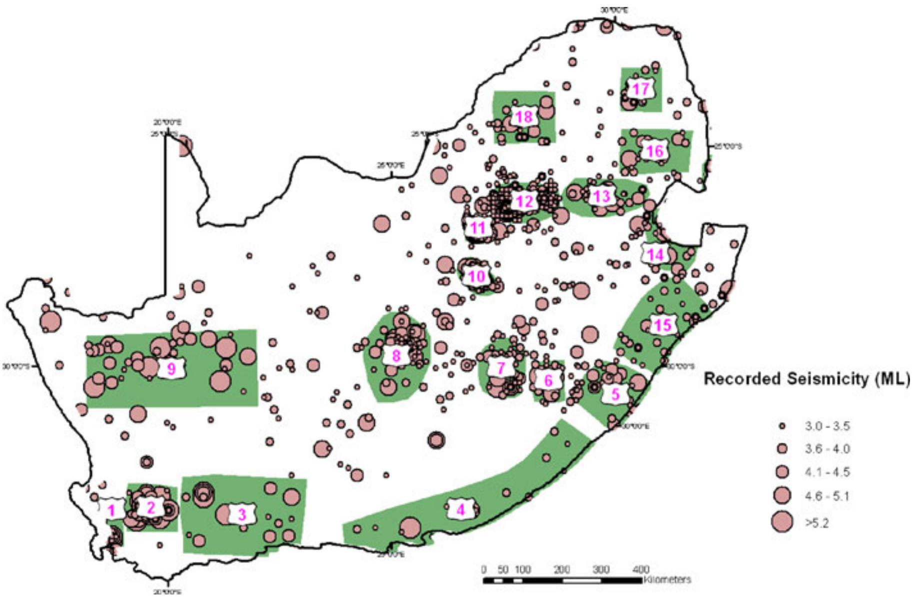

Fig. 3 CEF schema consisting of 18 clusters

Table 4 Visual identification of CEF

CEF cluster number	Comment
1	Historical earthquakes in Cape Town Cluster
2	Ongoing earthquake activity in the Ceres region
3	Sporadic low density (large > ML4) earthquakes along the CFB
4	Linear-like trace of relatively lower density events along the east coast
5	Cluster of events along the east coast—source unknown at this stage
6	Cluster of events identified visually in Lesotho—source unknown at this stage
7	Cluster of events identified visually in Lesotho—source unknown at this stage
8	Cluster of events identified visually near Koffiefontein—source unknown at this stage
9	Large > ML4 earthquakes—also known as the Grootvloer cluster
10	Cluster of events in Welkom gold-mining district
11	Cluster of events in Klerksdorp mining district
12	Cluster of events in Carletonville-West Rand mining district
13	Explosions in the coal fields
14	Cluster of events identified visually near Swaziland—source unknown at this stage
15	Cluster of events identified visually along the east coast—source unknown at this stage
16	Cluster of events identified visually—source unknown at this stage
17	Cluster of events identified visually—source unknown at this stage
18	Cluster of events—possible relation to platinum mines

Table 5 Classification of neotectonic evidence (faults only)

Feature	Abbreviation	Description of evidence	Source	Correlation with seismicity/ CEF zone	Category
Kango Baviaanskloof fault	KBF	Has reactivated fault scarps in some places of between 2 and 4 m high	Hill (1988)	Large part falls in Zone 3, some parts in Zones 2 + 4	AF 1
Kuiseb-Hebron fault	KHF	Displaced Cenozoic/ quaternary sediment up to 65 m	T. Partridge (personal communication)	Out of region of interest	
Rietfontein fault	RF	In Gauteng, the Rietfontein fault system runs from Edenvale in the east to beyond Krugersdorp in the west. A series of landslides are found along this fault. This fault system may be the source of localised distress in buildings and may also be the locus of low-level seismic events	Barker (2004)	Located in mining region of Rand—Zone 12	DF 4
Port Dunford-Mozambique coastal faults	PDMOZ	Late Pleistocene to Holocene faults are well exposed at Port Dunford near Richards Bay extending northwards, through the St. Lucia Lakes and the northern KwaZulu Natal coastal plain into southern Mozambique	Andreoli et al. (1996)	Few events, Ml 6.3 event of 1932 occurred in this vicinity	BF 2
Tshipise fault	THPSE	Have young fault scarps ranging from 2 to 10 m height displacing aeolian sands	T. Partridge (personal communication)	No seismicity	CF 3
Bosbokpoort	BBSBK	Have young fault scarps ranging from 2 to 10 m height displacing aeolian sands	T. Partridge (personal communication)	No seismicity	CF 3
Coega fault	CGA	Young fault	Hattingh and Goedhart (1997)	Some seismicity, low-station coverage Zone 4	DF 4
Thabazimbi–Murchison greenstone belt	TMB	Natural seismicity associated with this lineament, contains the Zebediela fault and Thabazimbi fault—related to subsidence of Bushveld Basin by 400 m and has a number of thermal springs	Andreoli et al. (1996)	Zones 17 and 18	AF 1

AF seismogenic faults, *BF* neotectonic faults with possible associated seismicity, *CF* tectonically active faults without known seismicity, *DF* tectonic faults with possible associated seismicity, 1–4 is given as level of importance to the model

CF are tectonically active faults without known seismicity as no seismic epicentres are correlated with them, but with indicators of recent tectonic activity.

DF are tectonic faults with possible associated seismicity as seismic epicentres are known along the faults (similar to BF) and some neotectonic indicators.

Neotectonic and seismogenic regions (N) were also classified (see Table 6) using a scheme similar to Terrier et al. (2000):

- AN are seismogenic and neotectonic regions that have a strong correlation with seismic epicentres.
- BN are neotectonic regions with possible associated seismicity as seismic epicentres are known in the regions, but the precision of the locations does not guarantee a reliable link.
- CN are neotectonic regions without known seismicity, but with indicators of recent tectonic activity.

The classified neotectonic faults and regions were digitised (Fig. 4) and neotectonic domains defined. Each neotectonic subdomain delineates the fault/region and extends this region to about 50 km in all directions in order to include those earthquakes that are possibly mislocated.

4.3.3.2 Stress and seismic wave anisotropy Tectonic stress indicators are used to determine the tectonic stress orientation. A sparse data set of such indicators is available for South Africa through the World Stress Map (WSM) database (Reinecker et al. 2004) and a database created by Bird et al. (2006). Data points derived from earthquake focal mechanisms and in situ stress measurements (overcoring), geological fault-slip observations (GFS) and borehole breakout orientation (BO) were accumulated. A detailed description of the different methodologies used can be found in Zoback and Zoback (1991) and Sperner et al. (2003). These data are plotted in Fig. 5, superimposed on CEF clusters. Only broad trends in the data can be observed owing to the sparse number of data points. Earthquakes forming clusters 2 and 3 have strike-slip regimes, while earthquakes in cluster 8 show normal faulting. Other earthquakes towards the north have normal faulting regimes. The orientation of the maximum horizontal stress (SH) varies from the north to the south. In the north, SH directions are NW–SE, corresponding to similar orientations of the Wegener stress anomaly (WSA). Stress indicators from earthquakes in the Koffiefontein region (cluster 8) have a NW–SE SH orientation with a normal faulting regime. The earthquake of 1 July 1976 was used for this measurement. For the data points in the south, the earthquakes of 2 September 1969 and 14 April 1970 were used.

Additional data included in Fig. 5 are the shear wave splitting data from Silver et al. (2004). In an anisotropic medium, the elastic parameters vary as a function of orientation. Seismic anisotropy occurs when some elastic waves vibrating or travelling in one direction travel faster than other waves vibrating or travelling in another direction within the same medium. This causes the waves to separate in orthogonal directions (shear wave splitting). Materials develop anisotropic properties because of the preferred ordering of minerals or defects, i.e. fractures or cracks. Anisotropy is linked to minerals, kerogen, fractures and stresses. The polarisation direction of the fast wave (phi) can be measured, and the delay time between the fast and slow waves (dt) gives us information about the magnitude of anisotropy. The values of phi exhibit systematic spatial variations. In the south-western KC, they are roughly NNE–SSW and rotate to NE–SW further north and to nearly E–W in the north-eastern part of the craton. Further south, in the NNMB, polarisation of waves varies from NW–SE to E–W. This anisotropic signature implies a pattern of ancient mantle lithospheric deformation beneath South Africa. Silver et al. (2004) observed that the anisotropic signature is delimited by the Colesburg magnetic lineament towards the south-west of the craton, by the Thabazimbi–Murchison Lineament (TML) in the north and by

Table 6 Classification of neotectonic evidence: reactivation of faults, thermal springs, altering of drainage lines, axis of warping and subsidence

Feature	Abbreviation	Description of evidence	Source	Correlation with seismicity/CEF zone	Use
Bultfontein (SW)	BLTSW	Recent fault zone reaching the surface 10 km south-west of Bultfontein	Andreoli et al. (1996)	Not sure	BN 4
Bultfontein (N60)	BLTN60	Widespread reactivation of Precambrian faults from the Wesselbron panneveld 60 km north of Bultfontein in the Krugersdorp area	Andreoli et al. (1996)	Not sure	BN 4
Griqualand-Transvaal Axis	GTA	Related to the subsidence of the Kalahari Basin. Small movements along this axis led to disruption of drainage networks and development of new drainage lines	T. Partridge (personal communication)	Three parts can be considered (West, Zone 9, Middlesome seismicity—no zone identified, East—gold-mining Zones 11, 12)	AN 1
Saldana-Agulhas-Axis	SAA	Along this axis, there are regions where lithologies occur below sea level. In the Cape Agulhas, fluvial terraces of probably Neogene ages are uparched across this axis. Neotectonic joints, faults and breccias cut consolidated and semi-consolidated Late Pliocene to Pleistocene calcarenites near Gansbaai, Quoin Point, Cape Agulhas and Gouriqua	Andreoli et al. (1996)	Occurs between Zones 1 and 2	AN 1
Ciskei Swaziland Axis	CSA	Earthquakes in Lesotho occur near the Cedarville fault and Cedarville flats alluvial deposits located on the inland flank of the CSA. Thermal springs in KwaZulu Natal and Mpumalanga also occur along this axis	Andreoli et al. (1996), Kent (1981)	Occurs along Zones 4, 6, 5, 15, 14. Several large earthquakes occurred along this axis for which macroseismic data are available	AN 1

AN seismogenic and neotectonic regions, *BN* neotectonic regions with possible associated seismicity, *CN* neotectonic regions without known seismicity, 1–4 is given as level of importance to the model

the Triangle Shear Zone in the Limpopo Belt. The delay time falls mainly in the range of 0.6–2 s. There is clearly strong anisotropy towards the NW of the craton compared to weaker anisotropy towards the SW. Silver et al. (2004) indicate that these differences are

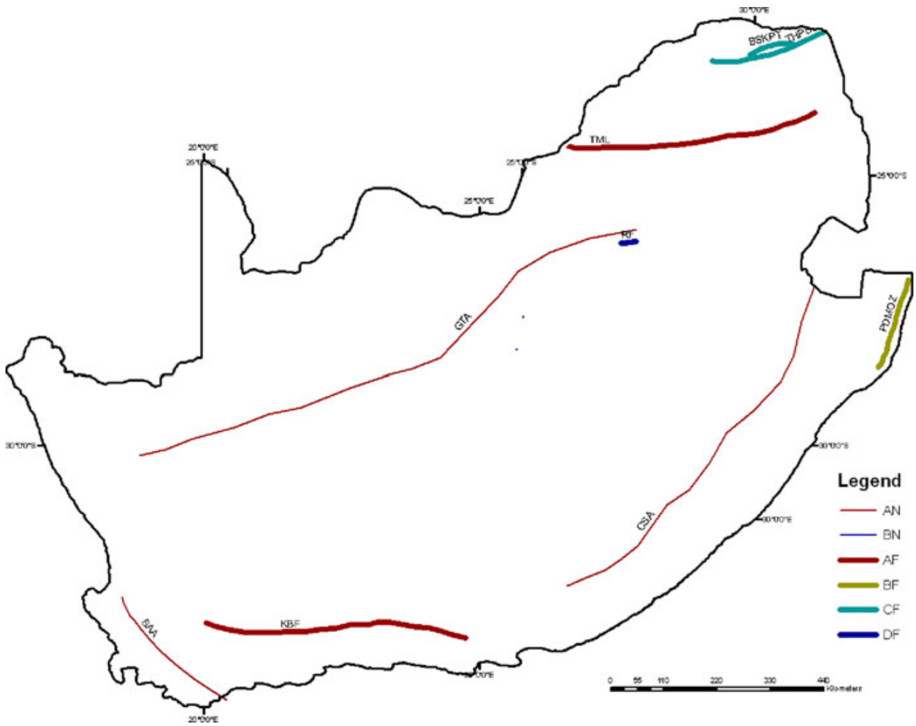

Fig. 4 Classification of neotectonic faults and reactivated features. Refer to Tables 5 and 6 for symbol meanings and full names of features

due to differences in lithospheric mantle fabric. The eastern part of the craton is devoid of rifting and magmatic events seen elsewhere in the craton, and hence, the lithosphere here is mechanically stronger than surrounding areas.

4.4 Stage 4: interpretation and synthesis: seismotectonic zonation

Based on the knowledge gained from the analysis so far, as well as the data availability and applicability, it was decided that it was best to use the categories proposed by Davis (2002) for seismotectonic zonation. Note that although Terrier et al. (2000) use similar labels to categorise the seismotectonic units, their definitions of the categories are much more rigorous. In our case, the data set is incomplete in several aspects; therefore, the more flexible definitions provided by Davis (2002) is more applicable.

Three general types of *seismotectonic units* are defined by Davis (2002):

1. Seismogenic structures—units that model active faults
2. Seismogenic systems—units that model "active" structures that may contain significant faults (i.e. active fold belts) and
3. Seismogenic domains—units that model distributed seismicity that cannot be assigned to specific geological structures.

Consideration was given to the schema obtained in stage 3, and polygons were created corresponding to major clusters of earthquake foci (CEF) and neotectonic domains (refer to

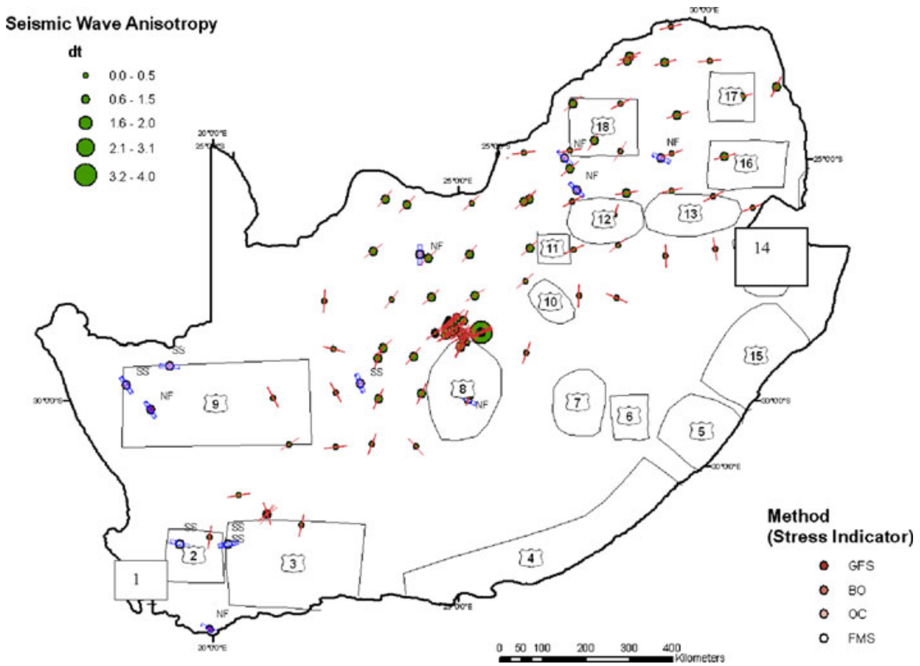

Fig. 5 World Stress Map data and data from Bird (2006). Earthquakes forming *Clusters 2 and 3* have strike-slip regimes. Earthquakes in *Cluster 8* show normal faulting. Other earthquakes towards the north have normal faulting regimes. The method used for calculating stresses are indicated (*FMS* focal mechanism solution, *OC* overcoring, *BO* individual breakouts, *GFS* geological fault slip). Orientation of *symbol* (*red line*) corresponds to the maximum horizontal stress (*SH*). *SS*: strike-slip SH > SV > Sh; *NF* normal faulting SV > SH > Sh

Figs. 6, 7). The large structural domains eventually made no contribution to the zonation because many of the neotectonic domains transect the structural domains. Probably the outline of the Great Escarpment, to some extent, is intrinsically included. Only two seismogenic structures were delineated: the reactivated region of the Kango Baviaanskloof Fault (KBF) and its linear extension towards the east. The main neotectonic domains form seismogenic systems. Clusters of earthquake foci with no association with large faults or neotectonic activity form the seismogenic domains. In Table 7, characteristics of the identified seismogenic structures and systems are summarised.

The Gutenberg–Richter frequency–magnitude relations were assessed using seismicity within each zone (Fig. 8). Where it is assumed that the number of earthquakes recorded within specified area and time interval can be described by the Gutenberg–Richter relation

$$\log N(m) = a - b \cdot m, \tag{1}$$

where a is a constant, b refers to the slope of the line, m is the earthquake magnitude and N the cumulative number of earthquakes occurring annually within a magnitude interval $<m, m + \Delta m>$, or the number of earthquakes equal or larger than m. The parameter a is the *measure of the level of seismicity*, whereas the parameter b, which is typically close to 1, describes the *ratio between small and large events*.

The software package Zmap (Wiemer 2001) was used for this purpose (assuming the maximum curvature method to evaluate m_{min} (the threshold of completeness of the

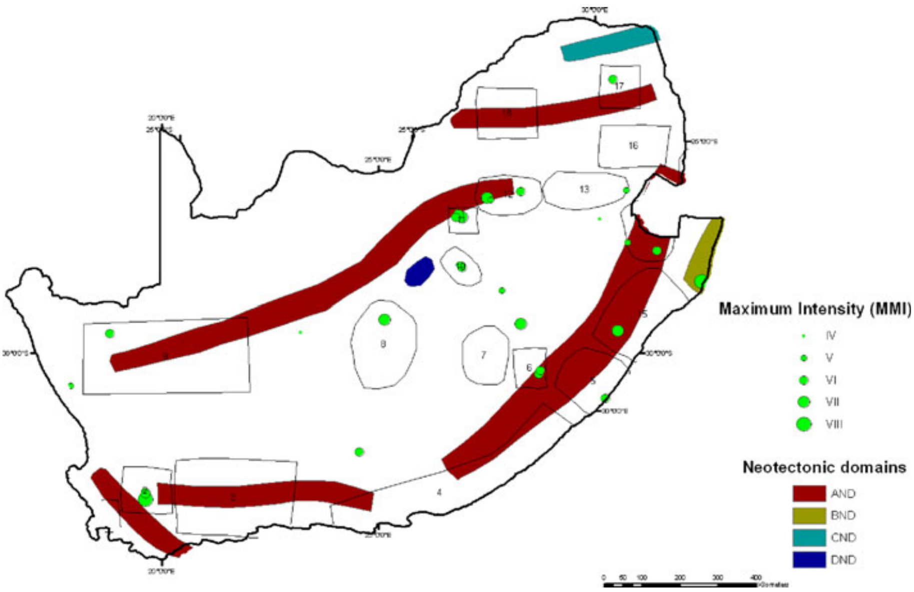

Fig. 6 Classified neotectonic domains and CEF schema. The neotectonic domains (AND-DND) are indicated according to the classification scheme implemented

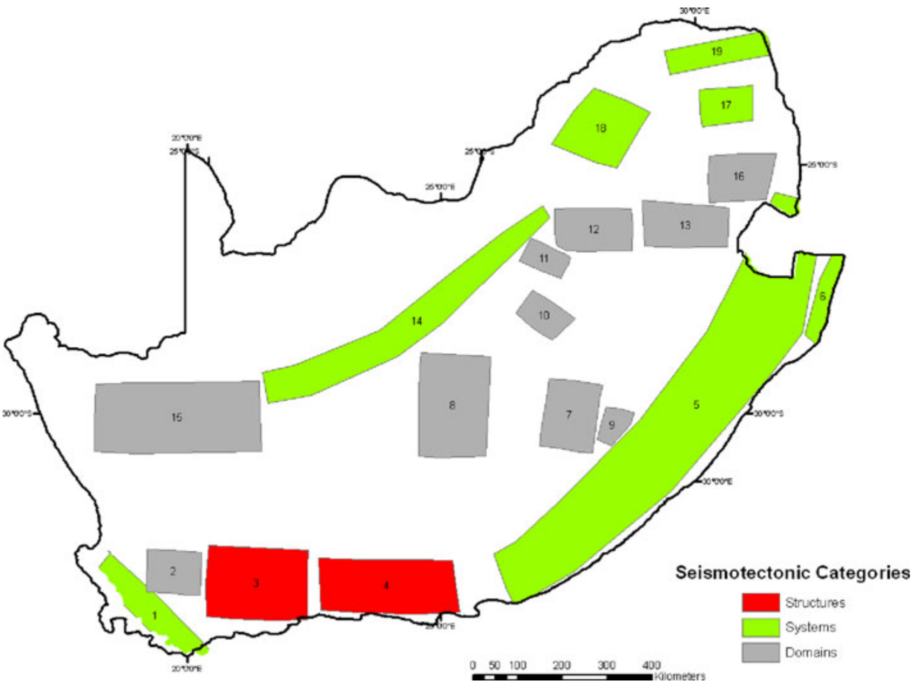

Fig. 7 Seismotectonic model for South Africa comprising seismotectonic systems, domains and structures (refer to text for explanation)

Table 7 Main characteristics of seismogenic structures and systems

	Reference earthquakes	Present deformation and stresses	Geological province	Strikes of main faults and other characteristics
Seismogenic structure AZ				
3	CEF 3	KBF-reactivated fault scarps	CFB—folded coastal delta sediments	E–W strike, strike-slip KBF(E–W strike, normal fault)
4	CEF 4	Continuation of KBF	CFB—folded coastal delta sediments	KBF(E–W strike, normal fault)
Seismogenic system BZ				
1	CEF 1 (mainly historically reported earthquakes)	SAA (see details in Table 6)	CFB—folded coastal delta sediments	
5	CEF 4, 5, 14, 15, several events available with macroseismic information	CSA (see details in Table 6)	Passes through all major geological provinces	
6	1932, Ml 6.3 St. Lucia Earthquake	PDMOZ (see details in Table 5)	Rocks forming the NNMB	
14	Low level of earthquake activity	GTA (see details in Table 6)	Rocks forming the Kheiss Graben and the KC	NE–SW anisotropy
17, 18	CEF 17, 18	TMB (see details in Table 5)	KC	EW—ENE anisotropy
19	Low level of earthquake activity	BBSBK and THPSE (see details in Table 5)	Limpopo Belt	EW anisotropy

subcatalogue) and the maximum likelihood method to assess *b*). The parameters obtained for each zone are listed in Table 8. Note that no solution could be obtained for Zones 1, 3, 4, 6 and 19 due to insufficient seismicity data within each zone.

The Welkom (Zone 10), Klerksdorp (Zone 11) and Carletonville-West Rand (Zone 12) mining regions clearly have relatively higher levels of seismic activity than other zones. *b* values for Zone 10 and 12 are similar (1.1 and 1.2) with Zone 12 displaying higher levels of seismic activity. Zone 11 has a somewhat lower *b* value (0.99) but very high levels of activity. Clearly, this is reminiscent of differences in mining activity in the different regions and different tectonic features affecting the mining environments.

The Ceres Zone (Zone 2) has much lower *b* values (0.63) but considerable levels of seismic activity. These levels of activity exceed that of the Koffiefontein Zone (Zone 8) with a similar *b* value (0.56). Zone 5 (which can be found along the east coast) shows considerable levels of activity with a much higher *b* value (1.08). The seismicity trends in Zone 15 are very similar to that of the Koffiefontein Zone (Zone 8). The Lesotho cluster (Zone 7 and 9) shows relatively lower levels of activity with *b* value of 0.8 and 0.68, respectively, which is somewhat different from all the other zones. Zone 14, corresponding to the Griqualand-Transvaal Axis (GTA), has the lowest levels of seismic activity. Similarly, relatively lower levels of seismic activity occur in Zones 13 and 16–18.

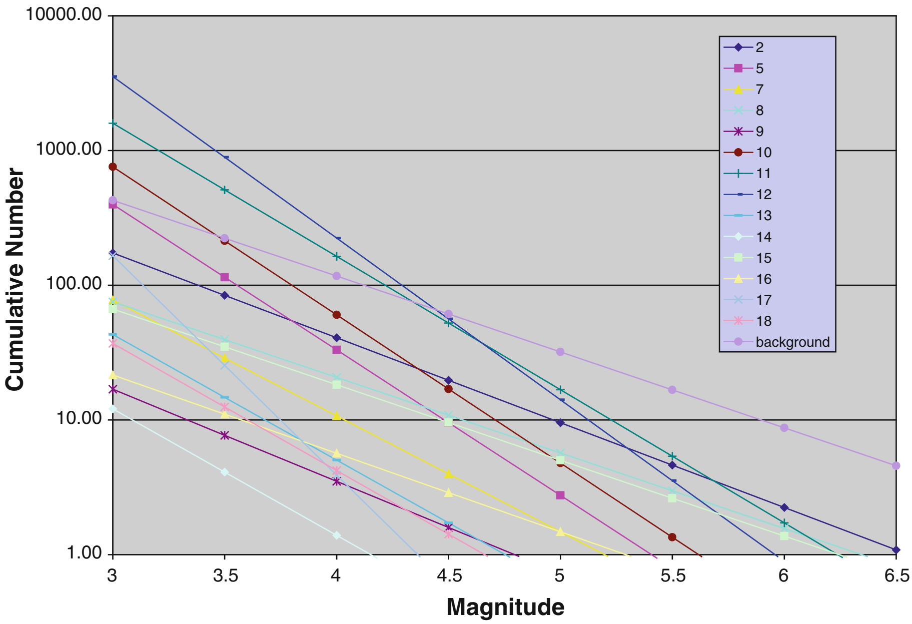

Fig. 8 Plot of Gutenberg–Richter frequency–magnitude relations for seismicity within each zone. Note that no solution could be obtained for Zones 1, 3, 4, 6 and 19 due to insufficient seismicity data within each zone

Table 8 Parameters for the Gutenberg–Richter frequency–magnitude relation

Zone number	m_{min}	b	Standard deviation of b	a	a (Annual)
2	3.4	0.63	0.06	4.13	1.96
5	3.7	1.08	0.2	5.84	3.64
7	3.4	0.86	0.1	4.47	2.38
8	3	0.561	0.06	3.56	1.55
9	3.2	0.684	0.2	3.28	1.54
10	3.1	1.1	0.03	6.18	4.45
11	3	0.989	0.02	6.17	4.42
12	3.1	1.2	0.02	7.15	5.15
13	3	0.932	0.2	4.43	2.43
14	3	0.939	0.2	3.9	1.6
15	3.7	0.562	0.09	3.51	1.23
16	3.2	0.582	0.1	3.08	1.1
17	3.7	1.63	0.7	7.11	5.12
18	3	0.944	0.2	4.4	2.4
Background	3	0.563	0.02	4.32	1.81

5 Perspectives

This work serves as a starting point for the development of the geoscientific database and seismotectonic model. Clearly, the structural domains are not critical for the zonation because the seismotectonic model transects the boundaries of the structural domains. Probably, more consideration is required in understanding the geodynamics associated with the stresses along regions such as the Great Escarpment, the Cape Fold Belt and the Lesotho mountain ranges. Localised seismotectonic domains exist in the interior of the country (Koffiefontein, Zone 15, Zone 16) for which its origin/source is still poorly understood. Seismicity in the mining regions (Zones 10–13) still forms a major component of the seismic history in the country. From a crude assessment of the parameters of the Gutenberg–Richter frequency–magnitude relation, relative levels of seismic activity and *b* values were obtained. Clearly, the highest levels of mining activity originate in the gold-mining regions. Naturally occurring earthquakes that have relatively higher levels of seismic activity originate from the Ceres, Koffiefontein and CSA domains. More detailed assessment of these parameters will be considered in another publication.

This is a regional model and should not be used as such in seismic hazard investigations for industrial applications but is suitable for hazard assessment at a regional level. In these cases, all attempts should be made to complete the database by using a higher resolution. Seismotectonic model development applying the methodology adopted here could be appropriate.

Following this study, an ongoing update of the geodatabase will be made. Other ideas for the future include statistical identification of seismic sources, seismic zonation using historical data, correlation of data using GIS techniques and appropriate spatial weighting of layers. A broader study in progress is the Seismotectonic Map of Africa (SeTMA) (Ingram 2008) that should add value to the understanding of seismotectonic zonation within the region.

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