Earthquake hazard in Africa: perspectives on the Nubia–Somalia boundary

C.J.H. Hartnady*

A wide plate boundary zone between the Nubia and Somalia plates extends through eastern and southern Africa, from the Red Sea–Gulf of Aden region to the mid-oceanic Southwest Indian Ridge. The observed pattern of earthquake activity divides it into seismic belts surrounding relatively stable aseismic blocks. In eastern Africa, the Ukerewe Nyanza plate and the Rovuma plate are separately distinguishable, but in southern Africa and the adjacent Southwest Indian Ocean, the separation of the Transgariep and Lwandle blocks remains to be demonstrated. Because of the slow rates of plate motion along the wide Nubia–Somalia plate boundary and the correspondingly long recurrence times of major events, the quantitative assessment of earthquake hazard requires a new method of estimating maximum magnitudes in the seismic belts, based on the principle of seismic moment conservation. Application of this method requires that the rates and directions of motion of the major plates and the boundary zone blocks be known with sub-mm/yr accuracy. A proposed new project to extend the network of space-geodetic observatory sites in Africa and establish a unified continental reference frame would determine these motions and thus contribute to a long-term African international strategy for natural disaster reduction.

Between 10 and 16 July 2002, three small to moderate earthquakes were recorded in East and South Africa, and a fourth occurred along the Southwest Indian Ridge (SWIR) (Table 1). These seismic events were aligned along or close to a major tectonic structure that has developed across the former African plate[1] during the last few million years, namely, the boundary between the Nubia (NB) and Somalia (SM) plates (Fig. 1). Their occurrence follows shortly after publication of recent work on the SWIR that dates the NB–SM boundary to probably greater than 11 Myr,[2] following earlier results that demonstrated resolvable tectonic motion since at least 3 Myr ago.[3]

At the foundation of plate-tectonic theory, the African plate was identified as one of the globe's principal regions of rigid lithosphere, but geological observations of the great East African Rift System (EARS) had long suggested that the continent was split between western and eastern tectonic blocks. In 1970, separate NB and SM plates were first proposed and named[4] around a triple junction between the Gulf of Aden and the Red Sea. For more than two decades, however, great difficulty was experienced in translating this concept into a quantitative model of the relative motion of the NB and SM plates, to the extent that the team responsible for the NUVEL-1 standard model[1] of global plate motions admitted frustration and defeat on this particular issue.

In some representations, the NB–SM boundary is shown as a wide zone of uniformly distributed, diffuse deformation.[5–7] In East Africa, however, the boundary structure is more complex. On seismological and structural grounds two relatively aseismic blocks — enclosed by narrower belts of neotectonic rifting, volcanism, and concentrated earthquake activity — are recognized (Fig. 2). These stable blocks lie between the EARS Western Branch, along the lakes belt of Tanganyika-Rukwa-Malawi (TRM), and the EARS Eastern Branch with its southerly extensions along the submarine Davie Ridge in the Mozambique Channel.[8]

Ancient continental lithosphere of the Tanzanian craton forms the central core of the Ukerewe Nyanza (UN) plate, formerly the Victoria plate.[9] South of the ENE/WSW-trending neovolcanic zone around the Kenya–Tanzania border, between the Chvulu Hills, Kilimanjaro and

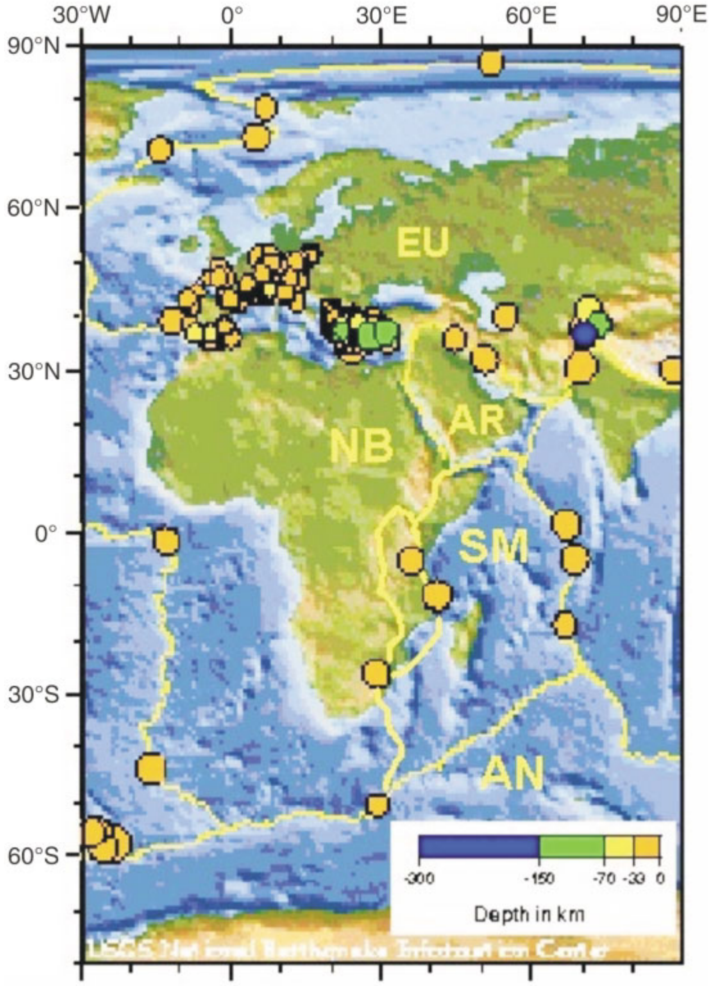

Fig. 1. African portion of global map of earthquakes in the Quick Epicentre Determination (QED) database of the USGS National Earthquake Information Center (NEIC), for the 30-day period prior to 1 August 2002. Yellow lines represent plate boundaries: African lithosphere junctions with Eurasian (EU), Arabian (AR) and Antarctic (AN) plates are from the original source, those between the Nubia (NB) and Somalia (SM plates have been added.

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*Umvoto Africa (Pty) Ltd, P.O. Box 61, Muizenberg 7950, South Africa. E-mail: chris@umvoto.com

Table 1. Recent earthquakes along the Nubia–Somalia plate boundary.

Date Time	Latitude (°S)	Longitude (°E)	Depth (km)	Magnitude	Region
2002/07/10 11:04:05.1	5.370	35.880	10	4.7	Tanzania
2002/07/12 03:16:55.0	26.357	28.972	5	4.7	South Africa
2002/07/12 10:55:23.1	50.658	29.103	10	4.1	South of Africa
2002/07/16 14:50:14.2	11.688	41.098	10	5.2	Northwest of Madagascar

Data from USGS/NEIC online catalogue at http://wwwneic.cr.usgs.gov/neis/qed/qed.html

Mount Meru, another stable continental block incorporates southern Tanzania and northern Mozambique, extending some distance into the oceanic lithosphere of the Mozambique Channel. Formerly grouped with the UN plate as part of the Mozambique microplate,[10] this block is now called the Rovuma (RV) plate,[11] after the river that marks the border between Tanzania and Mozambique (incidentally establishing a pattern of naming the block-like tectonic entities in this region after significant bodies of water).

A particular feature of the latest work on the SWIR[2] is the discovery that the triple junction between the NB, SM and Antarctic (AN) plates is restricted to a relatively narrow region along the Andrew Bain Fracture Zone, one of the longest transform fault zones on the planet, named after the 'Father of South African Geology' by the writer and Robert Fisher during the latter's 1984 Protea Expedition on R/V *Melville.* In a 1984 letter to Seth Stein and Richard Gordon, the principal authors of the NUVEL-1 plate-motion model,[1] I indicated that the NB–SM–AN triple junction might be located on this structure. Confirmation of this hunch after nearly 20 years is heartening.

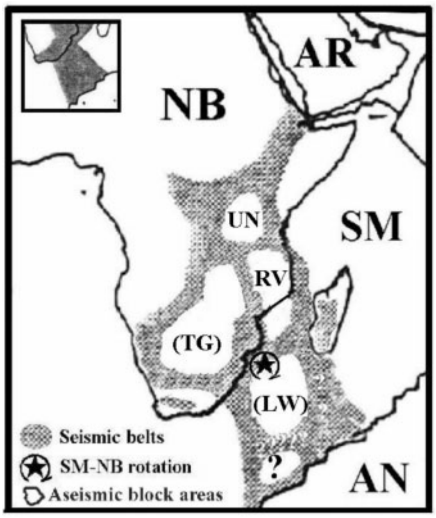

Fig. 2. African composite plate, subdivided (after ref. 11) into smaller, relatively stable blocks separated by seismically active belts (shaded zones). Identified aseismic or low-seismic areas are the Ukerewe Nyanza (UN) and Rovuma (RV) blocks in East Africa, and the Transgariep (TG) and Lwandle (LW) blocks in the southern African region. The UN block was-formerly called the Victoria plate.[9] Star symbol at 27.3°S, 36.2°E off the Mozambique coast marks the pole of SM finite rotation (clockwise at 0.089°/Myr) over the last 3 Myr, in the NB reference frame.[3] Modified from global diagrams by Gordon,[6,7] which show the NB–SM boundary as a homogeneous wide zone (see inset at upper left).

That the triple junction along the SWIR was not a diffuse feature (Fig. 2) during most of the period since 11 Myr ago, but instead was narrowly confined near longitude 30°E,[2] suggests that for much of that time the connection to the continental portion of the NB–SM boundary in southeastern Africa was also tightly constrained to a relatively narrow belt. In this regard the evidence of neotectonic activity around the submarine Natal Valley and the southern Mozambique Ridge[12,13] forms part of the link between the African continent and the SWIR, and is explained as a consequence of NB-SM plate motion.

The existence of two further stable blocks has been suggested from the distribution of earthquake epicentres in southern Africa. The Okavango Rift in Botswana, juvenile rift-grabens in southern Mozambique, and a discrete zone of seismicity across South Africa between southern Namibia and Lesotho (the Senqu Belt)[11] bound northern, western and southern margins of the Transgariep (TG) block (Fig. 2). Early very-long-baseline interferometry (VLBI) space-geodetic data from the Hartebeesthoek Radio Astronomy Observatory near Pretoria indicated that its motion was ~5 mm/yr different from the NUVEL-1 model motion for this part of the African (mainly the NB) plate.[14] However, more recent global positioning system (GPS) results indicate that the entire NB plate moves more slowly than NUVEL-1 predictions,[15] and that the relative motion of the TG and NB plates might be less than 1–2 mm/yr. For the time being, therefore, the TG block (Fig. 2) is included as part of the NB plate.

Likewise, a dominantly oceanic Lwandle (LW) block (the name is derived from the Xhosa word for ocean)[11] may extend southwards from the southern boundary of the RV plate in the Mozambique Channel between southern Mozambique and Madagascar. However, the pattern of oceanic earthquake epicentres (Fig. 3) is too sparse and poorly known to allow definite conclusions to be drawn at this stage. While sizeable earthquakes have occurred within the oceanic lithosphere between the SWIR and the continental margin of southeast Africa, their plate-tectonic significance is unclear, and the LW block is better included as a southerly portion of the SM plate (Fig. 2).

Some of East and southern Africa's largest and fastest growing urban centres are located close to the western margin of the SM plate, and are particularly vulnerable to neotectonic activity along this belt. In Kenya, the coastal city of Mombasa, with a population approaching 1 million people, depends almost entirely for its water supply on springs located in the Chyulu Hills, where the most recent volcanic activity occurred approximately only 500 years ago. The Tanzanian capital of Dar-es-Salaam lies close to the RV–SM plate boundary (Fig. 4), and Mozambique's two largest urban centres are likewise in seismically hazardous locations. Beira is close to the Urema Graben structure, a segment of the NB–RV boundary, and Maputo lies within a locally complex NB–RV–SM triple junction (Fig. 2). In KwaZulu-Natal, the cities of Durban and Pietermaritzburg are vulnerable to earthquake hazard along the NB–SM boundary.

The small earthquakes of July 2002, strung out along the NB–SM plate boundary (Fig. 1), should serve as a wake-up call to policy-makers and those with hazard- and disaster-reduction responsibilities in Africa. The Global Seismic Hazard Assessment Programme (GSHAP) had a specialist working-group for Eastern and Southern Africa,[16] but its earthquake catalogue (Fig. 2 in ref. 16) under-represents the seismic activity in the southern Mozambique coastal plain and nearby offshore Mozambique Channel. Hence the probabilistic seismic hazard assessment (PSHA) (Fig. 4) fails to recognize the continuity of seismically hazardous zones in this area, particularly the southern RV plate boundary along the offshore of the Quathlamba Seismicity Axis (QSA).[10]

The two largest earthquakes in the southern African region in historical times occurred along the offshore QSA. The International Seismological Centre's (ISC) online *Bulletin*[17] records that the

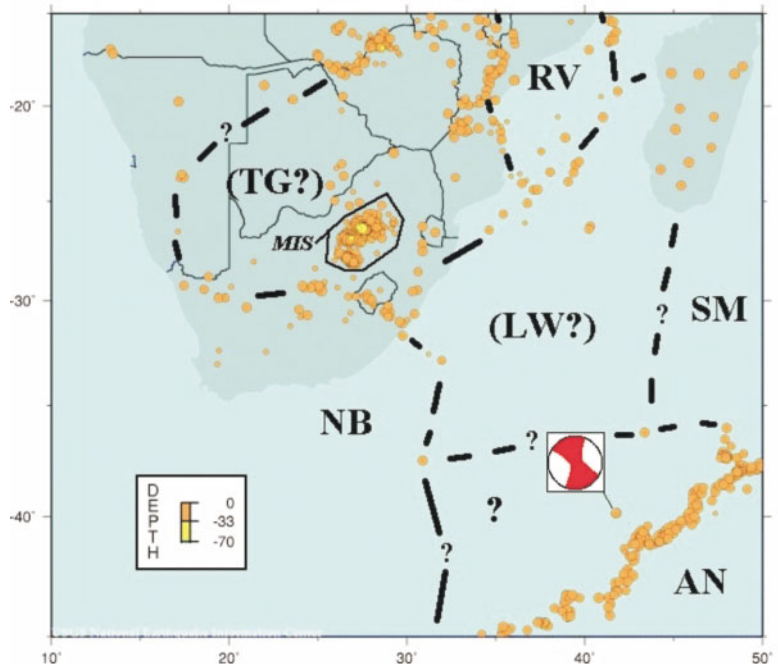

Fig. 3. Epicentres from USGS/NEIC Preliminary Determination of Epicenters (PDE) catalogue from 1973 to March 2002 (http://wwwneic.cr.usgs.gov/neis/epic/epic_rect.html), covering the NB–SM wide plate boundary zone south of latitude 15°S. Southern boundary of the Rovuma plate (RV) is drawn through a scattered belt of epicentres in the Mozambique Channel between Africa and Madagascar. Tentative boundaries of postulated Transgariep (TG?) and Lwandle (LW?) blocks are also indicated (thick black dashes). Mining-induced earthquakes of the Witwatersrand gold fields enclosed by the polygon labelled MIS. Beachball diagram north of the AN plate boundary represents focal mechanism [28] of intraplate magnitude 5.8 event on 8 September 2000.

seismologist Beno Gutenberg assigned a surface-wave magnitude of 6.8 to both the earthquake of 19 May 1915 in the central Mozambique Channel and that of 31 December 1932 off Cape St Lucia in KwaZulu-Natal. The occurrence of earthquakes of this magnitude or even greater in the same general area today would undoubtedly have disastrous consequences, due to the great increase in the region's population and the vulnerability of the physical infrastructure on which it depends.

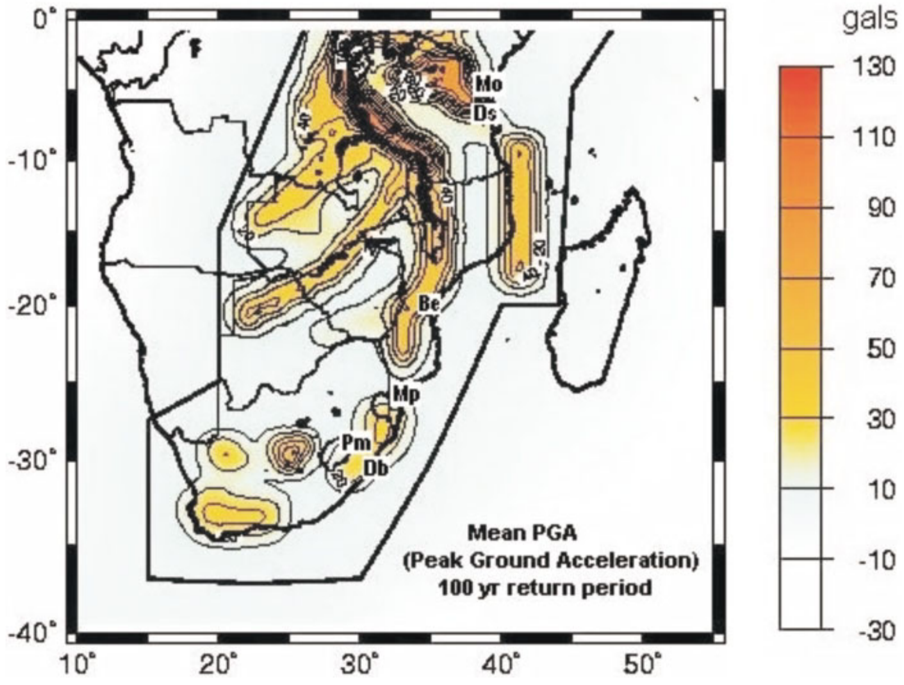

Fig. 4. Global Seismic Hazard Assessment Programme (GSHAP) map of peak ground acceleration (PGA) for a 100-year return period (after ref. 16). PGA contour interval is 10 gals (1 gal = 1 cm/s^2; 100 gals = ~0.1 g). Note that GSHAP model disregards the offshore Quathlamba Seismicity Axis[10] in the Mozambique Channel and the southeastern extensions towards the KwaZulu-Natal coastline that delineate the southern boundary of the RV plate. Cities at risk along the NB–SM boundary are Mombasa (Mo), Dar-es-Salaam (Ds), Beira (Be), Maputo (Mp), Pietermaritzburg (Pm) and Durban (Db).

During the 20th century, up to 80% of the release of seismic moment (a physical quantity measured in newton-metres) over the entire NB–SM boundary zone was achieved during just two earthquakes, namely, the Rukwa (southern Tanzania) event[18] of magnitude 7.4 on 13 December 1910, and the Juba (southern Sudan) event[19] of magnitude 7.3 on 20 May 1990. In the Bilila-Mtakataka fault scarp in southern Malawi, there is geological evidence of a prehistoric event of magnitude 8,[20] described as possibly the 'biggest normal faulting earthquake known on the continents' (ref. 20, p.148). With such large events in its recent tectonic past, Africa cannot afford a false sense of security about the maximum size of future earthquakes.

Fortunately, within the last decade, space-geodetic methods (for example, GPS) have been developed to measure current plate motions at the sub-mm/yr level of accuracy, and contribute quantitatively to the determination of maximum earthquake size in particular regions. In the NB-SM plate boundary region this kind of information is now becoming available from a few sites (Sutherland and Hartebeesthoek in South Africa, Malindi in Kenya, and Mahe Island in the Seychelles), and contributes to the Global Strain Rate Map Project.[15] In order to apply this new space technology for the mapping of seismic hazards in areas of slow to very slow intracontinental deformation, use can be made of the fact that the size distribution of moderate and large earthquakes is governed by a power-law function.

This relation between seismic moment and frequency is a transformation of the classic Gutenberg-Richter (G-R) law that relates earthquake magnitude and frequency. The power-law exponent (β) in this modified G-R law (the Gamma or tapered Pareto distribution) is assumed to have a 'universal constant' value of 0.60 ± 0.02 (ref. 21). A seismic moment rate, which depends only on maximum magnitude, is computed by integration of the moment–frequency relation.[21] In the case of the NB–SM boundary, where the >1000-year recurrence interval of large earthquakes far exceeds the period of seismological observation, the moment rate extrapolated from more frequent moderate events can be compared with the expected moment rate calculated from quantitative plate-tectonic theory[2] or space-geodetic observation[15], to provide a quantitative estimate[21] of the maximum moment in the region.

This use of this 'seismic moment conservation principle'[21] (SMCP) to calculate a maximum earthquake size is an alternative to conventional PSHA methods, which require a much longer historical and instrumental record of earthquake seismology than is generally the case for most parts of Africa. PSHA methods therefore underestimate the probabilities of rare extreme events, and because of the slow nature of NB-SM plate tectonics, it is often assumed that future large (magnitude 7+) or great (magnitude 8+) intracontinental earthquakes cannot occur in this recent extensional-tectonic environment.

With the recognition of two independently moving blocks within the NB–SM boundary zone, the quantitative use of the SMCP in particular tectonic zones requires that the motions of the intervening UN and RV blocks be established in more detail. Constraints on the *directions* of NB-UN, NB-RV, and RV-SM motions are potentially available through the database of earthquake focal mechanisms and fault trends in parts of the EARS, from which slip-vector results can be constructed (e.g. Fig. 10 in ref. 22). Determination of *rates* of motion, however, requires the extension of the current network of space-geodetic observatory sites to the UN and RV plates. There are no such sites with any usable time-series results currently available, although a GPS site has recently been established on the UN plate, at Mbarara in the Kyahi Forest Reserve of Uganda.

There is currently a proposal before the International Association of Geodesy and the International Council for Science for a project to establish a unified continental reference frame for Africa (AFREF).[23,24] A set of permanent or semi-permanent GPS stations distributed along the entire NB–SM boundary within continental Africa will be a core element of AFREF, and it is important to ensure that the GPS network is optimized to provide for early and accurate detection of UN and RV plate motions relative to the NB and SM framework. A subset of AFREF for the southern African region — SAFREF — proposes GPS stations on the RV plate in Dodoma, Tanzania, and at Beira, Mozambique (sites 2 and 7, respectively, in ref. 23, Fig. 3), but another site in the stable interior of the RV block (for instance, Nampula in northern Mozambique) would be more advantageous for plate-kinematic studies. An additional geotectonic GPS site in northern Tanzania [for example, at Mwanza on the southern shore of Lake Victoria (formerly Ukerewe Nyanza)] is also advisable.

The continuing break-up of the former African plate into Nubian and Somalian components occurs above the planet's largest mantle upwelling, the 'African Superplume'.[25] In the high mountainous areas around the EARS, within the extensive zone of anomalous elevation called the African Superswell,[26] earthquakes are not the only solid-earth geohazards.[27] As dramatically demonstrated by the January 2002 events around Goma in the DRC border area, volcanic activity and/or large-scale mass movement on steep slopes places many people at risk. Where the historical record of natural disasters is so short and the recurrence intervals of the most extreme seismic and volcanic events are so long (>10 000 years), the acquisition of fundamental geoscientific knowledge, such as is envisaged in the AFREF proposal,[23] is vital to future risk-reduction planning and to an informed, flexible response to potential disasters.[26]

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