INTRAPLATE SEISMICITY AND THE DISCRIMINATION OF NUCLEAR TEST EVENTS USING AN UPDATED GLOBAL EARTHQUAKE CATALOG

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ABSTRACT

In order to accurately discriminate the signatures of nuclear explosions from naturally-occurring seismic events, it is necessary to understand the frequency of earthquake occurrence, the stresses and mechanisms behind earthquakes in the regions of interest, as well as the properties of the crust in those regions. Areas of particular interest include many stable continental interiors such as the Gujarat Province of India, the Lop Nor test site in China, and the Semipalatinsk site in Kazahkstan. Such areas are often associated with intraplate seismicity. This seismicity must be identified and understood to discriminate suspect events and to serve as an accurate measure of ground truth. In this paper we present an updated earthquake catalog for Stable Continental Regions to examine the possible mechanisms of seismicity in these continental interiors. The last major global study of intraplate seismicity was the 1994 Electric Power Research Institute (EPRI) study, which included events up to 1990. Earthquake activity over the last 14 years therefore could not have been taken into account, a relatively long period considering that high-quality worldwide seismic monitoring only began in 1964. It is only from this year (1964) onwards that most M ≥ 4.5 events have well constrained locations, magnitudes and focal mechanisms.

We present an updated global catalog for Stable Continental Region (SCR) earthquakes that contains information on location, magnitude, seismic moment and focal mechanisms of 1373 M ≥ 4.5 crustal events from the year 495 to 2003. This is an increase of ~58% with respect to the last global study. This updated earthquake catalog, together with the recent publication of a catalog of rifts of the world provides an excellent opportunity to re-evaluate the correlation of earthquake activity and rifts on a global scale. This in turn will help us to further discriminate continental interior events that may be suspected nuclear events.

After removal of earthquakes that are considered to be non-tectonic, 1221 tectonic events were used for statistical analysis to re-evaluate the correlation of earthquakes with ancient rifts on a global scale. Earthquakes were then put into one of the following categories: interior rifts/ taphrogens (if located within ~20 km of identified ancient rift), rifted continental margins (if located within ~20 km of these rifted margins), or non-rifted crust (if located further than ~50 km of any of the above).

Our results are similar to those of previous studies, which found that 56% of all SCR earthquakes are associated with rifted crust. It is very important to note, however, that within continental interiors (i.e. excluding the rifted continental margins), more events in fact may be located within non-rifted crust. Of the 118 documented **M** ≥ 6.0 earthquakes, 30% are associated with interior rifts, 35% with rifted continental margins and 29% with non-rifted crust. However, the relative number of **M** ≥ 6.0 earthquakes in non-rifted crust increases from 29% to 32% and even 42% if we restrict the dataset to the instrumental or "complete" catalog events. Our earthquake database contains fourteen **M** ≥ 7.0 events, seven of which have occurred within interior rifts/taphrogens, six within rifted continental margins, and only one within non-rifted crust. Of these fourteen events, eight have been recorded instrumentally and are included in the "complete" catalog subset. Considering these eight events, two were located within interior rifts/ taphrogens and five within rifted margins. Due to the low number of samples, the statistics can be expected to change as more earthquakes occur.

OBJECTIVE

In order to accurately discriminate the signatures of nuclear explosions from naturally-occurring seismic events, it is necessary to understand the frequency of earthquake occurrence, the stresses and mechanisms behind earthquakes in regions of interest, as well as the properties of the crust in those regions. These study areas include many stable continental interiors where governments have been able to conceal their nuclear testing in relative secrecy, such as the Gujarat Province of India, the Lop Nor test site in China, and the Semipalatinsk site in Kazahkstan. Such areas are often associated with intraplate seismicity, and this seismicity must be understood both to discriminate suspect events, and to serve as an accurate measure of ground truth.

RESEARCH ACCOMPLISHED

In 1994, the Electric Power Research Institute (EPRI, 1994) published a benchmark global study on the seismicity in Stable Continental Regions. Stable Continental Regions (further referred to as SCRs) were defined as regions of continental crust that have not experienced any major tectonism, magmatism, basement metamorphism or anorogenic intrusion since the early Cretaceous, and no rifting or major extension or transtension since the Paleogene. The definition therefore is based on geology rather than seismic activity and uses the geological setting of the crust of the central and eastern United States as a reference. Although earthquakes are rare in SCRs, they have the potential to be large, thus making them excellent ground truth events.

Models that have been suggested to explain the occurrence of seismicity within continental interiors include localized stress concentration around weakened intrusions (Campbell, 1978), intersecting faults (Talwani, 1988, 1999) and ductile shear zones in the lower crust (Zoback, 1983). Fluids still present in the lower crust of ancient rift zones (Vinnik, 1989), and a weak zone in the lower crust (Kenner and Segall, 2000) have also been suggested. Liu and Zoback (1997) proposed the hypothesis that seismicity is related to elevated temperatures at depth. In their model plate-driving forces are largely supported by the (seismogenic) upper crust; the lower crust is weakened due to higher temperatures, and the cumulative strength of the lithosphere is reduced. Long (1988) suggested that intraplate seismicity is a transient phenomenon arising from a perturbation in crustal strength due to a disturbance in the hydraulic or thermal properties of the lower crust. Other models call for a perturbation of the regional stress field by forces associated with lithospheric flexure after deglaciation (Stein et al., 1979; Quinlan, 1984; Grollimund and Zoback, 2001), gravitational forces at structural boundaries (Goodacre and Hasegawa, 1980; Chandrasekhar and Mishra, 2002) or sediment loading (Talwani and Rajendran, 1991).

Many of the models for SCR seismicity listed above require features that are often found in ancient rifts: numerous large faults and intrusions, an anomalous crustal structure compared to the surrounding crust, rift pillows, and possibly remnant fluids. Thus the spatial correlation of some earthquakes with ancient rifts might be explained by the presence of these features. However, SCR seismicity is not unique to rift zones. Most of the models proposed have been based on case studies and have not been evaluated on a global scale, though a few that have show a correlation with ancient rifts (e.g. Sykes 1978; Johnston and Kanter, 1990; EPRI, 1994).

In this paper we use an updated earthquake catalog for Stable Continental Regions to examine the possible mechanisms of seismicity in these continental interiors. The EPRI (1994) study only included events up to 1990. Earthquake activity over the last 14 years therefore was not taken into account, a sizeable omission when considering that high-quality worldwide seismic monitoring only began in 1964, and that it is only from 1964 onwards that most $M \geq 4.5$ events have well constrained locations, magnitudes and focal mechanisms. This updated earthquake catalog, together with the recent publication of a catalog of rifts of the world (Sengör and Natal'in, 2001), provides an excellent opportunity to re-evaluate the correlation of earthquake activity and rifts on a global scale.

Figure 1 shows the seven main SCRs in the world: North America, South America, Africa (including the Arabian Peninsula), India, Eurasia, China (which consists of three smaller SCRs), and Australia. The Eurasian SCR has been subdivided into two regions. The region west of 20^{o} E will be referred to as Europe, whereas the region east of 20^{o} E will be referred to as Russia (Figure 1). In this paper we will discuss only the Indian, Eurasian and Chinese SCRs.

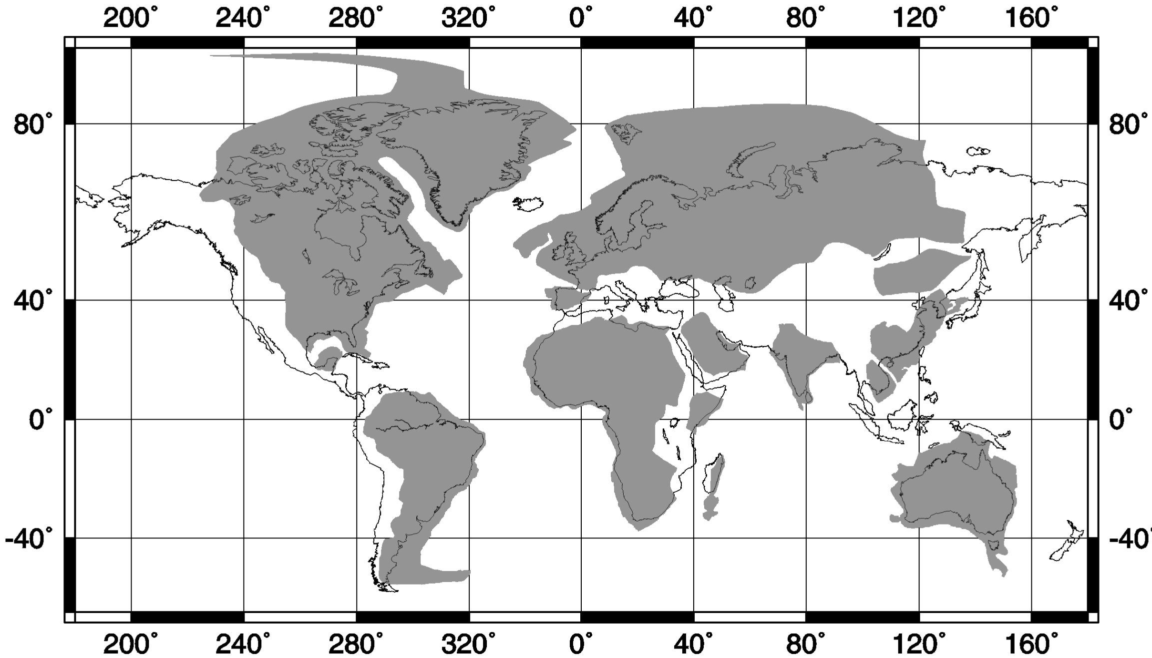

Figure 1. Stable Continental Regions (SCRs: light gray). Though there are seven large SCRs shown: North America, South America, Eurasia (subdivided into Europe; west of 20°E, and Russia, east of 20°E), Africa (including the Arabian peninsula), India, China (consisting of three separate SCRs) and Australia, we discuss only the Indian, Eurasian and Chinese SCRs here.

The earthquake catalog compiled for this study is available online at: http://earthquake.usgs.gov/scitech/scr_catalog.html. It contains crustal (maximum depth ≤ 45 km) events with Moment Magnitudes M ≥ 4.5 within SCRs. We chose not to restrict the catalog to the instrumental era (approximately from the beginning of the 20th Century), as, due to the relatively infrequent occurrence of large earthquakes in SCRs, such a restriction would severely limit the number of events to be included in the study. The catalog therefore includes documented historic events and instrumentally recorded events up to November, 2003. For each event, the epicenter, depth, Moment Magnitude, other reported magnitudes, and focal mechanism parameters (if available) are listed. The database contains 1373 events, which is an increase of approximately 58% with respect to the database developed for the EPRI (1994) report.

In order to have a sufficiently large dataset we did not restrict the study to the "complete" subsets of the earthquake catalog (Table 1). Magnitudes and locations of historic events, however, are often poorly determined. In addition, the time span over which events have been recorded varies greatly between, and in some cases even within, the different SCRs. The latter poses a problem with searching for spatial patterns in earthquake distribution, since these patterns may in fact reflect a difference in the time span of earthquake documentation and not in true seismic activity. In the analysis that follows we have therefore separately considered: (1) the entire earthquake dataset; (2) only instrumentally recorded events; and (3) events from the "complete" catalog (Table 1). The earthquakes for the various SCRs are presented in Figure 2.

Table 1. Subsets of the Compiled Earthquake Catalog that are considered "complete."

Period	*Magnitudes*
1900 – 2002	**M** ≥ 7.0
1964 – 2002	**M** ≥ 5.0

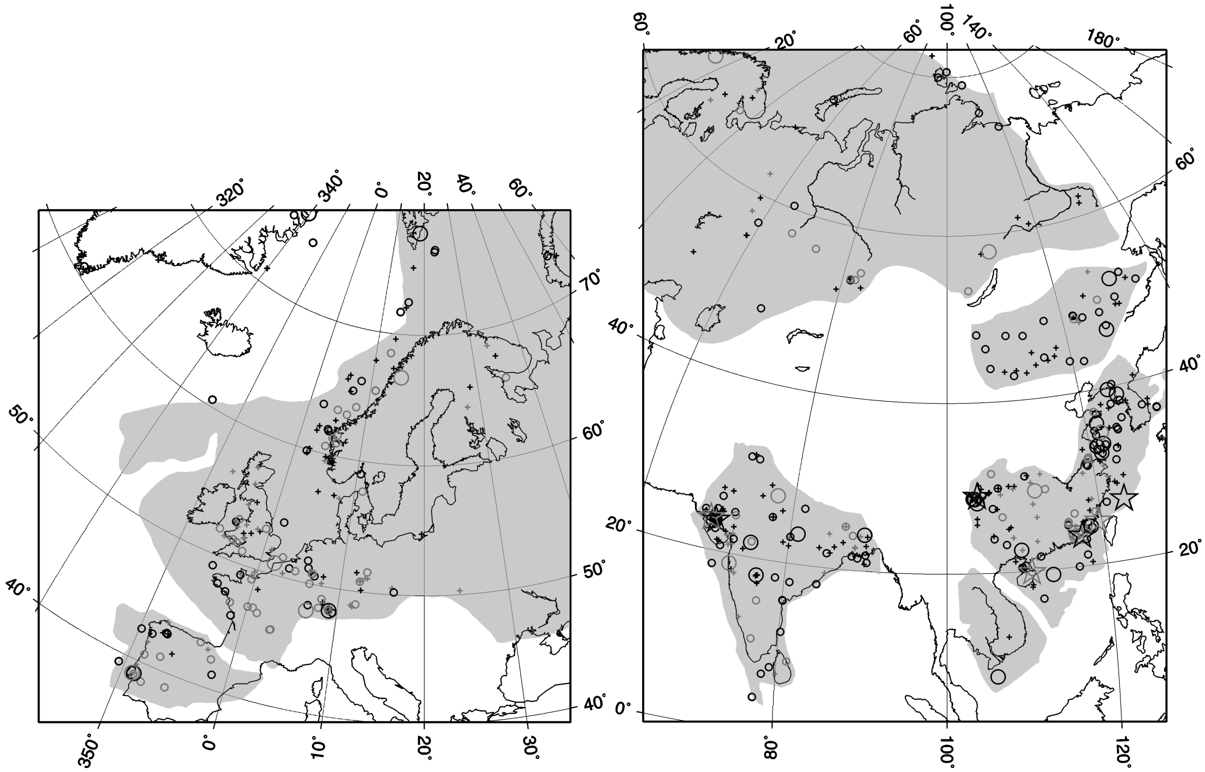

Figure 2: Earthquakes in the updated global database for different Eurasian SCRs. Events with an instrumentally-determined location and magnitude are denoted by circles, while historical events are denoted by crosses.

Taphrogens consist of a linked system of individual rifts and grabens. Interior rifts are sometimes referred to as “failed rifts”, as stretching did not lead to sea floor spreading and therefore they are still surrounded by continental crust. Rifted continental margins are the regions of extended crust that form the transition from continental to oceanic crust. They are formed when extension leads to sea floor spreading.

The catalog of “Rifts of the World” (Sengör and Natal’in, 2001) is the most complete global listing of rifts and contains information on a rift’s location, size, orientation, and age, as well as its placement among Sengör’s (1995) hierarchical classification of geometry and dynamics. It was used in combination with the Exxon Tectonic Map of the World (Exxon, 1985) to determine a rift’s exact location and extent. The Exxon (1985) map (eighteen sheets, each approximately 66 cm by 83 cm) is an unusually large-scale (1:10,000,000) map with a highly-detailed tectonic interpretation.

The inland boundaries of the extended margin regions were set at the most inland normal faulting identified at the edge of the continents. In regions where these could not be identified, the inland boundaries were based on interpolation, sudden transition on land from basement outcrop to sediment cover, gradients of sediment thickness, or the proximity of the boundary between SCR and oceanic crust. Interior rifts and their bounding faults were usually easily identified on the Exxon Tectonic Maps (Exxon, 1985). However, for some rifts in the Sengör and Natal’in (2001) catalog, it was difficult to establish the exact extent, or even to identify the rift at all on the Exxon (1985) maps.

The earthquakes of the compiled database were plotted onto individual sheets of the Exxon Tectonic Map of the World (Exxon, 1985). Based on their location, events were placed into one of five categories: (1) interior rifts/ taphrogens (within ~ 20 km from the bounding faults), (2) rifted continental margins (within ~ 20 km of rifted margins), (3) non-rifted crust, (4) possible interior rifts, and (5) possible rifted margins. In Figure 3 we have plotted the distribution of events over these five categories. In addition to considering the geographic distribution of the entire dataset, we also looked at the distribution of only the instrumentally recorded events (since they have much better-determined estimates of location and magnitude) and the distribution of all events within subsets of the "complete" catalog (see section 2). Our tectonic analysis showed 27% of all earthquakes in the catalog being incorporated in the interior rifts/taphrogens category, 25% in the rifted continental margins and 36% in non-rifted crust categories (Figure 3a). 12% of the earthquakes were included in the possibly interior rifts category, 2% of which are earthquakes located in central west Europe that, as evidenced by extensive faulting and a very thin (≤ 30 km) crust, might actually be considered rifted (extended) crust.

Our results are similar to those of previous studies (Johnston and Kanter, 1990; EPRI, 1994), which found that 56% of all SCR earthquakes are associated with rifted crust. It is very important to note, however, that within continental interiors (i.e. excluding the rifted continental margins), more events in fact may be located within non-rifted crust (36% vs. 27%-37%). The numbers remain fairly constant if instrumental or only "complete" catalog earthquakes are considered (Figure 3b and 3c). Of the 118 documented **M** ≥ 6.0 earthquakes (Figure 3d), 30% are associated with interior rifts, 35% with rifted continental margins and 29% with non-rifted crust. However, the relative number of **M** ≥ 6.0 earthquakes in non-rifted crust increases from 29% to 32% and even 42% if we restrict the dataset to the instrumental or "complete" catalog events (Figure 3e, 3f). Our earthquake database contains fourteen **M** ≥ 7.0 events, seven of which (50%, Figure 3g) have occurred within interior rifts/taphrogens, six (43%, Figure 3g) within rifted continental margins, and only one (7%, Figure 3g) within non-rifted crust. Of these fourteen events, eight have been recorded instrumentally and are included in the "complete" catalog subset. Considering these eight events, two were located within interior rifts/ taphrogens (25%, Figure 3h/i) and five within rifted margins (62%). Due to the low number of samples, the statistics can be expected to change as more earthquakes occur.

Naturally, total seismic energy release is dominated by the largest events. Thus of the total seismic moment in SCRs included in the earthquake catalog, 67% is associated with interior rifts/ taphrogens, 24% with rifted continental margins, and 9% with non-rifted crust (Figure 3j). There is however a large uncertainty in these numbers, as the seismic moment of historic earthquakes is poorly determined. Of the seismic moment release from instrumentally recorded earthquakes (Figure 3k) 34% is associated with interior rifts, 45% with rifted continental margins, and 20% within non-rifted crust (36%, 47%, 16% respectively for the "complete" catalog subsets, Figure 3l).

In Figures 4a-c we have plotted all earthquakes according to tectonic category. It is evident that seismicity is not distributed evenly, but rather within each category certain regions exist in which seismicity is strongly concentrated. It should be noted that the active regions differ greatly in size. Concentration of seismicity is particularly strong for earthquakes that are associated with interior rifts and taphrogens, including the Kutch rift, India and the East China Taphrogen, for which several **M** ≥ 7 events have been documented (Figure 4b). We shall examine these in greater detail below.

It should be noted that the East China Taphrogen is a very extensive structure: it comprises a large part of the China SCR. Within non-rifted continental crust seismicity is more diffuse. There are however several regions that seem to show a higher level of seismic activity with respect to their surroundings (Figure 4c). These regions account for 70% of the total seismic moment release, but comprise only 26% of the total events in the category.

Unfortunately, a large part (24% of all **M** ≥ 4.5, 31% of all **M** ≥ 6.0, and 43% of all **M** ≥ 7.0 events) of the earthquake database used for analysis consists of historical earthquakes. If we restrict the dataset to the instrumental era or to the "complete" catalog subsets, the majority of the regions considered to be relatively seismically active no longer have a much higher seismicity than their surroundings. Therefore, the lack of seismicity within apparently aseismic interior rifts, and also within rifted margins and non-rifted continental interiors, may in fact be due to lack of documentation throughout history and not a lack of actual seismicity. Due to the large recurrence interval of SCR seismicity, the available global earthquake dataset is almost certainly a "snapshot", rather than a true representation of the distribution of SCR earthquakes. We note that for the non-rifted category, the majority of the regions have experienced higher magnitude earthquakes (**M** ≥ 6.0) in the instrumental era, whereas for the interior rifts/ taphrogens, the largest events are dominantly historical.

Figure 5a shows the Kutch rift in northwestern India. It is the locus of two of the largest events within the compiled earthquake database: the 1819 **M** = 7.8 and the 2001 **M** = 7.7 events. Apart from the East China rift system, it is the only rift that has experienced an **M** > 7 event that was instrumentally recorded, and therefore, has a very well-determined epicenter and magnitude. The Kutch rift proper is Mesozoic in age. However, active faulting has also

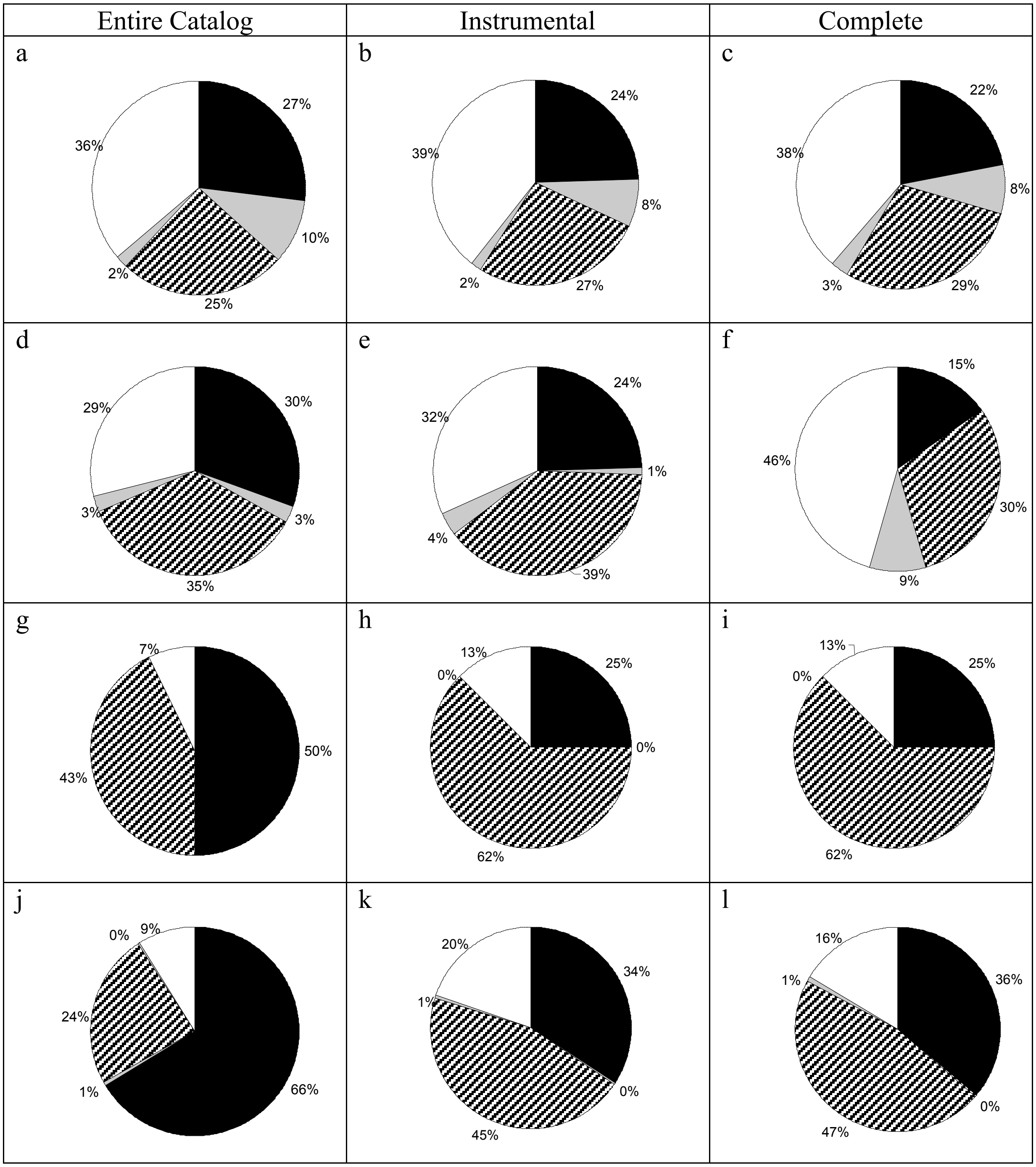

Figure 3: Distribution of seismicity over the five different categories for the entire database of instrumentally recorded events and "complete subset" events: Rifts (black), possible rifts (stippled), rifted margins (striped), possible rifted margins (gray), non-rifted crust (white). a-c) M ≥ 4.5 events, d-f) M ≥ 6.0, g-i) M ≥ 7.0 events and j-l) seismic moment release.

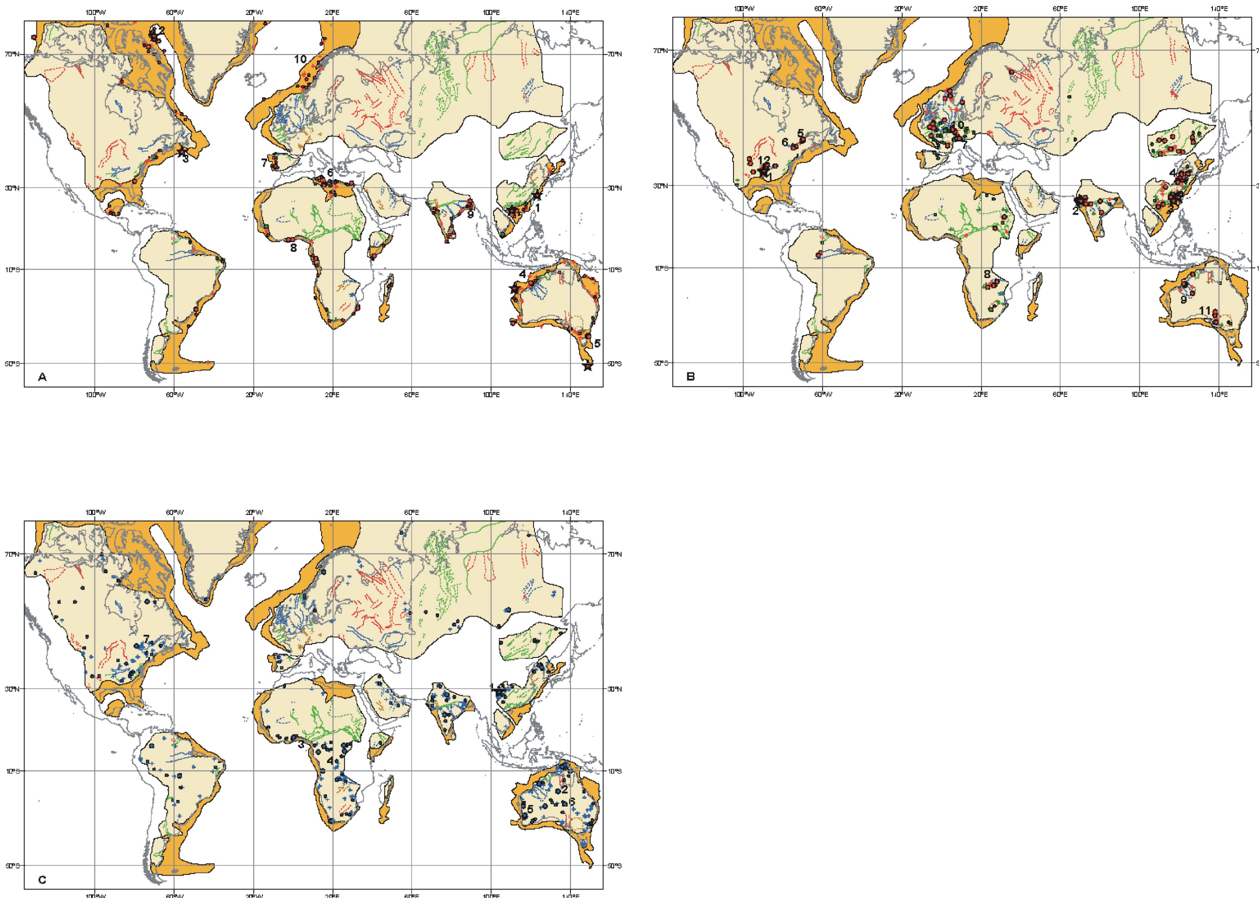

Figure 4: Earthquakes from the database for: a) rifted continental margins; b) interior rifts/ taphrogens; and c) non-extended continental crust. Extended margins are colored orange, continental interiors light gray. Rifts and taphrogens are indicated with solid (boundaries are well determined) or dashed (boundaries are poorly determined) lines. Precambrian rifts are indicated in red, Paleozoic in blue, Mesozoic in green and Cenozoic in brown. Red circles denote events that are and green circles events that might possibly be associated with rifted continental margins or interior rifts, blue circles denote events that are occur in non-rifted crust. Numbers indicate regions of concentrated seismicity.

been recognized (Stein et al., 2001). Furthermore, the Kutch rift is located relatively close (400 km) to the triple junction between the Eurasian, Indian and Arabian plate (Figure 5a). Thus, it has been suggested (Stein et al., 2001) that the Kutch area might in fact be an extension to the Indian diffuse western plate boundary described by Gordon (1998).

The East China Rift System comprises the largest part of the southeastern China SCR (Figure 5b). Though we do not distinguish the individual grabens, there are two regions within the East China Rift System that account for the majority of the events. The first is the Yellow Sea, with nineteen earthquakes, six of which (5 instrumentally recorded) were **M** > 6 events. The second is the region directly opposite the Ryuku trench at Taiwan with thirteen earthquakes, seven of which have **M** > 6.0. The two largest events located within the East China Rift System are: the historical 1604 **M** = 7.7 and the instrumentally recorded 1918 **M** = 7.3 events, both of which are located directly opposite the trench. Further inland, the East China Rift System does not show a significantly higher level of seismic activity than the non-rifted region west of it. Therefore, seismicity within the southeastern China SCR seems more likely to be related to the proximity to the plate boundary rather than to ancient rifting.

The strong concentration of events in the non-rifted SCR at the westernmost parts of Tibet, which has been categorized as non-rifted crust, has experienced four instrumentally recorded **M** > 6.5 events, including the 1917 **M** = 7.4 earthquake. The region shows large-scale intrusions and faulting, and directly borders the ACR (as defined by EPRI (1994)) of the Himalayas and Tibetan Plateau in the west. Seismicity might therefore be related to diffuse plate boundary processes of the Himalayas, such as the extrusion of the Tibetan Plateau, and may in fact lie in active continental crust.

For 209 events, focal mechanisms are available. Analysis of these focal mechanisms confirm results from earlier studies (Zoback, 1992; Reinecker et al., 2003) that compressive stress regimes dominate within the continental interiors, with maximum compressive stresses predominantly in accordance with absolute plate motion.

CONCLUSIONS AND RECOMMENDATIONS

We present an updated global catalog for Stable Continental Region (SCR) earthquakes that contains information on location, magnitude, seismic moment and focal mechanisms of 1373 M ≥ 4.5 crustal events from the year 495 to 2003. This is an increase of ~58% with respect to the last global study (EPRI, 1994). After removal of earthquakes that are considered to be non-tectonic, 1221 tectonic events were used for statistical analysis to re-evaluate the correlation of earthquakes with ancient rifts on a global scale. Earthquakes were then put into one of the following categories: interior rifts/ taphrogens (if located within ~20 km of identified ancient rift), rifted continental margins (if located within ~20 km of these rifted margins), or non-rifted crust (if located further than ~50 km of any of the above).

We found that 27% of the earthquakes fell in the interior rifts/ taphrogens category, 25% were rifted continental margins, 36% were non-rifted crust, and 12% remained uncertain. These numbers are similar to those of earlier studies (e.g. Johnston and Kanter, 1990; EPRI, 1994), who found that 56% of all SCR earthquakes are associated with extended crust (interior rifts/ taphrogens + rifted continental margins). However, if we consider continental interiors only (i.e. if the rifted continental margins are not taken into consideration), non-rifted crust has experienced more earthquakes compared with interior rifts/ taphrogens (27% interior rifts/ taphrogens vs. 36% non-rifted crust).

The percentages of earthquakes by tectonic affinity remain relatively constant if we consider only earthquakes from the instrumental era, for which magnitudes and locations are much better determined. The percentages remain fairly constant if only larger (**M** ≥ 6.0) events are considered, although for the largest events (**M** ≥7, N = 14), interior rifts/ taphrogens (50%) and rifted continental margins (43%) strongly dominate. Seismicity is not distributed evenly, however. For the interior rifts/ taphrogens category, only twelve rifts account for 74% of all events and 98% of the total moment release. The majority of interior rifts, in fact, show little or no seismicity. Several regions that have experienced multiple large (**M** ≥ 6.0) exist within apparently non-rifted crust.

The most seismically active rifts are the Kutch rift, India, (1819 **M** = 7.8 and 2001 **M** = 7.6 events) and the East China taphrogen (1604 **M** = 7.7 and 1918 M = 7.3). However, the Kutch rift is located relatively close to the triple junction between the Arabian, Indian and Eurasian plate. There is also evidence of active faulting, thus it has been suggested that the region is in fact part of the diffuse western Indian plate boundary (Stein et al., 2001). In addition, the majority of seismic energy that has been released within the East China rift/ taphrogen is located directly opposite the Ryuku trench at Taiwan. Plate boundary processes may therefore play an important role in these two regions and seismicity may not in fact be related to the presence of the ancient rift. The majority of the regions that are historically seismically active hardly show greater seismic activity than their surroundings if only the instrumental era is taken into account.

As these two regions are of particular interest for the nuclear test monitoring community, it is important that we consider future studies of these intraplate events. Although many earthquakes have occurred within rifted crust, the potential of seismicity within rifts should not be over-emphasized. Several regions within non-rifted crust have also shown strong seismic activity, and therefore a shift in focus of models for SCR seismicity from mainly rift-associated to a combination of rift-associated and non-rift-associated earthquakes is warranted. If a region of interest is seismically active, that makes discrimination somewhat more difficult, and this needs to be addressed.

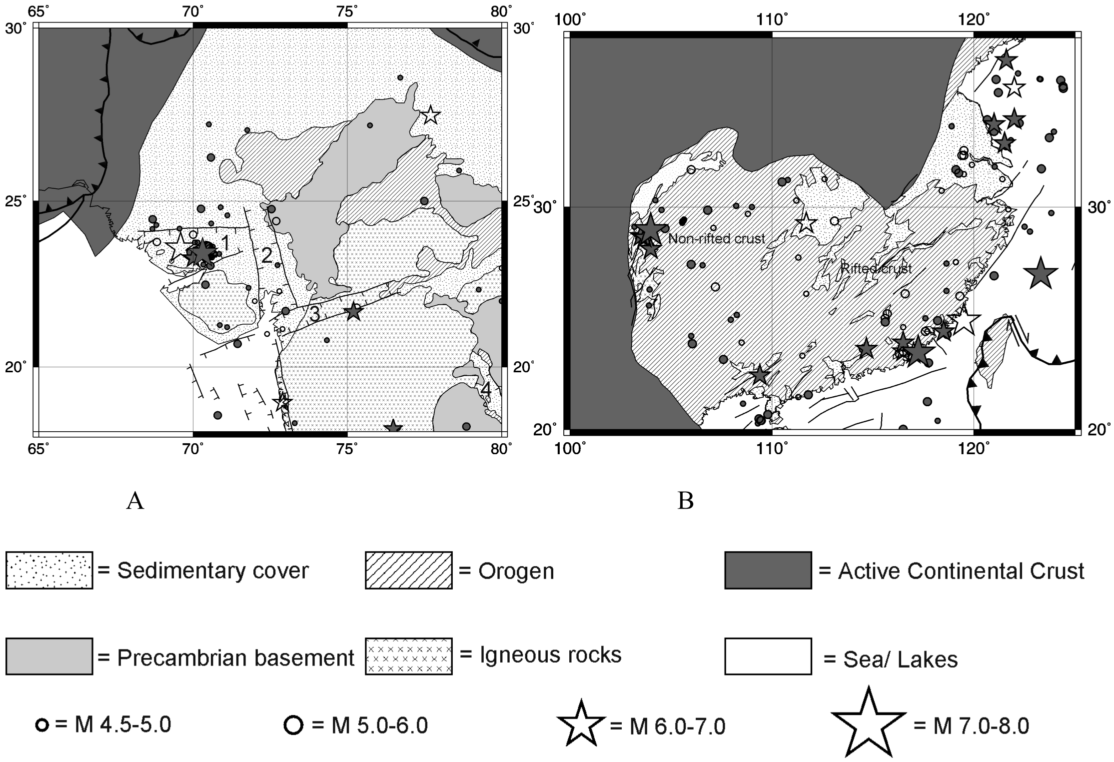

Figure 5: Simplified tectonic maps for different regions within Stable Continental crust, and earthquakes from the database. Events that were recorded instrumentally are colored dark gray, historic events are denoted by open symbols. a) India, with 1) Kutch Rift, 2) Cambay rift, 3) Narmada Son rift and 4) Pranhita-Godovari rift. b) Southern China, with the East China Rift system.

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