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An updated global earthquake catalogue for stable continental regions: reassessing the correlation with ancient rifts

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SUMMARY

We present an updated global earthquake catalogue for stable continental regions (SCRs; i.e. intraplate earthquakes) that is available on the Internet. Our database contains information on location, magnitude, seismic moment and focal mechanisms for over 1300 **M** (moment magnitude) $\geq$ 4.5 historic and instrumentally recorded crustal events. Using this updated earthquake database in combination with a recently published global catalogue of rifts, we assess the correlation of intraplate seismicity with ancient rifts on a global scale. Each tectonic event is put into one of five categories based on location: (i) interior rifts/taphrogens, (ii) rifted continental margins, (iii) non-rifted crust, (iv) possible interior rifts and (v) possible rifted margins. We find that approximately 27 per cent of all events are classified as interior rifts (i), 25 per cent are rifted continental margins (ii), 36 per cent are within non-rifted crust (iii) and 12 per cent (iv and v) remain uncertain. Thus, over half (52 per cent) of all events are associated with rifted crust, although within the continental interiors (i.e. away from continental margins), non-rifted crust has experienced more earthquakes than interior rifts. No major change in distribution is found if only large (**M** $\geq$ 6.0) earthquakes are considered. The largest events (**M** $\geq$ 7.0) however, have occurred predominantly within rifts (50 per cent) and continental margins (43 per cent). Intraplate seismicity is not distributed evenly. Instead several zones of concentrated seismicity seem to exist. This is especially true for interior rifts/taphrogens, where a total of only 12 regions are responsible for 74 per cent of all events and as much as 98 per cent of all seismic moment released in that category. Of the four rifts/taphrogens that have experienced the largest earthquakes, seismicity within the Kutch rift, India, and the East China rift system, may be controlled by diffuse plate boundary deformation more than by the presence of the ancient rifts themselves. The St. Lawrence depression, Canada, besides being an ancient rift, is also the site of a major collisional suture. Thus only at the Reelfoot rift (New Madrid seismic zone, NMSZ, USA), is the presence of features associated with rifting itself the sole candidate for causing seismicity. Our results suggest that on a global scale, the correlation of seismicity within SCRs and ancient rifts has been overestimated in the past. Because the majority of models used to explain intraplate seismicity have focused on seismicity within rifts, we conclude that a shift in attention more towards non-rifted as well as rifted crust is in order.

Key words: intraplate seismicity, rifts, stable continental.

GJI Seismology

1 INTRODUCTION

In 1994, the Electric Power Research Institute (Johnston *et al.* 1994) published a benchmark global study on the seismicity in stable continental regions (SCRs). 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, major extension or transtension since the Palaeogene. The definition therefore is based on geology rather than seismic activity and uses the geological setting of the crust of the central and eastern USA as a reference. Although earthquakes are rare in stable continental regions, they have the potential of causing enormous damage.

In 1811 and 1812 a sequence of three large (magnitudes $\geq$ 7) earthquakes occurred in New Madrid, Missouri, central eastern USA. The region is referred to as the New Madrid seismic zone (NMSZ) and occurs well away from any plate boundary, in so-called stable continental crust (Johnston *et al.* 1994). The NMSZ

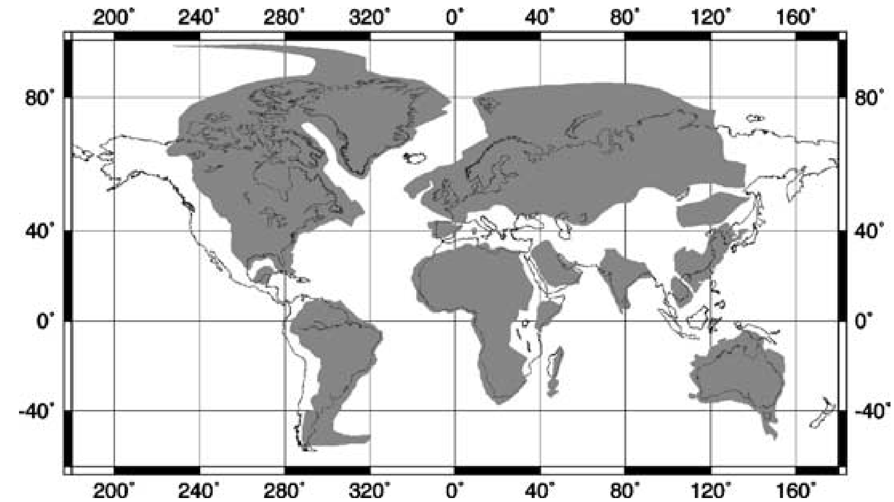

Figure 1. Stable continental regions (SCRs: light grey). We consider seven large SCRs in this study: North America, South America, Eurasia (subdivided into Europe, west of 20°E, and Russia, east of 20°E), Africa (including the Arabian peninsula), India, China (consisting of three separate SCRs) and Australia. Antarctica is not included.

is located within the Reelfoot rift, a Palaeozoic rift that experienced an episode of magmatic reactivation in the Cretaceous (Hamilton & Zoback 1982; Hildenbrand *et al.* 1982). The region seems to be the perfect example of intraplate seismicity associated with an ancient rift, a correlation that has been found on a global scale in several studies (Sbar & Sykes 1973; Sykes 1978; Hinze *et al.* 1988; Johnston & Kanter 1990; Johnston *et al.* 1994; Gangopadhyay & Talwani 2003).

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), a weak zone in the lower crust (Kenner & Segall 2000), and stress perturbation resulting from buried rift pillows (Zoback & Richardson 1996) have also been suggested. Liu & 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 as a result of 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 as a result of 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 & Zoback 2001), gravitational forces at structural boundaries (Goodacre & Hasegawa 1980; Chandrasekhar & Mishra 2002) or sediment loading (Talwani & 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 with 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. In fact, the NMSZ has been the area of study for the majority of the proposed models.

In this paper, we present an updated earthquake catalogue for SCRs that is available on the Internet. The previous global study of intraplate seismicity was the Johnston *et al.* (1994) EPRI study, which includes events up to 1990. Earthquake activity over the last 13 yr therefore could not have been taken into account, a relatively long period if you consider that high-quality worldwide seismic monitoring only began in 1964, and that it is only from this year onwards that most $\mathbf{M} \geq 4.5$ events have well constrained locations, magnitudes and focal mechanisms. This updated earthquake catalogue, together with the recent publication of a catalogue of Rifts of the World (Şengör & Natal'in 2001), provides an excellent opportunity to re-evaluate the correlation of earthquake activity and rifts on a global scale.

Fig. 1 shows the seven SCRs that are considered: 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°E will be referred to as Europe, whereas the region east of 20°E will be referred to as Russia (Fig. 1). The one large SCR that is not considered is Antarctica, as a result of a relative lack of both seismic monitoring and geological data. The interested reader is referred to Reading (2002) for a discussion of Antarctic seismicity.

Regions of continental crust that do not satisfy the criteria to be included as SCRs (active continental regions, ACRs) include the East African rift system, the Andes, North America west of the Rocky mountains, central Southeast Asia including the Himalayas, and the Mediterranean, which includes young orogenies such as the Alps. These regions are often referred to as diffuse plate boundaries (Gordon 1998) and they will not be considered in this study. Our boundaries of the SCRs are polygons extracted from the original boundaries on the EPRI maps (Johnston *et al.* 1994). For consistency with that earlier study, we have not redefined SCR boundaries.

2 THE EARTHQUAKE DATABASE

The earthquake catalogue compiled for this study is available online `http://earthquake.usgs.gov/scitech/scr_catalogue.html`. It contains crustal (maximum depth $\leq$ 45 km) events with moment magnitudes $\mathbf{M} \geq 4.5$ within SCRs. We chose not to restrict the

Table 1. Source catalogues for the earthquake database.

Source catalogue	Period	Parameters[d]
Triep & Sykes (1996)	Historical - 1994	l, t, d, m, sm, fm, stf, drz
Johnston *et al.* (1994)	Historical - 1990	l, t, d, m, sm, fm, ta
ISC Bulletin[a]	1990 – 2000	l, t, d, m, pr
PDE monthly/weekly (USGS–NEIC)[b]	2001 – 2002	l, t, d, m
CMT Catalogue (Harvard Seismology)[c]	1990 – 2002	l, t, m, sm, fm
Centennial Catalogue Engdahl & Villaseñor 2002)	1900 – 1999	l, t, d, m

[a]International Seismological Center (2001).
[b]Preliminary Determinations of Earthquakes (United States Geological Survey National Earthquake Information Center).
[c]Harvard Seismology: Centroid Moment Tensor Project.
[d]Parameters: l, location; t, origin time; m, magnitudes; sm, seismic moment; fm, focal mechanism; stf, source-time functions; drz, dimensions rupture zone; ta, tectonic association; pr, phase readings.

catalogue to the instrumental era (approximately from the beginning of the 20th century) because, as a result of 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 catalogue therefore includes documented historic events and instrumentally recorded events up to 2003 November. For each event, the epicentre, 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 per cent with respect to the database developed for the Johnston *et al.* (1994) EPRI report. We note that some events will have been excluded from our catalogue as a result of the fact that some events that are undoubtedly shallow are published with erroneous depths in excess of 45 km (*cf.* Engdahl & Villaseñor 2002).

Source catalogues for the updated earthquake catalogue are listed in Table 1, in decreasing order of information taken from them. For each source catalogue, Table 1 lists the period for which it was used and the parameters that it contains. Two selection methods were used to attempt to remove events that were in fact related to plate boundary deformation. First, events within 200 km of plate boundaries, as defined in the Johnston *et al.* (1994) EPRI report, were removed. Secondly, events located within 40 km of the ACR–SCR boundaries were rejected, because, with the possible error in epicentre and in the defined ACR–SCR boundary, we cannot rule out the possibility that these events were actually located within ACRs. Our choice of 40 km or less as a rejection distance represents a compromise between well-located events and poorly located ones. However, our conclusions are not very sensitive to this value because relatively few of our total events are affected by this parameter.

In order to compare the size of different earthquakes, it was desirable to apply a uniform magnitude scale. The moment magnitude **M** is defined as $\mathbf{M} = 2/3 \log M_o - 10.7$ (Hanks & Kanamori 1979), where M_o is the seismic moment (in dyne cm). For many earthquakes, M_o was not readily available and had to be estimated from other magnitudes; body wave magnitude m_b, surface wave magnitude M_s and for a few events (<1 per cent), a local magnitude scale ML. We used the existing regressions developed for the Johnston *et al.* (1994) EPRI study (*cf.* Johnston 1989), because a large number of the earthquakes for our study were taken from this compilation and had **M** determined from these regressions. The regressions can be found in Table 2, in decreasing order of preference. Johnston (1996) conducted similar regression analyses for SCR earthquakes. Although the resulting equations are somewhat different, comparison of **M** computed from his equations and from the Johnston *et al.* (1994) EPRI study shows that this difference rarely exceeds 0.1 **M** units and falls well within the estimated error margins of both studies. For 11 events in the period 1990–2003 that had only a local magnitude, ML, assigned to them, Johnston's (1996) equation (Table 2) was used. The errors estimated in the Johnston *et al.* (1994) EPRI study and Johnston (1996; Table 2), were adopted for this study, unless the difference between **M** estimated from the preferred method and from other regressions was larger, in which case, the error was estimated to be that difference.

The compiled earthquake database contains many historical events for which, by definition, no instrumental data are available. These events were all taken from the Catalogue of Shallow Intracontinental Earthquakes (Triep & Sykes 1996), and the EPRI report (Johnston *et al.* 1994). The latter estimated moment magnitude for these events from a regression of M_o on quoted intensity areas/radii, intensity based magnitudes or on epicentral intensity. However, recent studies on the magnitude estimations for the 1811–1812 New Madrid earthquake sequence, (Hough *et al.* 2000; Bakun & McGarr 2002; Bakun & Hopper 2004) have illustrated that large uncertainties exist in the magnitudes for historical events. We have therefore assigned errors of 1.0 **M** units to all historical events that do not have an independently determined M_o in order to reflect the very poor reliability of the magnitudes of these events in our database.

An earthquake catalogue is said to be complete over a certain magnitude range and time period if no earthquakes with magnitudes within that range are thought to be missing from the catalogue. The authors of Johnston *et al.* (1994) and Triep & Sykes (1996) estimated

Table 2. Regression curves used to determine M_o, in decreasing order of preference.

Magnitude scale	Equation	Estimated error in **M**	Source
$M_u = (m_b + 2\,M_s)/2$	$\mathrm{Log}(M_o) = 21.67 - 0.18(M_u) + 0.13(M_u)^2$	0.3 **M**	Johnston *et al.* (1994)
M_s	$\mathrm{Log}(M_o) = 22.47 - 0.40(M_s) + 0.14(M_s)^2$	0.3 **M**	Johnston *et al.* (1994)
m_b	$\mathrm{Log}(M_o) = 23.33 - 1.28(m_b) + 0.26(m_b)^2$	0.3 **M**	Johnston *et al.* (1994)
ML	$\mathrm{Log}(M_o) = 18.31 + 1.017\,\mathrm{ML}$	0.4 **M**	Johnston (1996)

Table 3. Subsets of the compiled earthquake catalogue that are considered complete.

Period	Magnitudes
1900–2002	$\mathbf{M} \geq 7.0$
1964–2002	$\mathbf{M} \geq 5.0$

their catalogues to be complete for SCRs for magnitudes $\mathbf{M} \geq 5.0$ from 1964 onwards (with the exceptions of South America, which is complete for $\mathbf{M} \geq 5.5$ between 1964 and 1968 and for $\mathbf{M} \geq 5.0$ from 1968, and Indochina, which is complete for $\mathbf{M} \geq 5.0$ only since 1980, as a result of the Vietnam war). Both catalogues are also considered complete for $\mathbf{M} \geq 7.0$ from 1900 onwards (Triep & Sykes 1996). We adopt these threshold magnitudes for completeness in the updated catalogue (Table 3), while bearing in mind that there is always the possibility that some events have been missed. Engdahl & Villaseñor (2002) discuss the issue of seismic catalogue completeness.

11 per cent of the events included in the catalogue are thought to be of non-tectonic origin (i.e. either reservoir triggered or mining induced). This estimate is based on information in the Johnston *et al.* (1994) EPRI earthquake data sheets and/or on the locations of known sites of mining and estimated hypocentre depth. These non-tectonic events were excluded from further statistical analysis. Because we may not be aware of all active mines and hypocentral depths may be erroneous, the process of excluding non-tectonic events is subject to error.

In order to have a sufficiently large data set, we did not restrict the study to the complete subsets of the earthquake catalogue (Table 3). 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, because 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: (i) the entire earthquake data set; (ii) only instrumentally recorded events; and (iii) events from the complete catalogue (Table 3). The earthquakes for the various SCRs are presented in Fig. 2.

3 EARTHQUAKES AND RIFTED CRUST

As noted above, many authors have emphasized the correlation of SCR earthquakes with palaeorifts. Here, we re-evaluate this correlation using our updated catalogue. We use the definition of rifts given by Şengör & Natal'in (2001) in their compilation of rifts of the world: 'Rifts are elongate troughs, under or near which the entire thickness of the lithosphere has been reduced in extension during their formation'. 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 seafloor 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 seafloor spreading.

The catalogue of Rifts of the World (Şengör & Natal'in 2001) is the most complete global listing of rifts and contains information on the location, size, orientation and age of a rift, as well as its placement among Şengör's (1995) hierarchical classification of geometry and dynamics. It was used in combination with the Exxon Tectonic Map of the World (Exxon Production Research Company 1985) to

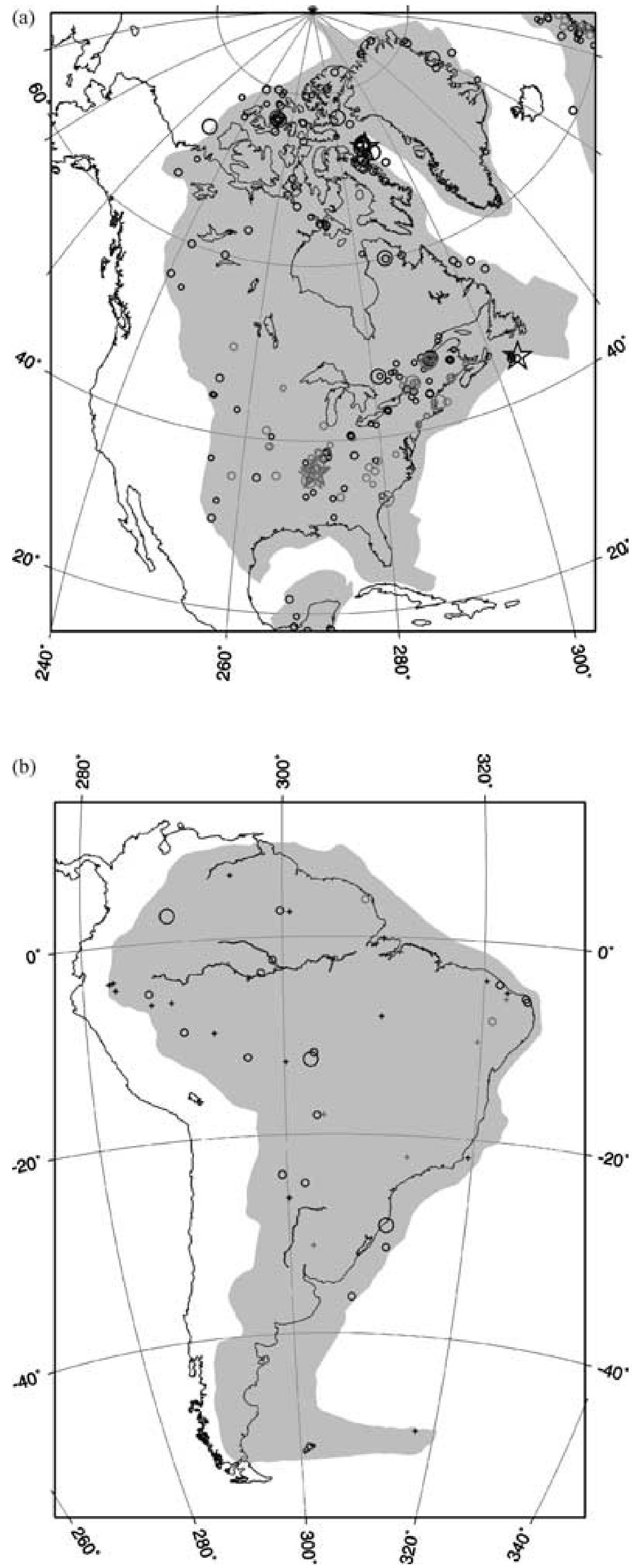

Figure 2. Earthquakes in the updated global database for the different stable continental regions (SCRs). Earthquakes with instrumentally determined location and magnitude are denoted by dark grey circles, historical events by light grey circles. (a) North America, (b) South America, (c) Europe, (d) Russia, India and China, (e) Africa, (f) Australia. Stars indicate $\mathbf{M} = 8$ events. In b–e, crosses are smaller (4.5–5.0) events.

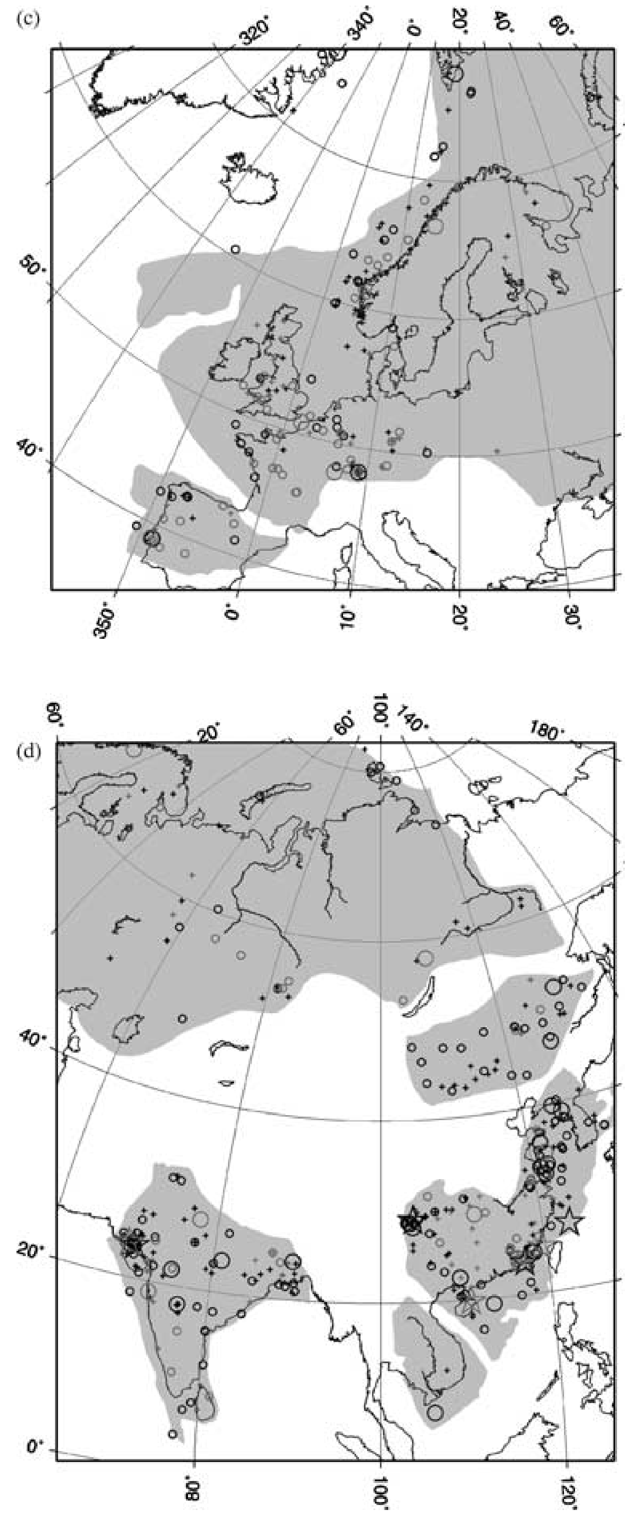

Figure 2. (*Continued*.)

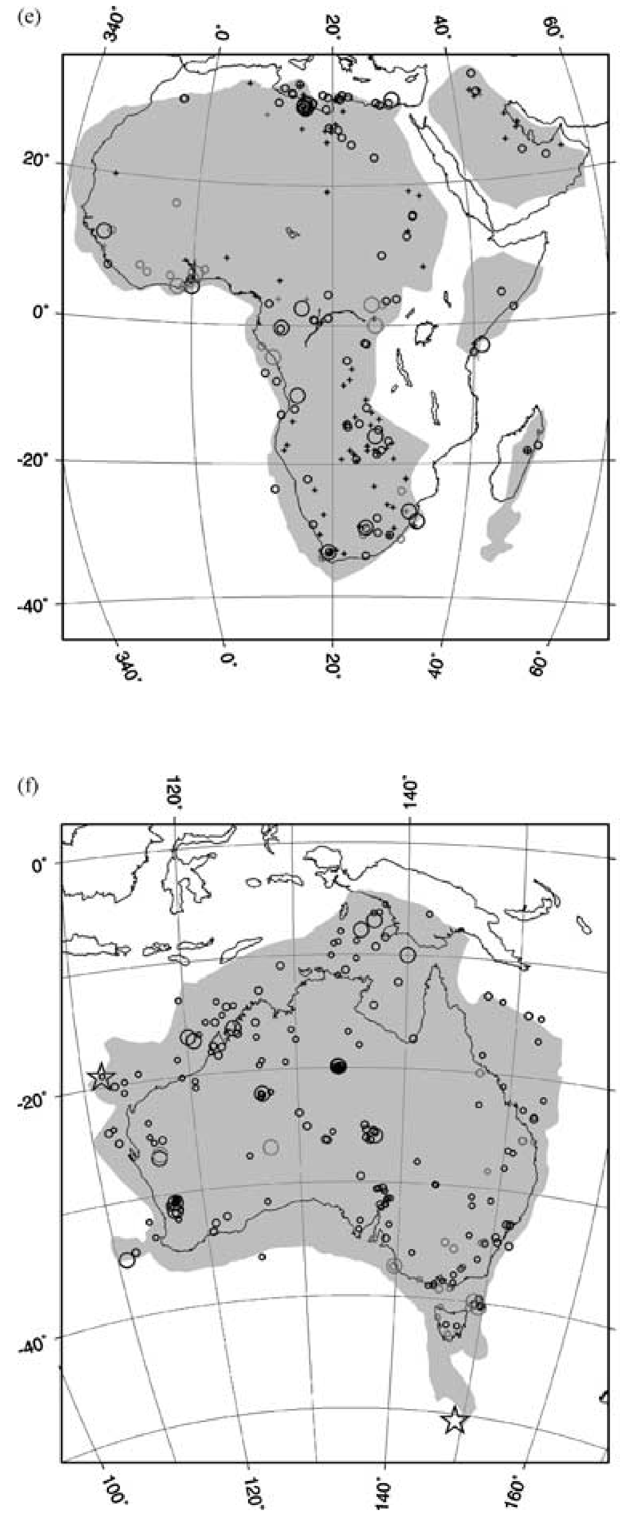

Figure 2. (*Continued*.)

determine the exact location and extent of a rift. The Exxon Production Research Company (1985) map (18 sheets, each approximately 66 × 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 Production Research Company 1985). However, for some rifts in the Şengör & Natal'in (2001) catalogue, it was difficult to establish the exact extent, or even identify the rift at all on the Exxon Production Research Company (1985) maps.

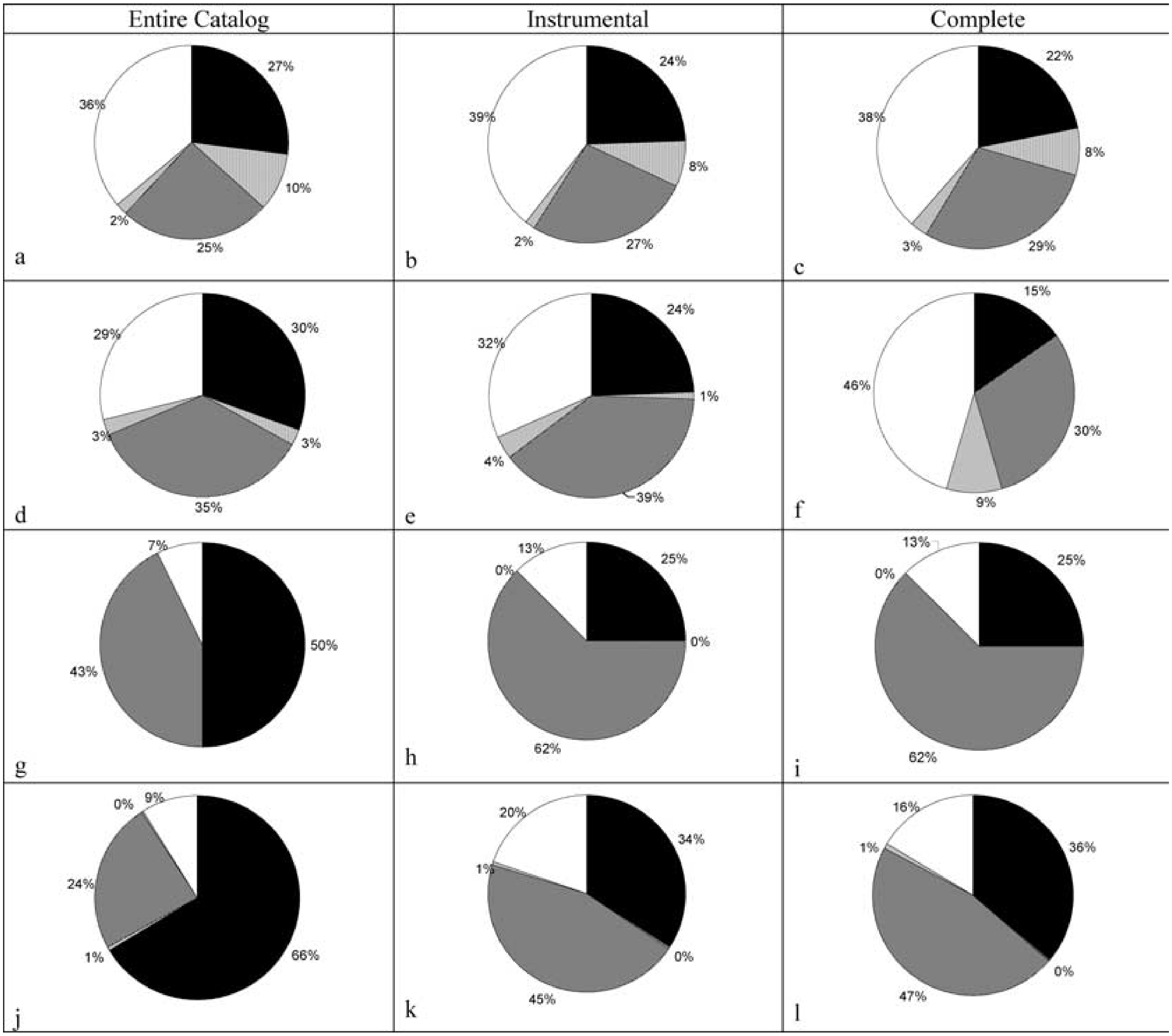

Figure 3. Distribution of seismicity over the five different categories for entire database of instrumentally recorded events and complete subset events: rifts (black), possible rifts (stippled), rifted margins (striped), possible rifted margins (grey), non-rifted crust (white). (a)–(c) $\mathbf{M} \geq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

In the initial stage of analysis, the earthquakes of the compiled database were plotted onto individual sheets of the Exxon Tectonic Map of the World (Exxon Production Research Company 1985). Based on their location, events were placed into one of five categories: (i) interior rifts/taphrogens (within $\sim$ 20 km from the bounding faults), (ii) rifted continental margins (within $\sim$ 20 km of rifted margins), (iii) non-rifted crust, (iv) possible interior rifts and (v) possible rifted margins.

In Fig. 3, we have plotted the distribution of events over these five categories. In addition to considering the geographic distribution of the entire data set, we also looked at the distribution of only the instrumentally recorded events (because they have much better determined estimates of location and magnitude) and the distribution of all events within subsets of the complete catalogue (see Section 2). Our tectonic analysis showed 27 per cent of all earthquakes in the catalogue being incorporated in the interior rifts/taphrogens category, 25 per cent in the rifted continental margins and 36 per cent in non-rifted crust categories (Fig. 3a). 10 per cent of the earthquakes were included in the possibly interior rifts category, 2 per cent of which are earthquakes located in central west Europe that, as evidenced by extensive faulting and a very thin ($\leq$ 30 km) crust, might actually be considered rifted (extended) crust. Our results are similar to those of previous studies (Johnston & Kanter 1990; Johnston *et al.* 1994), which found that 56 per cent 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 versus 27–37 per cent). The numbers remain fairly constant if instrumental or only complete catalogue earthquakes are considered (Figs 3b and c). Of the 118 documented $\mathbf{M} \geq 6.0$ earthquakes (Fig. 3d), 30 per cent are associated with interior rifts, 35 per cent with rifted continental margins and 29 per cent with non-rifted crust. However, the relative number of $\mathbf{M} \geq 6.0$ earthquakes in non-rifted crust increases from 29 to 32 per cent and even 46 per cent if we restrict the data set to the instrumental or complete catalogue events (Figs 3e and f). Our earthquake database contains 14 $\mathbf{M} \geq 7.0$ events, seven of which (50 per cent, Fig. 3g) have occurred within interior rifts/taphrogens, six (43 per cent, Fig. 3g) within rifted continental margins and only one (7 per cent, Fig. 3g) within non-rifted crust. Of these 14 events, eight have been recorded instrumentally and are included in the complete catalogue subset. Considering these eight events, two were located within interior rifts/taphrogens (25 per cent, Figs 3h/i) and five within rifted margins (62 per cent). As a result of 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 catalogue, 66 per cent is associated with interior rifts/taphrogens, 24 per cent with rifted continental margins and 9 per cent with non-rifted crust (Fig. 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 (Fig. 3k), 34 per cent is associated with interior rifts, 45 per cent with rifted continental margins and 20 per cent within non-rifted crust (36, 47 and 16 per cent respectively for the complete catalogue subsets, Fig. 3l).

3.1 The distribution of Earthquakes within the different settings: concentration of seismicity

In Figs 4(a)–(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. These regions are indicated in Figs 4(a)–(c) and are listed in Table 4. 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. The majority of interior rifts show little or no seismicity. In fact, the 12 rifts/taphrogens listed in Table 4 account for 74 per cent of all events and 98 per cent of the total moment release associated with rifted crust within the continental interiors. The latter is dominated by the Kutch rift, India, the Reelfoot rift, USA, and the East China taphrogen, for which several $\mathbf{M} \geq 7$ events have been documented (Fig. 4b, Table 4). It should be noted that the East China taphrogen is a very extensive structure: it comprises a large part of the China SCR. For the rifted continental margin category, the regions listed in Table 4 account for 50 per cent of the events and 67 per cent of the moment release. 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 (Fig. 4c, Table 4). These seven regions

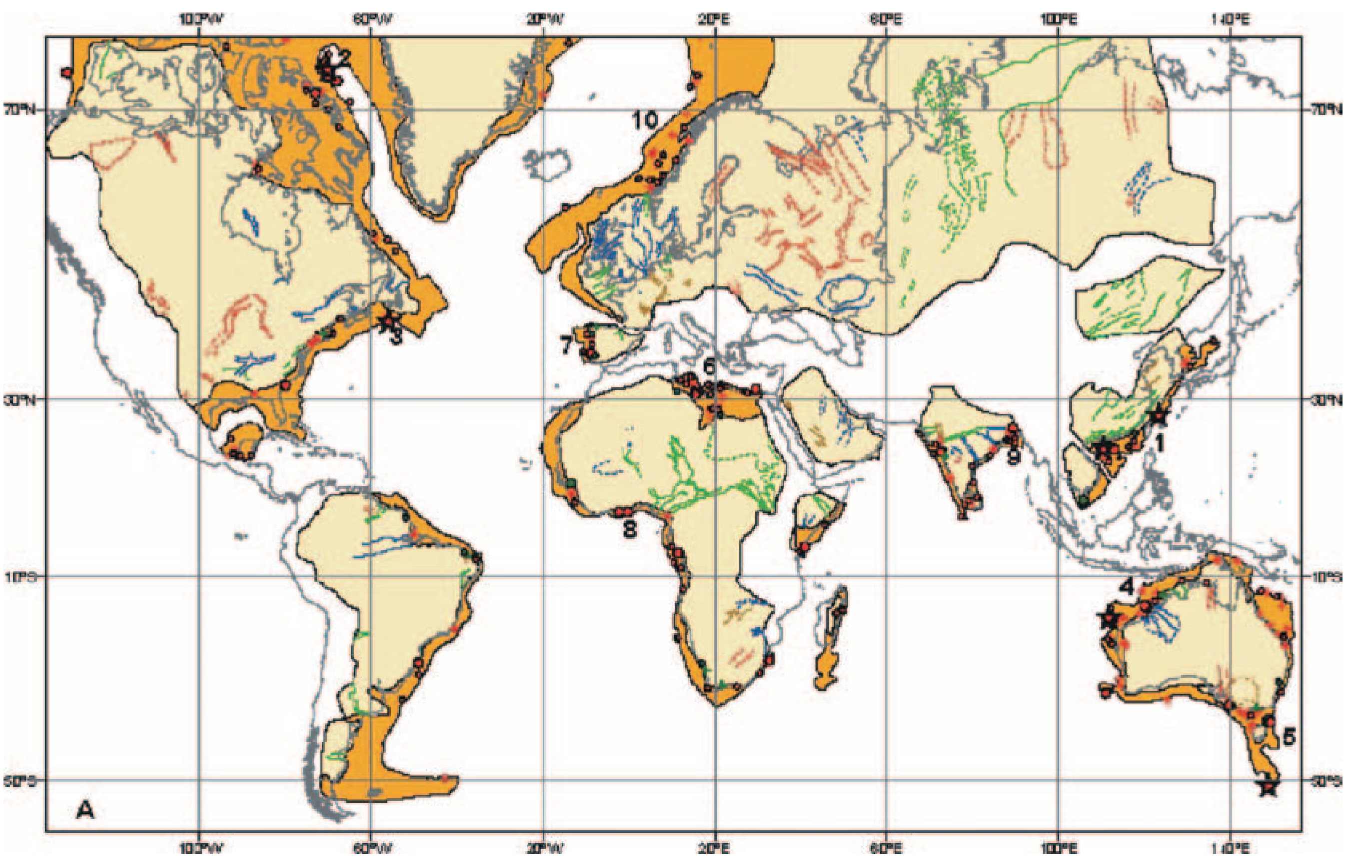

Figure 4. Earthquakes from the database for: (a) rifted continental margins; (b) interior rifts/taphrogens; and (c) non-extended continental crust. Extended margins are coloured orange, continental interiors yellow. Rifts and taphrogens are indicated with solid (boundaries are well determined) or dashed (boundaries are poorly determined) lines. Precambrian rifts are indicated in red, Palaeozoic in blue, Mesozoic in green and Cenozoic in brown. Maps were constructed from the Exxon tectonic maps (Exxon Production Research Company 1985) and the rift catalogue (Şengör & Natal'in 2001). 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 occur in non-rifted crust. Numbers indicate regions of concentrated seismicity and are those from Table 4.

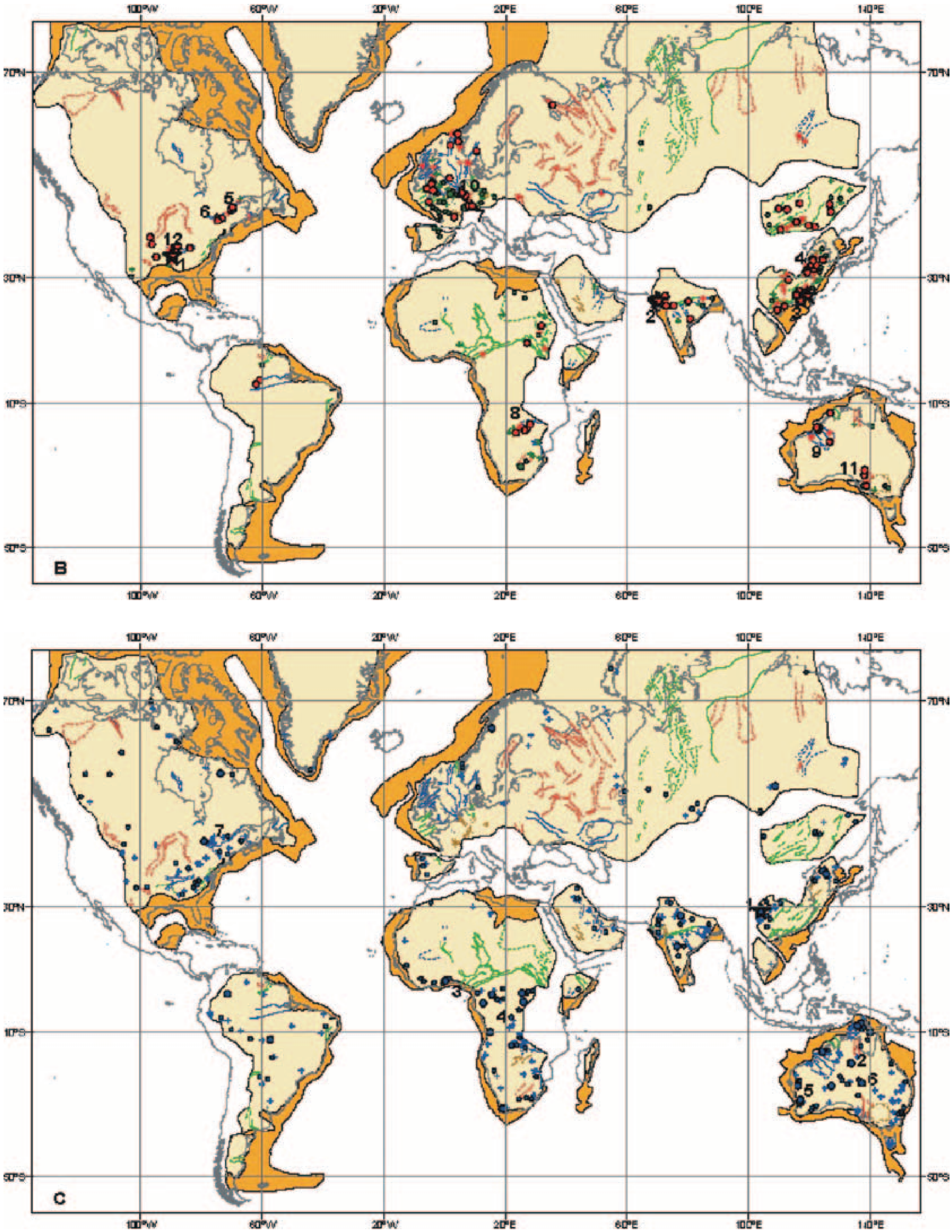

Figure 4. (*Continued*.)

Table 4. Regions of concentrated seismicity. (f/a) stands for events considered to be either fore- or aftershocks of other events.

Region	Entire Catalog no. events(f/a)	6.0 < **M** < 7.0	**M** > 7.0	Σmo (Nm)	Instrumental no. events(f/a)	**6.0 < M < 7.0**	**M** > 7.0	Σmo (Nm)	Complete no. events(f/a)	**6.0 < M < 7.0**	**M** > 7.0	Σmo (Nm)
Rifted continental margins												
Southeastern China	9(1)	1931 **M** = 6.7	1605 **M** = 7.5	1.9E+20	6(0)	1931 **M** = 6.7	-	1.4E+19	1(0)	-	-	4.2E+16
Baffin Bay/ Island	18(5)	1934 **M** = 6.5 (a) 1945 **M** = 6.5 (a) 1947 **M** = 6.0 (a) 1957 **M** = 6.2 1963 **M** = 6.2	1933 M = 7.4	1.5E+20	18(5)	1934 M = 6.5 (a) 1945 M = 6.5 (a) 1947 M = 6.0 (a) 1957 M = 6.2 1963 M = 6.2	1933 M = 7.4	1.5E+20	4(0)	-	1933 M = 7.4	1.3E+20
Grand Banks, Canada	7(2)		1929 **M** = 7.3	8.3E+19	7(2)	-	1929 **M** = 7.3	8.3E+19	2(0)	-	1929 **M** = 7.3	8.3E+19
Northwest Australia	19(0)	1929 **M** = 6.3 1979 **M** = 6.1	1906 **M** = 7.2	7.6E+19	19(0)	1929 **M** = 6.3 1979 **M** = 6.1	1906 **M** = 7.2	7.6E+19	7(0)	1979 **M** = 6.1	1906 **M** = 7.2	7.3E+19
Southeast Australia	19(0)	1885 **M** = 6.0 1892 **M** = 6.4	1951 **M** = 7.1	4.8E+19	10(0)	-	1951 **M** = 7.1	4.3E+19	2(0)	-	1951 **M** = 7.1	4.2E+19
Northern Margin Africa	40(10)	1935 **M** = 6.8 1935 **M** = 6.4 (a) 1935 **M** = 6.4 (a) 1939 **M** = 6.0 (a) 1955 **M** = 6.4	-	4.0E+19	39(10)	1935 **M** = 6.8 1935 **M** = 6.4 (a) 1935 **M** = 6.4 (a) 1939 **M** = 6.0 (a) 1955 **M** = 6.4	-	4.0E+19	12(0)	-	-	2.1E+18
Portugal	10(0)	1531 **M** = 6.9 1909 **M** = 6.4	-	3.4E+19	4(0)	1909 M = 6.4	-	4.8E+18	-	-	-	-
Ghana	4(0)	1636 **M** = 6.2 1939 **M** = 6.5	-	8.3E+18	1(0)	1939 **M** = 6.5	-	5.9E+18	-	-	-	-
Bay of Bengal	12(0)	1935 **M** = 6.1	-	2.4E+18	8(0)	1935 **M** = 6.1	-	2.3E+18	4(0)	-	-	8.2E+17
Coast of Norway	16(1)	-	-	2.1E+18	11(0)	-	-	7.2E+17	1(0)	-	-	2.7E+17
Interior rifts/ taphrogens												
Reelfoot	12(0)	1843 **M** = 6.5 1895 **M** = 6.8	1811 **M** = 7.6 1812 **M** = 7.5 1812 **M** = 7.8	1.1E+21	3(0)	-	-	3.4E+16	-	-	-	-
Kutch	62(54)	1956 **M** = 6.5	1819 **M** = 7.8 2001 **M** = 7.6	1.0E+21	59(54)	1956 **M** = 6.5	2001 **M** = 7.6	3.5E+20	15(14)	-	2001 **M** = 7.6	3.5E+20
East China Taphrogen	53(6)	1067 **M** = 6.1 1600 **M** = 6.8 1631 **M** = 6.4 1906 **M** = 6.0 1919 **M** = 6.1(a) 1921 **M** = 6.2(a) 1936 **M** = 6.2	1604 **M** = 7.7 1918 **M** = 7.3	4.6E+20	22(5)	1906 **M** = 6.0 1921 **M** = 6.2(a) 1936 **M** = 6.2	1918 **M** = 7.3	9.4E+19	10(2)	-	1918 **M** = 7.3	8.8E+19

Table 4. (*Continued*.)

Region	Entire Catalog no. events(f/a)	6.0 < **M** < 7.0	**M** > 7.0	Σmo (Nm)	Instrumental no. events(f/a)	**6.0 < M < 7.0**	**M** > 7.0	Σmo (Nm)	Complete no. events(f/a)	**6.0 < M < 7.0**	**M** > 7.0	Σmo (Nm)
Yellow Sea (ECT)	19(3)	1910 **M** = 6.5 1921 **M** = 6.4 1927 **M** = 6.6 1927 **M** = 6.4(a) 1932 **M** = 6.3 1984 **M** = 6.1	-	3.1E+19	18(3)	1921 **M** = 6.4 1927 **M** = 6.6 1927 **M** = 6.4(a) 1932 **M** = 6.3 1984 **M** = 6.1	-	2.5E+19	9(2)	1984 **M** = 6.1	-	1.9E+18
St. Lawrence	14(0)	1663 **M** = 6.7 1860 **M** = 6.1 1870 **M** = 6.6 1925 **M** = 6.4	-	2.6E+19	7(0)	1925 **M** = 6.4	-	5.2E+18	-	-	-	-
Ottawa	9(0)	1732 **M** = 6.3	-	3.3E+18	2(0)	-	-	5.2E+17	1(0)	-	-	1.7E+16
Illies Graben	8(1)	1911 **M** = 6.2	-	2.5E+18	7(0)	1911 M = 6.2	-	2.4E+18	1(0)	-	-	5.0E+16
Mid Africa	14(1)	1968 **M** = 6.8	-	1.9E+18	14(1)	1968 **M** = 6.8	-	1.9E+18	3(0)	1968 **M** = 6.8	-	7.1E+17
Canning	15(1)	1970 **M** = 6.0	-	1.7E+18	15(1)	1970 **M** = 6.0	-	1.7E+18	5(0)	1970 **M** = 6.0	-	1.5E+18
Rhine Graben	14(0)	-	-	1.3E+18	7(0)	-	-	4.0E+17	1(0)	-	-	1.1E+17
Adelaide	13(0)	-	-	8.2E+17	13(0)	-	-	8.2E+17	1(0)	-	-	7.1E+16
Rough Creek	9(0)	-	-	4.7E+17	5(0)	-	-	1.5E+17	2(0)	-	-	1.3E+17
Non-rifted crust												
China/ Tibet	12(0)	1936 **M** = 6.8 1936 **M** = 6.8 1974 **M** = 6.8	1917 **M** = 7.4	1.8E+20	12(0)	1936 **M** = 6.8 1936 **M** = 6.8 1974 **M** = 6.8	1917 **M** = 7.4	1.8E+20	5(0)	1974 **M** = 6.8	1917 **M** = 7.4	1.4E+20
Tennant Creek	20(17)	1988 **M** = 6.5 1988 **M** = 6.6 1988 **M** = 6.3	-	1.7E+19	20(17)	1988 **M** = 6.5 1988 **M** = 6.6 1988 **M** = 6.3	-	1.7E+19	13(10)	1988 **M** = 6.5 1988 **M** = 6.6 1988 **M** = 6.3	-	1.7E+19
Ghana	6(1)	1862 **M** = 6.8	-	1.6E+19	2(0)	-	-	5.3E+17	2(0)	-	-	5.3E+17
Africa 5N-15S	39(1)	1903 **M** = 6.3 1908 **M** = 6.3 1914 **M** = 6.2 1945 **M** = 6.1 1974 **M** = 6.0	- - - - -	1.4E+19	34(1)	1914 **M** = 6.2 1945 **M** = 6.1 1974 **M** = 6.0	-	7.7E+18	14(1)	1974 **M** = 6.0	-	2.4E+18
Meckering	17(5)	1968 **M** = 6.6 1979 **M** = 6.1	-	1.2E+19	16(5)	1968 **M** = 6.6 1979 **M** = 6.1	-	1.2E+19	7(2)	1968 **M** = 6.6 1979 **M** = 6.1	-	1.2E+19
Eromanga	10(3)	1941 **M** = 6.5	-	8.2E+18	10(3)	1941 **M** = 6.5	-	8.2E+18	1(0)	-	-	3.7E+16
Outside Ottawa	9(0)	1935 **M** = 6.2	-	3.1E+18	9(0)	1935 **M** = 6.2	-	3.1E+18	1(0)	-	-	6.9E+17

account for 70 per cent of the total seismic moment release, but comprise only 26 per cent of the total events in the category.

Unfortunately, a large part (24 per cent of all $\mathbf{M} \geq 4.5$, 31 per cent of all $\mathbf{M} \geq 6.0$ and 43 per cent of all $\mathbf{M} \geq 7.0$ events) of the earthquake database used for analysis consists of historical earthquakes. If we restrict the data set to the instrumental era or to the complete catalogue subsets, the majority of the regions considered to be relatively seismically active no longer have a much higher seismicity than their surroundings (Table 4). The Reelfoot rift, for instance, has experienced three large $\mathbf{M} \geq 7$ historical earthquakes, but only three earthquakes of $\mathbf{M} \geq 4.5$ have been instrumentally recorded. Therefore, the lack of seismicity within apparently aseismic interior rifts, and also within rifted margins and non-rifted continental interiors, may in fact be the result of a lack of documentation throughout history and not a lack of actual seismicity. As a result of the large recurrence interval of SCR seismicity, the available global earthquake data set 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 listed in Table 4 have experienced higher magnitude earthquakes ($\mathbf{M} \geq 6.0$) in the instrumental era, whereas for the interior rifts/taphrogens, the largest events are dominantly historical.

4 EARTHQUAKES IN INTERIOR RIFTS/TAPHROGENS: A CLOSER LOOK

4.1 The Kutch rift, India

Fig. 5(a) shows the Kutch rift in northwestern India. It is the locus of two of the largest events within the compiled earthquake database: the 1819 $\mathbf{M} = 7.8$ and the 2001 $\mathbf{M} = 7.6$ events (Table 4). Apart from the East China rift system, it is the only rift that has experienced an $\mathbf{M} > 7$ event that was instrumentally recorded, and therefore has a very well determined epicentre and magnitude. The Kutch rift proper is Mesozoic in age. However, active faulting has also 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 plates (Fig. 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).

4.2 Eastern USA and Canada

A map of the eastern USA and Quebec, Canada, is shown in Fig. 5b. It is evident that seismicity is very strongly concentrated in the Reelfoot rift and (to a lesser extent) the adjoining Rough Creek graben (rift). Within the Reelfoot rift, three $\mathbf{M} > 7$ events have occurred: the 1811 $\mathbf{M} = 7.6$, the 1812 $\mathbf{M} = 7.5$ and the 1812 $\mathbf{M} = 7.8$ events. However, no events with magnitude $\mathbf{M} > 5.0$ have been documented instrumentally.

Within historical times, there has been a large difference in seismic activity between the Reelfoot rift and the large Precambrian Midcontinent rift of the central USA. The latter is accompanied by the largest positive isostatic residual gravity anomaly in the central USA. An anomalously dense lower crust (Simpson *et al.* 1990) is the preferred interpretation of this positive gravity anomaly. The Midcontinent rift, obviously a major lithospheric scale discontinuity, has experienced only four minor events ($\mathbf{M} \geq 4.5$) located within approximately 300 km of each other, the largest of which was the historical 1867 $\mathbf{M} = 5.5$ event. Most of this rift seems to be completely aseismic.

The St. Lawrence depression in Quebec, Canada (Fig. 5b), is categorized as an ancient rift in this study. However, besides rifting, the region has experienced several other tectonic events, including collision and meteorite impact (Vlahovic *et al.* 2003). As is evident in Fig. 5(b), the St. Lawrence depression is located at the boundary between Precambrian shield, the Grenville terrain in the northwest and the Appalachians in the southeast. Four $\mathbf{M} > 6$ events have been documented: the historical 1663 $\mathbf{M} = 6.7$, 1860 $\mathbf{M} = 6.1$ and 1870 $\mathbf{M} = 6.6$ events, and the instrumentally recorded 1925 $\mathbf{M} = 6.4$ earthquake.

In the Ottawa rift, Canada (Fig. 5b), nine earthquakes have been documented, the largest of which was the historic 1732 $\mathbf{M} = 6.3$ event. However, the region directly northwest of the Ottawa rift consists of a Precambrian shield that has not experienced rifting and this region shows an equal number of events. Nine events have been documented for this shield, the largest being the 1935 instrumentally recorded $\mathbf{M} = 6.4$ event. The equal level of seismic activity in the Quebec region in non-rifted and in rifted lithosphere suggests that the seismicity may not actually be related to the presence of an ancient rift. Furthermore, the Ottawa rift borders the Appalachian front on the east, which is the area where the majority of the documented earthquakes have occurred.

4.3 Mid-Africa

In Africa, a large cluster of rifts exists in the region between 10°–20°S and 20°–30°E (Fig. 4b), ranging in age from Palaeozoic (the Kafue and Mid Zambezi rifts) to Cenozoic (the Ngami Mabebe and Kariba depressions; Şengör & Natal'in 2001). 13 earthquakes, the largest of which was the 1968 $\mathbf{M} = 6.8$ event, have been documented within this rift cluster (Table 4). However, the non-rifted region north of the rift cluster also seems to be seismically active: it has experienced at least 12 events, including the 1959 $\mathbf{M} = 5.9$ earthquake. The age of the Cenozoic depressions is Pleistocene to Holocene, which means that, strictly speaking, the region is not actually an SCR, as it has experienced extension younger than Palaeogene. Perhaps the Cenozoic depressions are actually related to the East African rift system, which therefore might extend further to the west than defined by the Johnston *et al.* (1994) EPRI study.

4.4 Southeastern China

The East China rift system comprises the largest part of the southeastern China SCR (Fig. 5c). The individual grabens were not identified in this study and therefore we cannot say how many of the earthquakes within the taphrogen are located within the individual grabens. However, 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 19 earthquakes, six of which (5 instrumentally recorded) were $\mathbf{M} > 6$ events (see Table 4). The second is the region directly opposite the Ryuku trench at Taiwan with 13 earthquakes, seven of which have $\mathbf{M} > 6.0$ (Table 4). The two largest events located within the East China rift system are the historical 1604 $\mathbf{M} = 7.7$ and the instrumentally recorded 1918 $\mathbf{M} = 7.3$ 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.

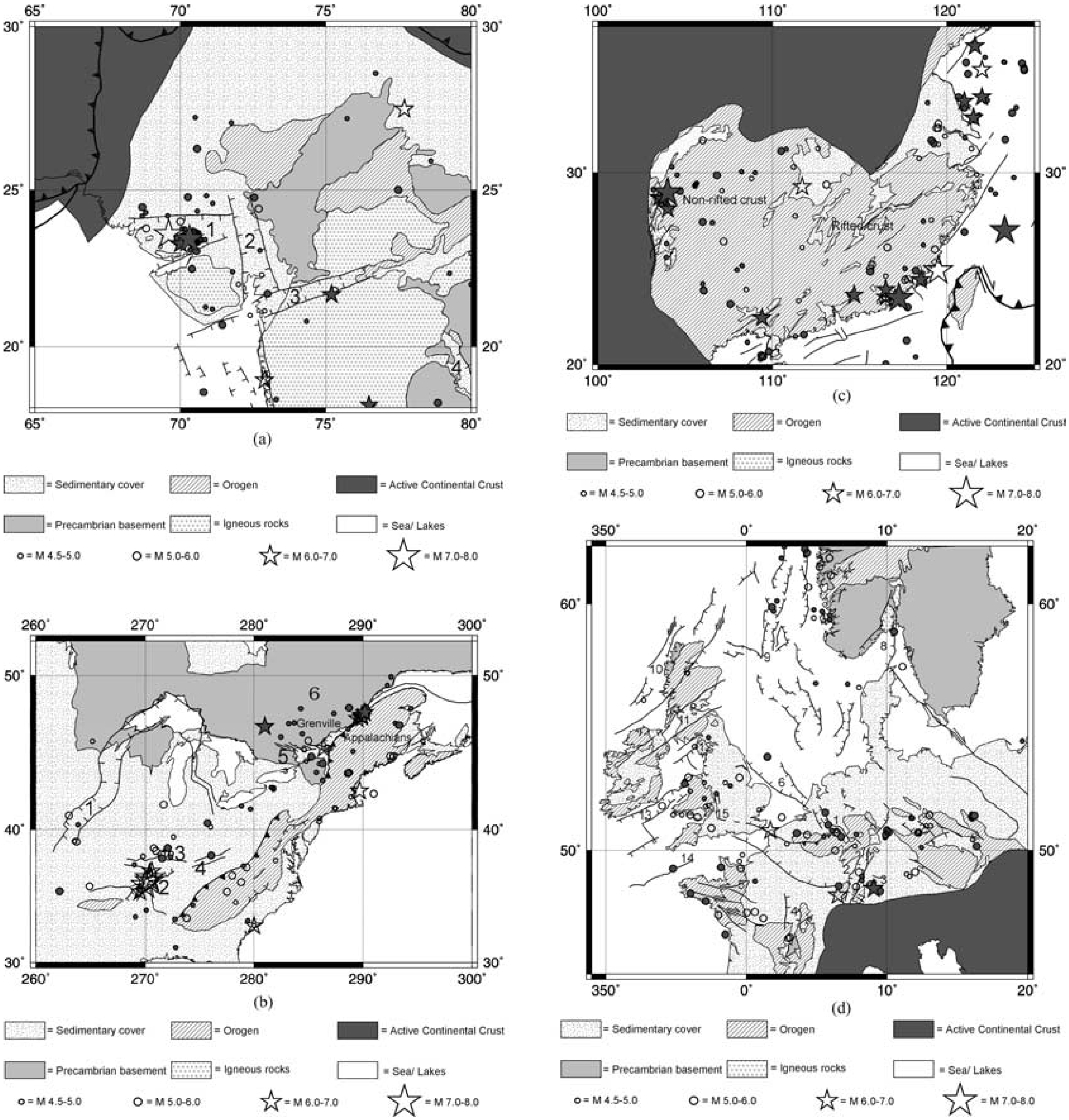

Figure 5. Simplified tectonic maps for different regions within stable continental crust and earthquakes from the database. Events that were recorded instrumentally are coloured dark grey, historic events are denoted by open symbols. (a) India, with (1) Kutch Rift, (2) Cambay rift, (3) Narmada Son rift and (4) Pranhita-Godovari rift. (b) Northeastern USA/Canada with (1) Midcontinent rift, (2) Reelfoot rift, (3) Rough Creek rift, (4) Rome trough, (5) St. Lawrence depression and (6) Ottawa rift. (c) Southern China, with East China rift system. (d) Europe with (1) Lower Rhine rift, (2) Upper Rhine rift, (3) Illies rift cluster, (4) Limange rift, (5) Brittany rift cluster, (6) West Netherlands Sole Pit, (7) Central graben, (8) Oslo rift, (9) Viking graben, (10) Minches basin, (11) Midland valley, (12) Solway–Northumberland basin, (13) North Celtic sea basin, (14) Western Approaches basin and (15) Worcester basin.

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 $\mathbf{M} > 6.5$ events, including the 1917 $\mathbf{M} = 7.4$ earthquake. The region shows large-scale intrusions and faulting, and directly borders the ACR (as defined by Johnston *et al.* 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.

4.5 Central Western Europe

Fig. 5(d) is a map of central Europe. The region has experienced large-scale extension since the Palaeozoic. Rifts within the North sea and the northern part of Britain and Ireland are dominantly Palaeozoic in age, whereas the age of rifting on the mainland is Cenozoic. The youngest rift is the Brittany rift cluster (Şengör & Natal'in 2001), which is not readily identified on the Exxon tectonic map (Exxon Production Research Company 1985). This rift cluster is Pliocene to Quaternary of age and therefore, like the Ngami and Kariba depressions in central Africa, is in fact too young to allow inclusion of the region in SCRs according to the Johnston *et al.* (1994) definition. Other Cenozoic rifts in central Europe, however, have ages no younger than Palaeogene and therefore the largest part of Europe qualifies as an SCR.

The Rhine graben (Fig. 5d), consisting of two parts, the Upper and Lower Rhine grabens, is one of the few rifts in Europe in which seismicity is highly concentrated (Table 4, Fig. 5d). 14 events have been documented, although none with a magnitude $\mathbf{M} > 5.6$.

The presence of large faults, salt deposits and the low average crustal thickness (approximately 27 km; Mooney *et al.* 2002) all indicate that central Western Europe has undergone large-scale thinning, and that extension is not limited to individual rifts. However, seismic activity within Europe is not very high. Although the earthquake database contains 148 European tectonic events, this relatively high number seems to be the result of the very long period of earthquake documentation in comparison with other SCRs. The first events for Europe in the earthquake database date back to the 11th and 12th centuries, which apart from China is the longest historical record of the regions considered. Only 67 events have been instrumentally recorded, none of which has a magnitude $\mathbf{M} > 6.4$. Considering the large-scale extension Europe has experienced, we would expect a much higher level of seismic activity if in fact a very strong relationship would exist between the two.

5 FOCAL MECHANISMS AND STRESS

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

6 SUMMARY AND CONCLUSIONS

We have presented an updated global catalogue for SCR earthquakes that contains information on location, magnitude, seismic moment and focal mechanisms of 1373 $M \geq 4.5$ crustal events from the year 495 to 2003. This is an increase of ∼ 58 per cent with respect to the last global study (Johnston *et al.* 1994). The database is available online at `http://earthquake.usgs.gov/scitech/scr_catalogue.html`. 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. Ancient continental interior rifts and rifted continental margins were identified using the Rifts of the World catalogue (Şengör & Natal'in 2001) and the Exxon Tectonic Map of the World (Exxon Production Research Company 1985). 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 main results and conclusions are listed below.

(i) 27 per cent of the earthquakes fell in the interior rifts/taphrogens category, 25 per cent were rifted continental margins, 36 per cent were non-rifted crust and 12 per cent remained uncertain. These numbers are similar to those of earlier workers (Johnston & Kanter 1990; Johnston *et al.* 1994), who found that 56 per cent of all SCR earthquakes are associated with extended crust (interior rifts/taphrogens + rifted continental margins).

(ii) 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 per cent interior rifts/taphrogens versus 36 per cent non-rifted crust).

(iii) 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.

(iv) The percentages remain fairly constant if only larger ($\mathbf{M} \geq 6.0$) events are considered, although for the largest events ($\mathbf{M} \geq 7$, $N = 14$), interior rifts/taphrogens (50 per cent) and rifted continental margins (43 per cent) strongly dominate.

(v) Seismicity is not distributed evenly. For the interior rifts/taphrogens category, only 12 rifts account for 74 per cent of all events and 98 per cent of the total moment release. The majority of interior rifts, in fact, show little or no seismicity.

(vi) Several regions that have experienced multiple large ($\mathbf{M} \geq 6.0$) events exist within apparently non-rifted crust.

(vii) The most seismically active rifts are the Kutch rift, India (1819 $\mathbf{M} = 7.8$ and 2001 $\mathbf{M} = 7.6$ events), the East China taphrogen (1604 $\mathbf{M} = 7.7$ and 1918 $M = 7.3$), the Reelfoot rift, USA (1811 $\mathbf{M} = 7.6$, 1812 $\mathbf{M} = 7.5$ and 1812 $\mathbf{M} = 7.8$) and the Canadian St. Lawrence depression (1663 $\mathbf{M} = 6.7$, 1870 $\mathbf{M} = 6.6$, 1925 $\mathbf{M} = 6.4$). However, the Kutch rift is located relatively close to the triple junction between the Arabian, Indian and Eurasian plates. 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. Furthermore, the St. Lawrence depression, besides having experienced rifting, has also experienced two other tectonic events: terrane collision and meteorite impact (Vlahovic *et al.* 2003). It coincides with the Grenville and Appalachian province suture. Therefore, it is not clear whether rifting is the ultimate cause of seismicity. The NMSZ within the Reelfoot rift is the only rift for which very large ($\mathbf{M} > 7.0$) earthquakes have been documented for which there are no other clear tectonic features. It seems to be unique in its kind.

(viii) 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. For example, the Reelfoot rift, which was the locus of three historical $\mathbf{M} \geq 7.0$ earthquakes, has experienced no $M \geq 5.0$ events within the instrumental era.

(ix) Europe, one of the most extensively rifted regions in the world, has in fact experienced few large earthquakes.

In conclusion, although many earthquakes have occurred within rifted crust, the potential of seismicity within rifts should not be overemphasized. 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.

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