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A Catalog of Felt Intensity Data for 570 Earthquakes in India from 1636 to 2009

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A Catalog of Felt Intensity Data for 570 Earthquakes in India from 1636 to 2009

by Stacey Martin and Walter Szeliga

Abstract Eight thousand three hundred thirty-nine intensity observations have been evaluated for earthquakes that occurred on the Indian subcontinent and surrounding plate boundaries from the seventeenth century to the present. They characterize 570 earthquakes, more than 90% of which occurred in the past two centuries. The electronic supplement to this article lists these data using European Macroseismic Scale (EMS-98) intensities with their geographic coordinates. We summarize these data graphically in the form of a spatially averaged intensity map for the subcontinent, a map that emphasizes the features of many previously published earthquake hazard maps for the Indian plate, but which more faithfully depicts regional amplification and attenuation. We also estimate the probable return time for future damaging shaking in five of India's largest cities.

Online Material: Annotations for select earthquakes with tables listing source locations and number of reports.

Introduction

Catalogs of historical Indian earthquakes occurring in the past 450 years contain errors in date, location, and magnitude, and list few intensity data in a form suited to numerical analysis. The following account addresses this deficiency by presenting a unified analysis of intensity data assessed from accounts of damage or from felt perceptions of earthquakes. As such it omits some earthquakes for which no intensity data are available. In contrast, it includes several earthquakes missing from previous catalogs. With few exceptions, the listing is based on original source materials archived in Indian and European libraries, regional newspapers, private letters and diaries, and government reports. For earthquakes later than 2000, eyewitness accounts provided via the World Wide Web or communicated in person have also been included. In total, 570 earthquakes are listed using 8339 intensity evaluations based on the European Macroseismic Scale (EMS-98) (Grünthal and Levret, 2001). Of these earthquakes, 7 occurred before 1800, 240 occurred between 1800 and 1900, 158 occurred between 1900 and 1960, and a further 165 earthquakes occurred in the period from 1960 to 2009 (Fig. 1). The data are provided in the form of an electronic supplement listing the latitude, longitude, and location of each felt report and its inferred intensity (Ⓔ see Tables S1 and S2 in the electronic edition of *BSSA*). We omit estimates of magnitude in the electronic supplement because magnitude determination is sensitive to the methodology chosen (Szeliga *et al.*, 2010). The formats for these electronic supplements are shown in Tables 1 and 2.

Early earthquake catalogs for India consist of anecdotal information, dates, and locations, but few data are suited to quantitative evaluation of intensity (Baird Smith, 1843a,b, 1844; Mallet and Mallet, 1858; Oldham, 1883; de Montessus de Ballore, 1896). Events listed in early catalogs were often repeated in later catalogs; these events were subsequently included in more recent compilations (Bapat *et al.*, 1983; Srivastava and Ramachandran, 1985; Ramachandran and Srivastava, 1991), supplemented by new earthquakes and by newly discovered archival information. Hence, these new catalogs include many erroneous entries from earlier catalogs. The global *Catalog of Significant Earthquakes* by Dunbar *et al.* (1992) lists all these earthquakes uncritically, making it impossible to judge which accounts should be rejected. As Ambraseys (1971) noted, the repetition of error is common to many catalogs of earthquakes that have not been evaluated from primary source materials.

This article includes data assessed from primary sources or from sources that reproduce the raw data from which intensity may be evaluated or verified (Ⓔ see Sections 1, 2, 3, 4 in the electronic edition of *BSSA*). We emphasize that our list of the locations of Indian earthquakes (Ⓔ see Table S1 in the electronic edition of *BSSA*) is subordinate to the listing of perceived and felt observations of intensity (Ⓔ see Table S2 in the electronic edition of *BSSA*) because the determination of epicentral location is subject to interpretation. The tabulated intensity data are quantified from reports at locations that are rarely at the epicenter. Therefore, the location and magnitude

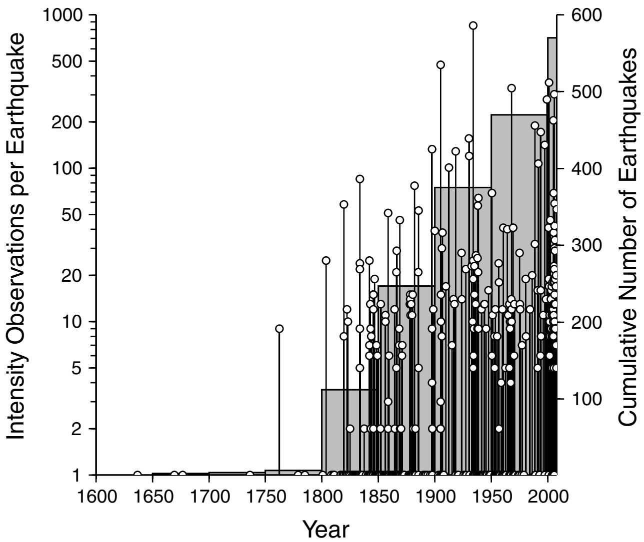

Figure 1. A cumulative histogram of earthquakes per 50-year period in the historical seismic catalog (right axis). Vertical bars topped with circles (left axis) show observations per earthquake.

of all preinstrumental earthquakes in India derived from these data are uncertain except in those rare locations where surface deformation has been recorded (e.g., 1819 Kachchh and 1897 Shillong). The entries are listed in chronological order. In a companion article (Szeliga *et al.*, 2010), we calculate epicentral locations for many of these earthquakes using the methods of Bakun and Wentworth (1997).

Beginning in the late 1800s, the Geological Survey of India and other agencies compiled studies of significant earthquakes. In many official government reports, a simplified description of the building stock considered characteristic of a whole village is used (e.g., 1967 Koyna earthquake; Tandon and Chaudhury, 1968). In some cases this generalized description of the building stock is classified into Types A, B, and C as defined in Grünthal and Levret (2001). However, many of these reports omit descriptions of shaking experienced by people. From these government reports, we have used descriptions of damage, in some instances accompanied by photographs, to evaluate intensities. We have reevaluated 28 of 43 events from Ambraseys and Douglas (2004) where it was possible to locate firsthand accounts or official reports. None of our listed intensities have been repeated from maps or previously published listings. Where authentic primary source materials are unavailable for a particular earthquake, those accounts have been excluded from the final listing.

Intensity Scale

In previous studies, various intensity scales were used to evaluate earthquakes in India. Oldham (1899) notes that early European scales listed inappropriate criteria for the assessment of acceleration-related damage to indigenous structures, and for the 1897 Assam earthquake he chose to use his own simplified scale rather than the then prevalent Rossi-Forrel scale. Later studies of earthquakes adopted the Modified Mercalli scale (e.g., Middlemiss, 1910) or the Medvedev–Sponheuer–Karkik scale (MSK-64; Medvedev *et al.*, 1965). Intensities in this article use the European Macroseismic Scale (EMS-98; Grünthal and Levret, 2001; see also Table A1 in the Appendix), a successor to the MSK-64 intensity scale. We note

Table 1
The First Dozen Earthquakes from Ⓔ Table S1 in the Electronic Edition of *BSSA* to Illustrate Format

Date (mm-dd-yyyy)*	Longitude†	Latitude†	Number of Observations‡	Earthquake§
08-29-1636			1	
06-23-1669			1	
08-26-1676			1	
03-24-1736			1	
04-02-1762	22.4	92.2	9	Chittagong 1762
NA-NA-1779			1	
12-NA-1784			1	
10-19-1800			1	
09-01-1803	30.7	78.8	25	Barahat 1803
06-04-1808			1	
04-01-1810			1	
05-13-1810			1	

*Month, day, and year refer to the date of an event in local time.

†For earthquakes with more than seven intensity observations (see the Number of Observations column), the approximate epicentral location is listed in the Longitude and Latitude columns.

‡The number of observations corresponds to the number of intensity reports listed in Ⓔ Table S2 in the electronic edition of *BSSA*.

§A geographic region designator is defined for some events. This column serves as a reference column to groups of intensity observations in Table 2.

Table 2
The First 5 Earthquakes of 570 from Ⓔ Table S2 in the Electronic Edition of *BSSA*

Date (mm-dd-yyyy)*	Longitude†	Latitude†	EMS-98 Intensity‡	Location§	Earthquake‖
08-29-1636	72.81	21.19	III	Surat	
06-23-1669	74.79	34.08	V	Srinagar	
08-26-1676	86.94	21.48	IV	Balasore	
03-24-1736	74.79	34.08	VII	Srinagar	
04-02-1762	88.35	22.57	III	Calcutta [Kolkata]	Chittagong 1762
04-02-1762	88.386	22.88	III	Chandernagore	Chittagong 1762
04-02-1762	91.838	22.342	V	Goyparah	Chittagong 1762
04-02-1762	91.665	22.552	VI	Akulpoor-Bansbaria	Chittagong 1762
04-02-1762	91.773	22.297	VI	Howla	Chittagong 1762
04-02-1762	91.826	22.349	VII	Chittagong/Islamabad	Chittagong 1762
04-02-1762	92.101	22.133	VII	Dahrampoor	Chittagong 1762
04-02-1762	92.065	22.168	VII	Do Hazari	Chittagong 1762
04-02-1762	92.084	22.367	VIII	Bahngoo Changee	Chittagong 1762

*Month, day, and year refer to the date of an event in local time.
†Longitude and Latitude refer to the location of the intensity observation.
‡From the intensity scale of Grünthal and Levret, 2001.
§Earthquakes with fewer than two observations are not assigned geographic locations.
‖The earthquake column groups observations from the same earthquake and refers to the geographic location of each earthquake in Table 1.

that the MSK-64 listings of Ambraseys and Douglas (2004) are numerically indistinguishable from our EMS-98 evaluations for those accounts we have compared. As in Ambraseys and Douglas (2004), we have avoided assessing local intensities based on, or contaminated by, ground deformation, landslides, liquefaction, seismic seiches, and surface faulting. Numerous accounts that fall into these categories have thus been excluded from the catalog.

Many of the intensities we have evaluated lie in the intensity range II–V. These are differentiated from sparse data as follows: Reports that stated an earthquake was barely felt or very slight were assigned intensity II, while those that stated an earthquake was slight or mild were assigned intensity III. Reports that spoke of tremulous motion, rumbling sounds, and other similar results were assigned intensity IV. Grade I damage (Grünthal and Levret, 2001) to structures begins at intensity V with the appearance of structural cracks, tiles and plaster being dislodged, and other visible damage. Above intensity V, the following criteria are used: Masonry damage begins at intensity VI, and accounts of this level of damage often estimate the numbers of buildings affected; that is, a few, many, or most, which together with human perceptions, permit us to distinguish between intensities VI and VII. Photographs, if available, were used only to supplement intensity assignment. We recognize that photographic evidence is often biased toward the most damaged structures, because undamaged structures are rarely photographed (Hough and Pande, 2007). Because of this known bias, photographs were never used solely to determine intensities.

Reporting Consistency and Completeness

Earthquakes in India, as elsewhere, result in felt reports where the density of reporting is proportional to the density of population. The number of felt reports is further dependent on the propensity of a population to commit their perception of shaking or perceived damage to some form of permanent record. Large urban centers contain a range of vulnerable structures, with people of different levels of awareness, and the record of their perceptions depends much on the prevailing traditions of personal diaries and responsibilities of the press and government offices to print these materials. Not only have these reporting habits changed throughout the past few hundred years, but so have the styles of buildings and construction materials used to make these buildings.

Prior to the eighteenth century, reporting was sparse and mainly undertaken by official historians and intellectuals. By the late nineteenth century the reporting of earthquakes by scattered colonial observers became more verbose and eloquent. During the twentieth century, seismologists began proactively collecting intensity data and initiating studies of specific earthquakes. The mid-twentieth century is characterized by a decline in the number of people writing and presenting personal diaries or sending notes to newspapers, instead, trusting the record of professional reporters trained to gather and print information in the local and national media. In the past decade the Internet has given many people the opportunity to report their perceptions rapidly. Specific blackouts in reporting have also occurred, such as during the Second World War, when damage to some cities was classified.

Although reporting improved considerably after 1800, many areas are not represented well, even at the present time. Thus, it is certain that unevenness in reporting prevails during the time spanned by our catalog. This is partly because the density of people reporting earthquakes varies spatially, and partly because public interest in reporting felt intensities has varied significantly with time. Many small earthquakes may be noted by people but not recorded in news media or public reports. Thus, we anticipate that additional earthquakes and accounts of existing earthquakes will surface in future years that will supplement the recorded observations we list.

We emphasize that the present catalog is not a complete list of all Indian earthquakes. We estimate that only for $M > 8$ is the list complete for the Indian subcontinent since 1800. In a companion article (Szeliga *et al.*, 2010), we calculate the Gutenberg–Richter b-value for magnitudes estimated from the intensity data listed here (Ⓔ see Table S1 in the electronic edition of *BSSA*). The b-value thus determined is approximately 0.3 (compared with instrumental catalogs where the b-value is ≈ 1.0). This suggests that we are missing substantially more than half of all earthquakes $M < 6$. We note, however, that the earthquakes recorded by people are those where populations are dense and have steadily increased in the past few hundred years. The resulting catalog is thus of intrinsic utility for estimating seismic hazards to these present large populations.

Summary of Results

The spatial coverage of intensity observations for India is plotted in Figure 2a. Regions with low population density, such as the Rajasthan desert, parts of Baluchistan, the Nepal and Assam Himalaya ranges, and the Indo-Burman ranges are sparsely sampled. In contrast, trade and communication routes are manifest and appear as strings of observations across otherwise uninhabited regions. At many points in Figure 2a we have multiple estimates of shaking intensity, both from individual earthquakes and from multiple earthquakes.

From these raw data, we have prepared maps that show the maximum felt intensities at every point where a felt report has been obtained (Fig. 3a; Quittmeyer *et al.*, 1979). In regions where the population is sparse, the points so obtained are often from isolated accounts. In contrast, in regions of dense population the larger sample size results in a broader spectrum of observed shaking intensity. To account for uncertainties in named felt locations, we group all intensity data within a 10 km radius and calculate the maximum shaking intensity observed in each grouping (Fig. 3a).

Various forms of spatial averaging are possible to make it easier to form general conclusions and to suppress extreme values that may be caused by anomalous observations. We choose to interpolate our grouped data set using a nearest-neighbor scheme with a 50 km search radius (Fig. 3b, upper right).

Although a more thorough statistical treatment (e.g., Kozuch, 1995; Bozkurt *et al.*, 2007) would require even greater sampling in time, for several cities with large and growing populations, sufficient intensity data are available to begin to form a statistical view of past, and possibly, future shaking. The five largest modern cities in India (Mumbai, Delhi, Bangalore, Kolkata, and Chennai) have been shaken numerous times in the past 200 years by earthquakes. Figure 4a illustrates maximum shaking as a cumulative number of observations per year experienced in each major city; Figure 4b shows the frequency of shaking at different intensities. Figure 4b reveals well-behaved curves from which it is possible to conclude the probability for shaking in a given time window. Although the intensity data for these curves include both infrequent large and distant earthquakes, and more frequent small but closer earthquakes, the return times are

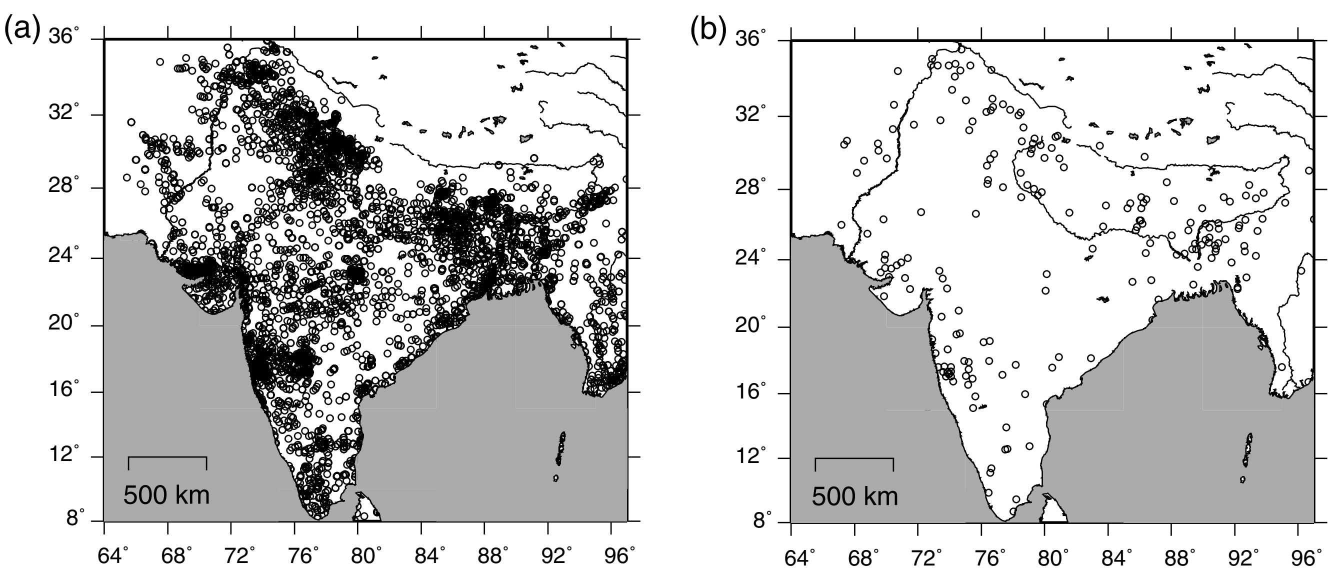

Figure 2. (a) Circles indicate the locations of intensity data listed in Ⓔ Table S2 in the electronic edition of *BSSA*. Regions with low population density, such as the Rajasthan desert, parts of Baluchistan, the Nepal and Assam Himalaya, and the Indo-Burman ranges are poorly represented historically. Communication routes and rail lines show up as faint lines in the data. (b) Epicenters for historic earthquakes listed in the Ⓔ electronic edition of *BSSA* were determined using the method of Bakun and Wentworth (1997).

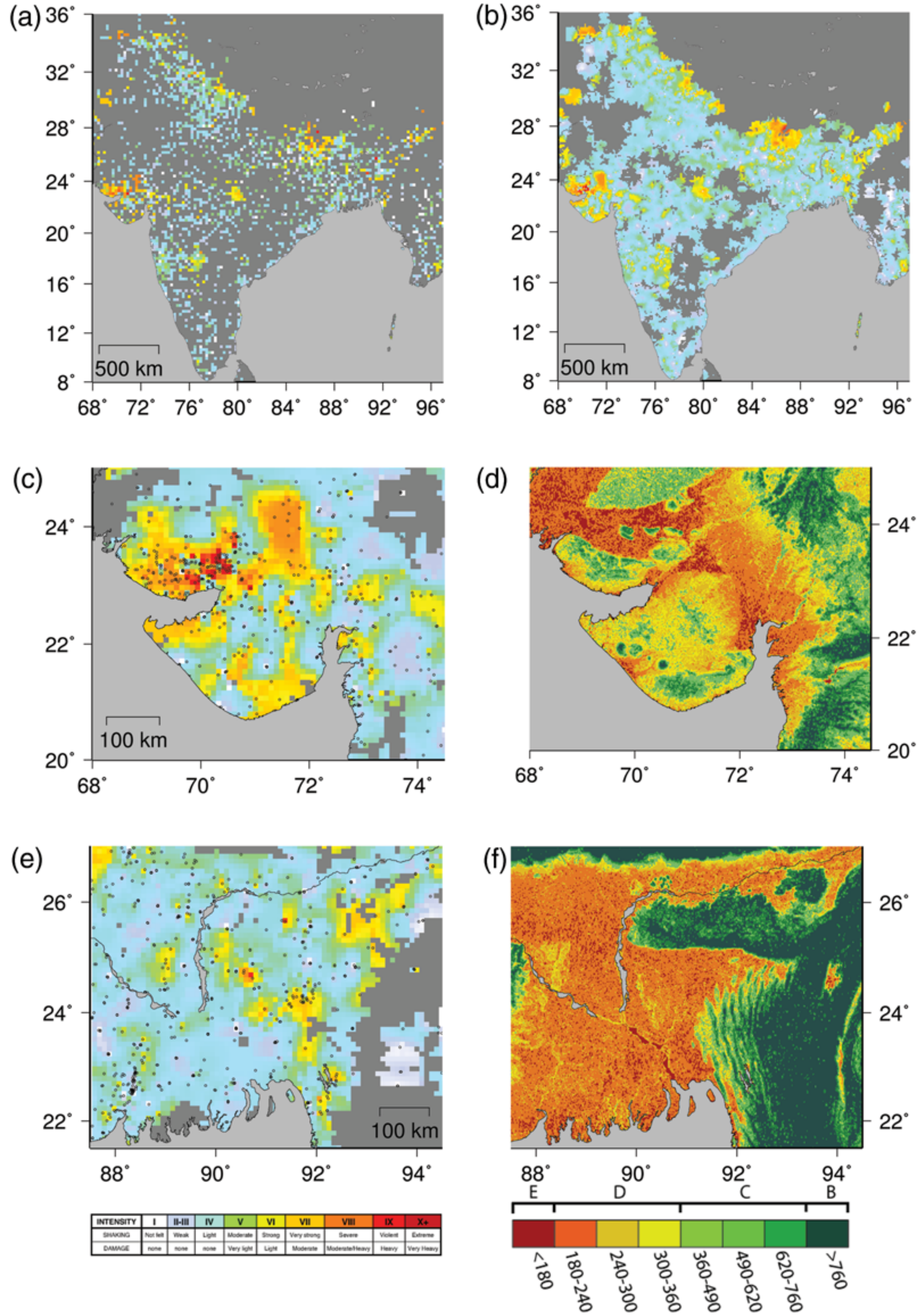

Figure 3. (a) Maximum shaking intensity observed during the period 1636–2009. (b) Interpolated maximum shaking intensity observed during the period 1636–2009. (c) Interpolated maximum shaking intensity in Gujarat. (d) Map of average shear wave velocity down to 30 m (V_{S30}) for the Indian state of Gujarat. (e) Interpolated maximum shaking intensity in northeast India. (f) V_{S30} map of the northeastern India. In producing interpolated maximum shaking intensity maps, locations within 10 km of one another were binned to account for differences in location names and centers of population over time. Maximum shaking intensity data were interpolated using a nearest-neighbor schema. V_{S30} maps were derived from 30 arc second SRTM V 2.0 data (Farr *et al.*, 2007) using the techniques outlined in Wald and Allen (2007).

probably reliable estimates of future shaking. That is, the infrequent larger earthquakes do not substantially bias the statistics to shorter return times, because there are fewer of them.

The projection of the curves in Figure 4b to larger intensities than those recorded in the past 200 years in each city is possible, but the predictions are of uncertain reliability. The data in Figure 4b follow a function of the form

$$\log(N) = a + b(I - 2), \tag{1}$$

where N is the cumulative number of observations per year for each EMS-98 intensity value I, and a and b are to be determined. The results of regressing the data to this function are shown in Table 3. Certain of India's largest cities report shaking (intensity II) more frequently than others. The a values for Delhi and Kolkata are 50% greater than those for Chennai and Bangalore. This is partly due to their tectonic setting, with cities that are far from plate boundaries, such as Bangalore, showing the longest interval between shaking at any intensity. Cities closer to plate boundaries, such as Delhi (the Himalaya range) or Kolkata (the Indo-Burman ranges) show the shortest intervals between shaking at a given intensity. Intensity V shaking in these cities occurs approximately every 15 years. Intensity VII shaking, where well-built structures begin to show damage, has a forecast return time of approximately 30 years in major cities such as Delhi and Kolkata, an interval of time comparable to the design life of most structures.

We recognize that the data in Figure 4b show evidence for incompleteness at both high and low intensity values. The lowest EMS-98 intensity (I) is, in effect, a not-felt observation, and as such, is expected to be underrepresented in any data set. The number of earthquakes observed in each city we consider is constant over the past 200 years (Fig. 4a). However, we know of no earthquake in India or its surroundings that, in the past 500 years, has repeated. No fault segment has reruptured in this time, with the exception of the eastern plate boundary. Hence, 200 years is a short time interval compared with the recurrence interval for earthquakes in India. We therefore recognize that high intensity shaking is undersampled in our data.

Discussion

Our intensity data sample fewer than four centuries of earthquakes and are largely populated by earthquakes from the past 200 years. We know of no moderate or large earthquake that has repeated in this time period, even at India's plate boundaries where crustal deformation rates are at their highest. Hence, an important conclusion is that Figure 3 represents an incomplete view of anticipated future shaking. It is only necessary to reflect that had the Koyna, Killari, or Jabalpur earthquakes not occurred in the past half century, our view of shaking in central India would be very different. Because the recurrence interval for earthquakes near the boundaries of the Indian plate are shorter, the intensity maps are more reliable in these regions than those constructed within central India. It is improbable that the rate of occurrence of earthquakes prevailing in central India will provide sufficient shaking data to provide reliable maximum intensity maps for many hundreds of years. For this reason

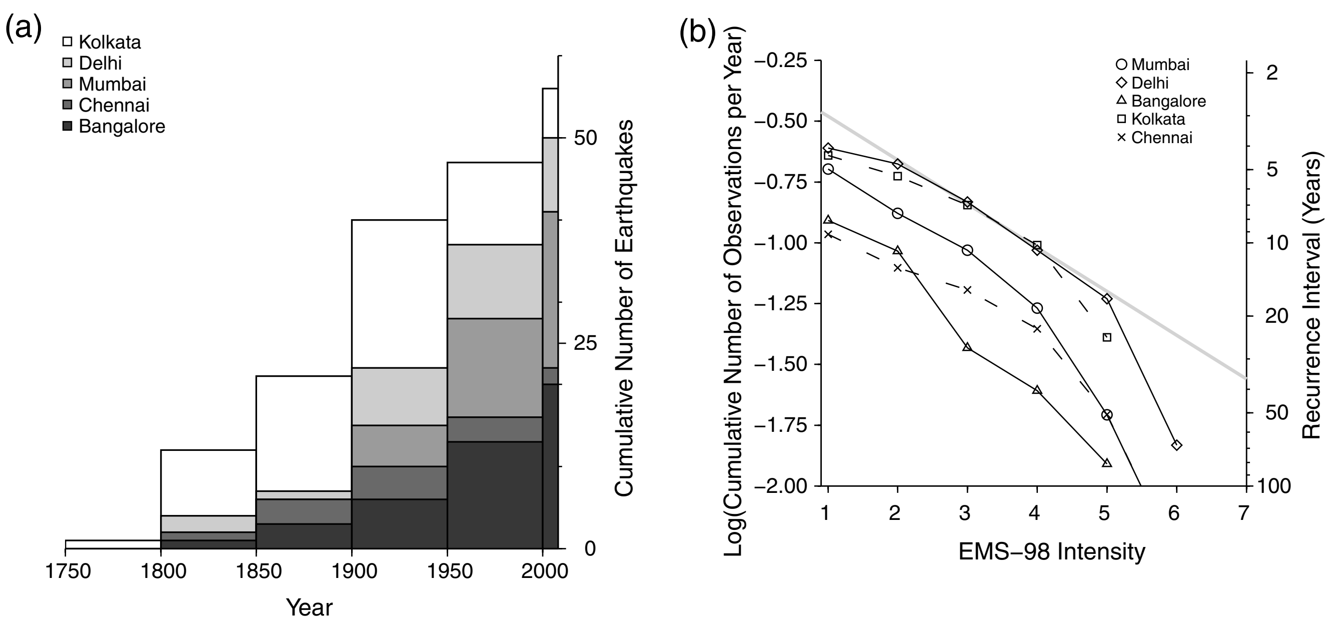

Figure 4. (a) Cumulative number of earthquakes felt in major Indian cities since 1762. (b) Frequency of maximum shaking intensities observed in these cities in the past 200 years. The regression coefficients to these data, fit between intensity II and V are shown in Table 3. The well-behaved form of these curves suggests that the probability for future shaking from modest earthquakes can be estimated with reasonable confidence. The estimation of the probable return time of higher intensity shaking from these curves is less well constrained. The light gray line is the regression line for Delhi using the coefficients from Table 3.

Table 3
Regression Coefficients and Anticipated Mean Return Time in Years for Shaking at EMS-98 Intensities V, VI, and VII for the Five Largest Cities in India

			Return Time (Years) for Intensity		
City	*a*	*b*	V	VI	VII
Mumbai	−0.81	−0.27	42	78	145
Delhi	−0.66	−0.18	16	24	36
Bangalore	−1.07	−0.28	81	155	295
Kolkata	−0.72	−0.14	14	19	26
Chennai	−1.04	−0.20	44	69	110

alternative methods to estimate potential future shaking will be needed to supplement future hazard studies. These may include the study of surface and subsurface faults and surface liquefaction features (Rajendran *et al.*, 2008), archaeological and archival research (Ambraseys and Jackson, 2003; Raghu Kanth and Iyengar, 2006), and the development of physical models for characterizing stress caused by India's collision with Asia (Bilham *et al.*, 2003).

We note that Figure 3b resembles many previously published seismic hazard maps of the Indian subcontinent (e.g., from the Global Seismic Hazard Assessment Program at http://www.seismo.ethz.ch/GSHAP/). We caution however, that our maps, based as they are on felt reports or catalogs of historical earthquakes, are maps of past shaking rather than future shaking. With this caveat, Figure 3b is potentially superior to previous hazard maps of India because it represents a spatial average of intensities that includes the effects of local amplification or attenuation caused by surface properties, but excludes data such as reports of liquefaction and surface faulting. The averaging we impose on this all-India scale smooths the details of local amplification of most utility to hazard estimates. In some regions finer zonation is possible from the data we provide in the Ⓔ electronic edition of *BSSA* (Figs. 3c,d,e). Figures 3d,f show the estimated average shear-velocity to 30 m derived from the roughness of 30 arc second Shuttle Radar Topography Mission (SRTM) version 2.0 data (Farr *et al.*, 2007) using the techniques outlined in Wald and Allen (2007). These maps summarize seismic site conditions and are a proxy for ground-motion amplification, which are partially reflected in our maximum shaking intensity maps.

Conclusions

We have used primary sources to assess 8339 macroseismic observations from 570 historical earthquakes occurring on the Indian subcontinent using the EMS-98 intensity scale. We have summarized these data graphically and note similarities between maps of maximum felt intensity and previously published seismic hazard maps.

Using the maximum observed intensity per earthquake, we have sufficient data to form conclusions concerning the average time between strong shaking for five large Indian cities. Our use of maximum shaking intensity is biased toward regions in a city where amplification may occur, thus the intervals between shaking at a given intensity are pessimistically short. Our data are insufficiently dense to undertake microzonation within each city. In Delhi and Kolkata, we find that the interval between potentially damaging shaking (EMS-98 VII) is comparable to the design life of most structures, and should thus be included in construction codes.

A companion article (Szeliga *et al.*, 2010) analyzes the data presented here in terms of their implications for attenuation of seismic waves traversing the Indian craton and its plate boundaries. In this second article the location and magnitude of the historical earthquakes discussed here are evaluated from relationships derived between recent intensity observations and instrumental magnitudes.

Data and Resources

Intensity data were assessed from primary sources listed in the Ⓔ electronic edition of *BSSA*. Additionally, all assessed intensity data are also available in the Ⓔ electronic edition of *BSSA*. All figures were created using Generic Mapping Tools (Wessel and Smith, 1998).

Acknowledgments

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Appendix A

Table A1

The Short Form of the EMS-98 Intensity Scale Reproduced from Grünthal and Levret (2001)*

EMS Intensity	Definition	Description of Typical Observed Effects (Abstracted)
I	Not felt	Not felt.
II	Scarcely felt	Felt only by very few individual people at rest in houses.
III	Weak	Felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	Largely observed	Felt indoors by many people, outdoors by very few. A few people are awakened. Windows, doors and dishes rattle.
V	Strong	Felt indoors by most, outdoors by few. Many sleeping people awake. A few are frightened. Buildings tremble throughout. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.
VI	Slightly damaging	Many people are frightened and run outdoors. Some objects fall. Many houses suffer slight nonstructural damage such as hairline cracks and fall of small pieces of plaster.
VII	Damaging	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many well-built ordinary buildings suffer moderate damage: small cracks in walls, fall of plaster, parts of chimneys fall down; older buildings may show large cracks in walls and failure of fill-in walls.
VIII	Heavily damaging	Many people find it difficult to stand. Many houses have large cracks in walls. A few well-built ordinary buildings show serious failure of walls, while weak older structures may collapse.
IX	Destructive	General panic. Many weak constructions collapse. Even well-built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure.
X	Very destructive	Many ordinary well-built buildings collapse.
XI	Devastating	Most ordinary well-built buildings collapse, even some with good earthquake resistant design are destroyed.
XII	Completely devastating	Almost all buildings are destroyed.

*For a more detailed description of the criteria used to assign intensities, refer to Grünthal and Levret (2001), specifically pages 14–20.