Global fatalities from earthquakes in the past 2000 years: prognosis for the next 30.

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By 2025 more than 5500 million people will live in cities; more than the entire 1990 global rural and urban population. Dwelling units for this growing urban population will be constructed in the next 30 years in regions that are known to have experienced damaging historic earthquakes. In some locations the recurrence interval for damaging earthquakes is similar in time for the local population to have increased tenfold. In view of the association between earthquakes and the collapse of structures this is cause for concern for it may be accompanied by a tenfold increase in fatalities from earthquakes. However, this forecast does not account for changes in urban construction methods that might reduce or intensify seismic risk, nor does it account for an unfavorable distribution of future earthquakes, that might aggravate seismic risk. This article reviews the population and earthquake fatality data base for the past 2000 years to discern trends in global earthquake fatalities. The data appear to be reasonably complete only for the past 400 years, during which time the mean annual number of fatal earthquakes has increased roughly in proportion to population growth. The number of fatalities involved in these earthquakes, however, shows no simple relation to total population. For earthquakes in which fewer than 5000 fatalities occur, a smooth growth in their number can be used to forecast the probable future frequency of these events. However earthquakes with fatalities exceeding 5000 contribute substantially to the historic fatality count. The cumulative fatality count for the past 400 years is apparently oblivious to the four-fold growth in global populations that has occurred during the present century. Given that this time is short compared to the recurrence interval of large earthquakes it is not unreasonable to conclude that the earthquake fatality rate will increase by a factor of ten in the next century should several large earthquakes occur near developing mega-cities.

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Global Urbanization

Between 100 BC and about 1600 AD global populations doubled from perhaps 300 million to more than 600 million (Calder, 1984). In the following 200 years improvements in medicine and living conditions resulted in a dramatic reduction in mortality rates resulting in a second doubling in world population to 1200 million by 1800. Between 1800 and 1950 global populations doubled for the third time to 2500 million. The fourth doubling occurred in less than 40 years bringing global populations in 1990 to more than 5000 million. Although the rate of population increase has slowed, a fifth, and perhaps final, doubling of population in the next 50 years is projected (United Nations, 1990).

TABLE 1 Global Population figures used in this article. Pre-1950 Calder, 1984, post 1950 (UN Nations 1991).

year	population (millions)
0	295
1000	325
1500	515
1750	770
1900	1680
1950	2516.44
1955	2752.11
1960	3019.65
1965	[illegible]
1970	3697.85
1975	4079.0[illegible]
1980	4448.04
1985	4851.43
1990	5292.19
1995	5770.29
2000	[illegible]
2005	[illegible]
2010	7204.34
2015	7659.26
2020	8091.63
2025	8504.22

While rural population growth continues, the bulk of world population growth is concentrated in urban areas in the developing nations. Urban populations in most developed nations are declining or showing minor growth (Los Angeles is an exception with a 1990 growth rate of 1.6%/year), but urban populations in the developing nations vary from 2% to 6%, driven both by internal growth and by a migration from the villages to the towns. In China, India and Africa the rate of urban growth exceeds 4%, resulting in a doubling urban populations in less than 20 years.

Global urbanization is a new development for Homo Sapiens: prior to 1800 less than 2.5% of the world's population is estimated to have lived in cities. Diseases and epidemics moderated city populations and despite migration from surrounding rural communities, few cities exceeded 20,000 (McNeill, 1976). Calder grimly observes that "until 1900 cities killed more people than they bred: they not only mopped up surplus agrarian population but buried much of it". The medicinal control of contagious diseases upset this balance, releasing uncontrolled urban growth. By 1930 the percentage of urban dwellers had increased sixfold, and by 1990 global cities contained 2400 million people (45% urban, 55% rural). By the year 2025, city population may exceed 5500 million (65% urban, 35% rural). The percentage of people living in urban communities in the developing nations is expected to increase from 37% in 1990 to 61% in 2025. Urban populations in the developed nations will increase from 73% (1990) to 83% in 2025 (United Nations, 1990). These changing demographic trends are illustrated in Fig. 2.

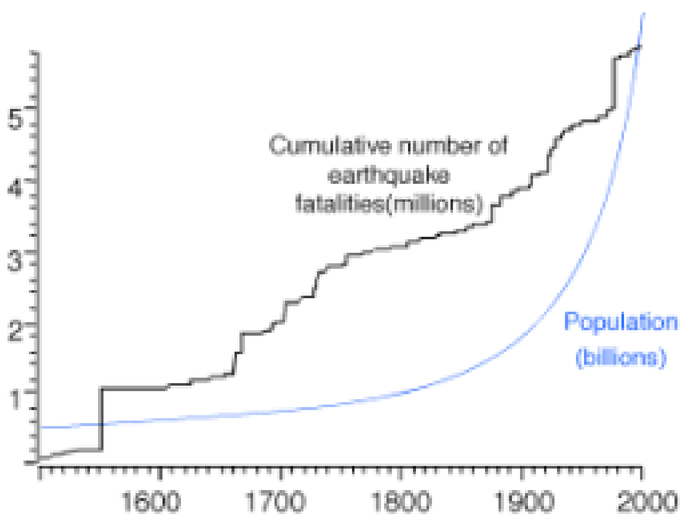


Fig. 1 2000 years of population growth and earthquake fatalities. Data prior to 1600 must be treated with reservation, since both population estimates and fatalities from earthquakes are speculative. Data since 1600 are increasingly more complete.

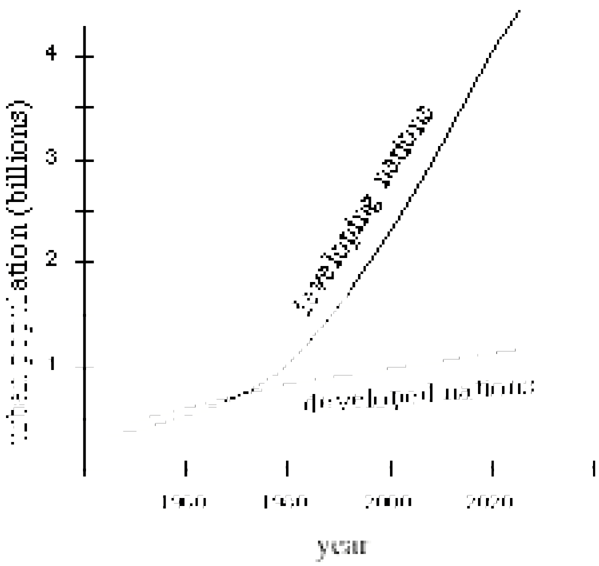


Fig. 2 Past and projected urban populations in the developing and developed nations show radically different patterns. Despite the increase in urban populations in the developing nations the percentage of urban population in 2025 will represent only 65% of their total population, whereas the urban percentage in the developed nations already exceeds 73% (27% rural), and in 2025 it will have increased to 83% (17% rural).

Earthquakes

Indigenous materials are sometimes unsuited to the construction of single story buildings resistant to horizontal shaking (e.g. adobe). Multi-story dwellings may make excessive demands on otherwise tough building materials. Structural failure may be followed by fire, and sometimes by catastrophic flooding should a natural or artificial dam fail. However, prior to this century most fatal earthquakes ~~have~~ typically buried people beneath their dwellings. The estimated cumulative number of fatalities attributable to earthquakes in the past 2000 years is close to 8 million with an estimated uncertainty of ±1 million (Dunbar et al. 1992).

Dunbar et al. (1992) include historical seismic data from many previous catalogs with the notable exception of Mallet's 4 volume catalog (1851-1854). A critical compilation to merge historical earthquake catalogs and eliminate duplicate and spurious entries is desirable but has not been attempted. In this article I have edited Dunbar et al.'s data principally by removing multiple entries. Most multiple entries offer several fatality counts of which the median value was usually selected, except where this appeared unreasonably high or low. In some cases multiple entries are not obvious by inspection, e.g. the 20 May 1202 Syrian event is manifest in six separate entries in some secondary sources; under three Muslim dates (597±1 AD) and three Gregorian dates, 1202±2 (Ambraseys and Melville, 1990). There may be other early events in the catalog that have similar multiplicity. The Calcutta 30 September 1737 earthquake was omitted (Bilham, 1994), as were all earthquakes that caused fewer than 10 fatalities. The edited list contains 1042 entries from 186 BC to 1994 AD Fatality estimates are few and unreliable before the 17th century, but improve in coverage following the Voyages of Exploration and the invention of printing. Nevertheless, even recent fatality counts may be unreliable, particularly for severe events (e.g. Tangshan, 1976), and the cumulative numbers may be in error by more than 20%.

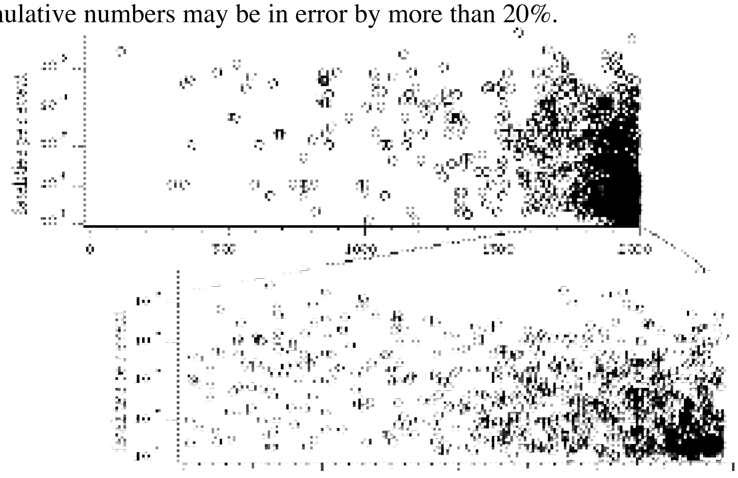


Fig. 3 Global earthquake fatalities for the past 200 years, shown with an expanded scale for earthquakes since 1600.

A relation between the number of people at risk from earthquakes and the number of people on the planet is expected. This relation is manifest in Figures 1, 3 and 4. In Figure 1 an inflection in the rate of earthquake fatalities occurs in about 1500, before and after which the data approximate linear trends. This may correspond to the colonial expansions that occurred at this time resulting in more complete reporting. The European, Middle East, Japanese and Chinese catalogs are reasonably complete for most of the past 2000 years, but India, the Americas, SE and NE Asia, south-Saharan Africa and Australasia are largely unrepresented prior to the 16th century. After 1500 the world became more widely explored and in 1600 numerical reports become available often in the form of administrative reports, and accounts of travelers.

Fig. 3 shows that from 1500 to 1994 a tenfold increase in global populations from 0.6 billion to 6 billion was accompanied by a tenfold increase in the mean rate of fatal earthquakes from 0.7 per year prior 1500, to 7 per year at present. An understanding of trends in this period of time may thus be of value in interpreting the expected tenfold increase in populations 1800-2100. Figures 3-5 also confirm that prior to 1500 there are insufficient events to provide meaningful statistics.

That the number of fatal earthquakes should be proportional to total population is not entirely obvious since neither populations nor earthquakes are uniformly distributed on the earth's surface. Were earthquakes and people uniformly distributed on the Earth we should anticipate a relation between the total number of fatalities and world population. This relation is not evident in Figure 1. If anything the 5.7 million earthquake-related fatalities reported since 1500 show an approximately linear trend (11.4 k/yr) with large variance caused by the substantial contribution from infrequent disastrous events (Figure 5). For example, the mean global fatality rate for contiguous 125 year intervals since 1500 fluctuates with no simple relation to global population: 9k/year 1500-1625, 13 k/year 1626-1750, 4 k/year 1751-1875, 20 k/year 1786-1995. Fatalities in the first and last interval are dominated by events in China where more than 0.5 million people died in single events.

Fig. 4 Global population compared to the mean number of fatal earthquakes per year. An order of magnitude increase in population in the past 400 years (600 million to 6000 million) is accompanied by a corresponding order of magnitude increase in the number earthquakes resulting in fatalaties (0.7/year to 7/year).

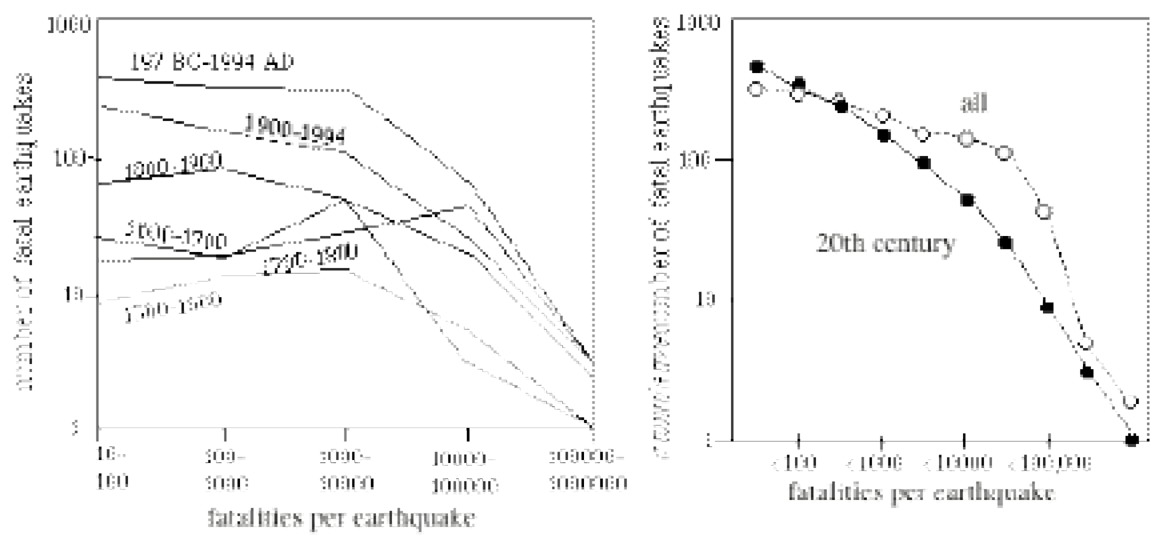


Fig. 5. Relations between numbers of fatalities and number of earthquakes for different epochs (5a, left), and the contribution to the cumulative number of fatalities from individual catastrophes (5b, right).

The mean rate of earthquake fatalities since 1800 shows a clear increase in rate in Figure 5. However, the rate of increase is similar to one observed in 1650, when no quadrupling in global population occurred. In Figure 5a, the increase in the number of fatalities per century is shown graphically for events with different degrees of mortality. The growth is steady for events with fewer than 10,000 fatalities, but this may also reflect reporting shortcomings for smaller events. The statistics for larger events might be considered insufficient to draw meaningful conclusions, yet the cumulative graph (Figure 5b) demonstrates that a smooth relation exists even for an epoch during which populations increase by a factor of 4. Nishenko and Barton (1995) have examined similar fractal relations for different epochs as a function of region.

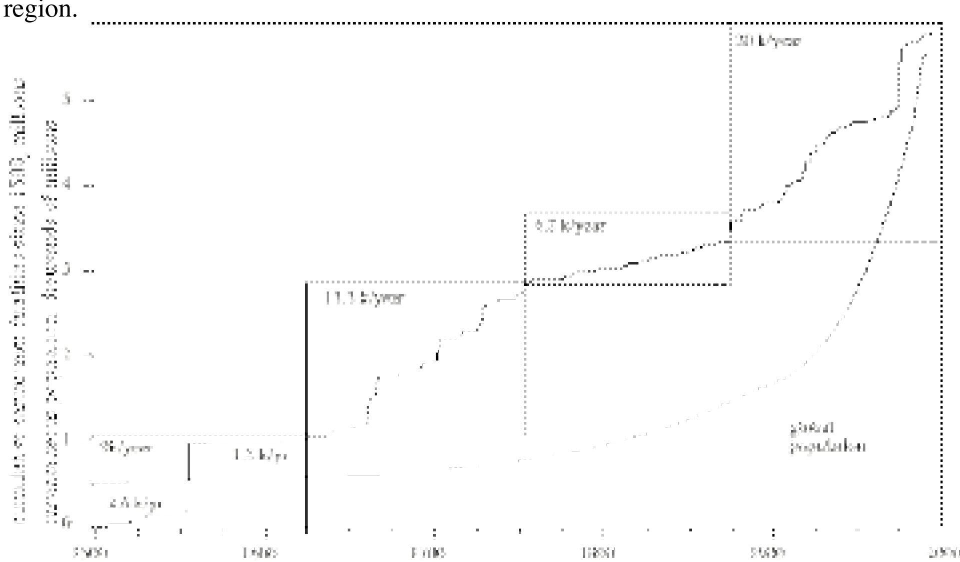


Fig. 6 A closer view of cumulative fatalities in the past 500 years. The earthquake data are dominated by catastrophic earthquakes in China in the first and last 125 year intervals.

A curious result of increased global populations is that the *fraction* of the global population killed in events has declined significantly in the past 200 years (Figure 7). Thus in one sense the risk to each individual on a global basis has declined. The data in Table 1 are interpolated using a smoothing spline to yield the estimated global population at the time of each earthquake, and the value plotted in Figure 7 is the quotient of the number of fatalities and the global population for each event. The mean value is obtained using a 50 point gaussian smoothing function. The units on the figure are earthquake fatalities per million people (fpM). The fpM falls from approximately 100 fpM (pre-1600) to 10-60 fpM in the following 200 years, to approximately 1 fpM at present.

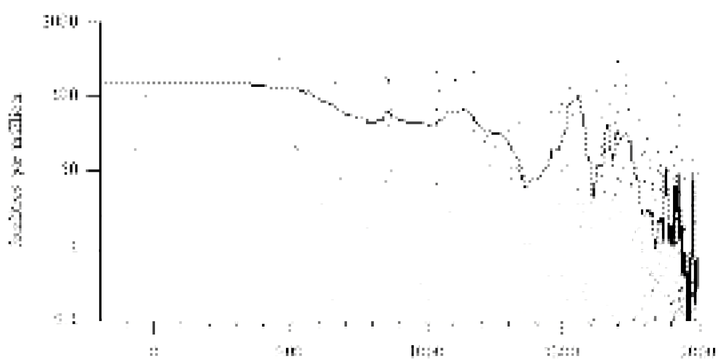
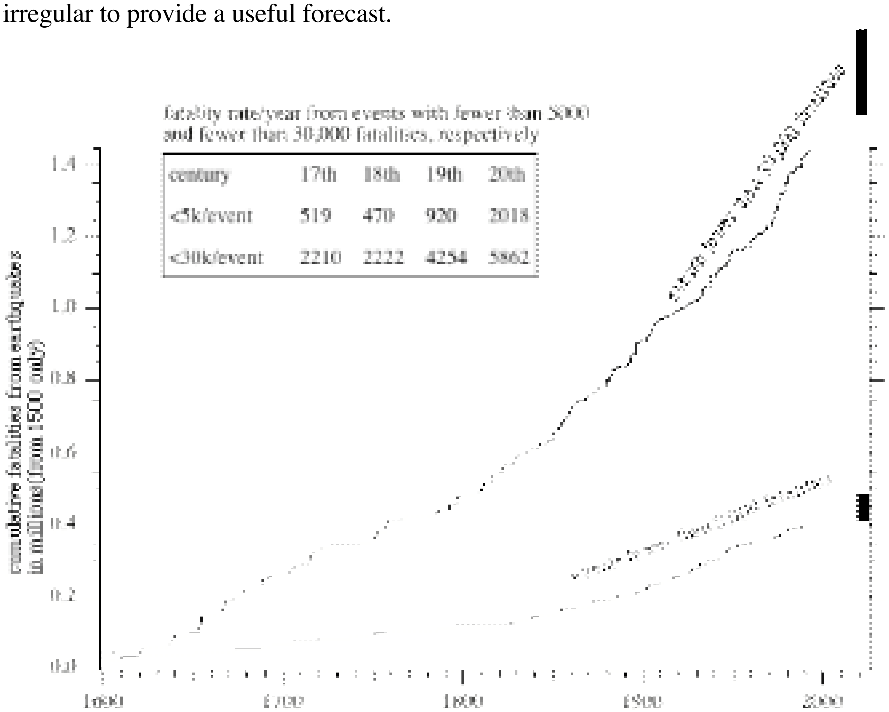


Fig.7 Earthquakes fatalities in the past 200 years normalized against global population. The solid line is a smoothed mean value. Each dot is an event in which the number of deaths has been divided by the inferred global population. The global mean fatality rate falls by approximately an order of magnitude since 1600, the earliest time when records can be considered reasonable reliable.

Discussion

Clearly, the fatality rate is coupled not so much to the mean global population but to the rate at which cities are shaken. The statistical fluctuations in the selective targeting of cities have similarities to the random targeting of nuclei in a particle accelerator. Borrowing from this analogy, if we assume that the diameter of the area of damaging shaking (say Mercalli Intensity>VIII) represents the size of the "particle", and that each city is a target with a physical diameter of 1-50 km with a reaction "mass" proportional to population density, and separated from neighboring cities by distances very much larger than the size of each city, a reaction cross-section may be estimated to determine the probability of future interactions. The enlargement of urban centers increases the probability for future disaster, as for example, the development of urban sprawl in Los Angeles that makes parts of this city vulnerable to moderate earthquakes simply because it has become spatially a larger target. The ill-advised development of Mexico City in a region sensitive to long-period shaking from distant events makes urban agglomerations here a target for low intensity shaking, from several M>7.5 events along the coast with a mean recurrence interval of ≈30 years. However, the growth of cities from villages, which in the developing nations is often attended by the construction of multistory dwellings with little or no earthquake resistance, is probably a more important factor in increasing the probability of future fatal interactions between earthquakes and people. In some parts of the world, the recurrence of earthquakes which may have resulted in little damage to former villages may result in significant damage to the great cities that have now replaced them.

Although there is a random element in the targeting of large cities by large earthquakes, the cumulative fatalities involved in smaller events are sufficiently well behaved to form useful conclusions about future rates (Figure 8). For example, if all earthquakes with fatality counts exceeding 5000 people, are removed from the catalog, a smooth increase in cumulative rate is obtained rising steadily from the 16th century to the present. Using this growth curve it is possible to estimate that in the next 30 years approximately 2000±300 people/year will be killed in this kind of disaster. The fatality rate in events involving fewer than 30,000 fatalities is approximately 5900±500 people/year. For larger events the curves become too irregular to provide a useful forecast.



century	17th	18th	19th	20th
<5k/event	519	470	920	2018
<30k/event	2210	2222	4254	5862

Fig. 8 Earthquakes in which fatalities do not exceed 5000 and 30,000 respectively are sufficiently well behaved to forecast their probable rate early in the next century. For events involving fewer than 5000 fatalities the anticipated rate is 2020±300/year; for events with fewer than 30,000 fatalities per year the rate is 5860 ±500/year. For larger events the curves become irregular and consequently unpredictable.

Perhaps the most sinister societal development in terms of earthquake risk is the growth of supercities (populations exceeding 2 million), and megacities, which the UN define to contain more than 8 million people. In 1950 there were only two megacity agglomerations: London and New York. By 1990 there were 10, and in the year 2000 the UN has projected that 28 cities will attain this status (Figure 9). The Mexico City population will have reached 28.6 million people. The selective growth of many of the worlds largest cities near plate boundaries aggravates long term urban seismic risk (Bilham, 1986).

The locations of disastrous earthquakes in the past 1000 years are shown in Figure 9 together with urban populations in cities greater than 1 million people projected for the year 2000. The total urban population held within these 353 cities is 1102 million. Approximately 30% of the world's megacities are located close to a strike-slip or convergent plate boundary where the largest earthquakes occur. 80% of these are in the developing nations housing approximately 80 million people. 290 million people live in cities of 2 million or more in seismogenic zones. Many more live in cities with 1 million people.

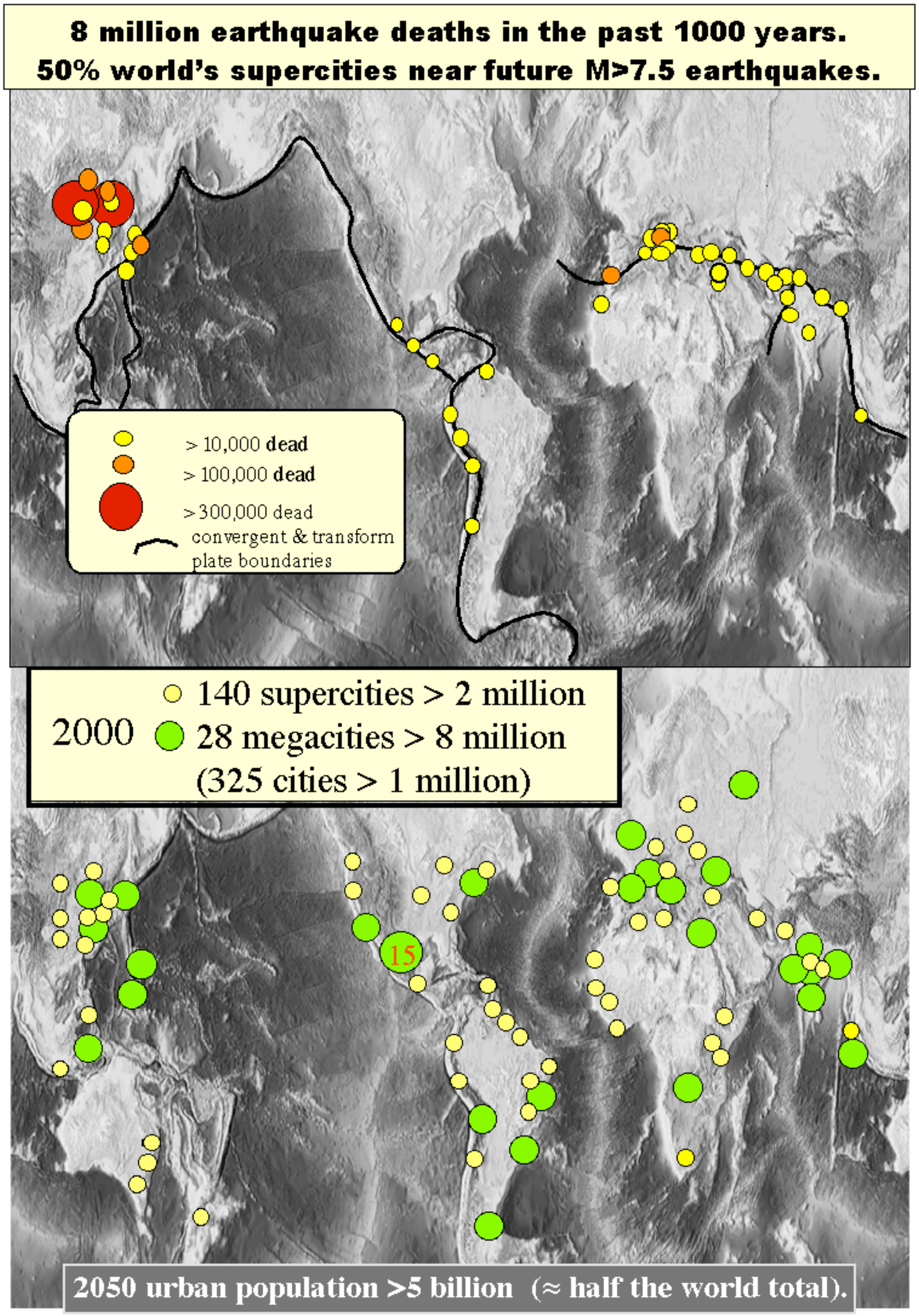


Fig. 9 Fatalities from earthquakes in the past 1000 years compared to urban populations in cities greater than 1 million in the year 2000. More than half of the worlds total population (6.3 billion) will live in cities: only the largest are shown here, housing 20% of the worlds population.

Of particular concern are those cities that are also capital cities because fatalities and disruption in these cities are likely to jeopardize the national economies of these countries. Mexico City and Teheran have populations that include substantial fractions of their national populations (24% and 12% respectively). Other countries may have an even greater fraction of their total population concentrated in one city: Santo Domingo (35%), Athens (37%), Tel Aviv (42%), Lima (31%), Santiago (36%).

Conclusions

The number of earthquakes resulting in fatalities has increased approximately in proportion to global populations, and although a decreasing fraction of the global population has been killed by earthquakes in this century compared to former centuries, seismic risk in certain regions has increased substantially. The cause of the apparent paradox lies in the growth of urban agglomerations where most of the world's growing population will live, and the location of many of these cities near plate boundaries where earthquakes occur quasi-periodically. The development of statistical predictions of seismic risk for these many urban areas must obviously be undertaken on a regional and local scale.

A few global trends are evident in the data of the past 500 years. The clearest is the number of fatalities involved in earthquakes resulting in fewer than 5000 fatalities. The cumulative number of deaths from these events has increased monotonically since 1600 (520 fatalities/year), to a 19th century rate of 2020±300 fatalities per year. The rate is likely to increase moderately in the next 30 years. Similar growth is noted for earthquakes involving larger numbers of fatalities, although rates in future years are less easy to forecast because the curves become decreasingly regular. However, for earthquakes involving fewer than 30,000 fatalities the future rate is also fairly reliable rising by perhaps 30% from its current rate of approximately 6000 fatalities/year. Daunting though these figures are, these events do not contribute more than 30% to the past 125 years of earthquake fatalities (≈20,000/year).

The growth of giant urban agglomerations near regions of known seismic hazard is a new experiment for life on Earth. With few exceptions (Tokyo 1923; Tangshan, 1976), recent large earthquakes (M>7.5) have spared the world's major urban centers, this will not persist indefinitely. The recurrence interval for damaging earthquakes varies from 30 years to 3000 years and if population densities remain high in the next millennium, several megacities will be damaged by significant earthquakes. We are most certain of the fate of those cities near plate boundaries, however, mid-continent earthquakes also occur, albeit infrequently (c.f. M>8 events at New Madrid and Charleston in the 19th century US), and these events will perhaps wreak great havoc in mid-continent cities where earthquake resistant construction is not mandated. Until dwellings and civil structures are made resistant to earthquake shaking the earthquake fatality rate will remain high.

It is probable that the annual fatality rate from earthquakes will rise by a factor 4-10 in the next 30 years, attributable partly to an increase in the fatality rate from moderate earthquakes near large cities, but principally from a few catastrophic earthquakes near supercities (populations 2-28 million). Fatality counts exceeding 1 million from individual events are not unreasonable given that >50% of an urban population can be lost in a single earthquake (Tangshan population 1976), and that there are now dozens of cities near seismic belts with populations exceeding 2 million.

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References

Ambraseys, N. N., A note on the chronology of Willis's list of earthquakes in Palestine and Syria, Bull. Seism. Soc. Amer., 52, 1, 77-80, 1962.

Ambraseys, N. N. and C. P. Melville, An analysis of the Eastern Mediterranean Earthquake of 20 May 1202, Proc. Symp. Historical Seismograms and Earthquakes, IASPEI/UNESCU Working Group on Historical Earthquakes, ed. W. H. Lee, (Tokyo Aug. 1985) 1987 San Francisco.

Bilham, R., Earthquakes and Urban Development, Nature, 336, 625-626, 1988.

Bilham, The 1737 Calcutta Earthquake and Cyclone Evaluated, *Bull. Seism. Soc. Amer*. 84(5), 1650-1657, 1994.

Calder, N., *Timescale*, pp. 88., Chatto and Windus, London 1984.

Dunbar, P. K., P. A. Lockridge and L. S. Whiteside. Catalog of Significant Earthquakes 2150 B.C. to 1991 A.D., Including Quantitative Casualties and Damage, *National Geophysical Data Center Report* SE49 pp. 320 Sept 1992.

Mallet, R., 1852, Second Report on the Facts of Earthquake Phenomena, 272-320, Report of the Twenty-first meeting of the British Association for the Advancement of Science, Ipswich, 1851.

Mallet, R., 1855, Catalogue of Recorded Earthquakes from 1606 B.C. to A. D. 1850 (continued from Report for 1853), 2-326. Report of the Twenty-fourth meeting of the British Association for the Advancement of Science, Liverpool, 1854.

McNeill, W. H., *Plagues and Peoples*, pp 340. Anchor Books, 1976, reprint 1989.

Nishenko, S, and R. Buland, Scaling Laws for Natural Disaster Fatalities, Santa Fe Institute Workshop, 1994.

United Nations, World Urbanization Prospects 1990, ST/ESA/SER.A/121.,Sales No. E.91.XIII.11, pp. 223., United Nations, New York, 1991