Aggravated Earthquake Risk in South Asia: Engineering vs. human nature

Roger Bilham, CIRES and Geological Sciences,
University of Colorado, Boulder CO 80309-0399, USA

Abstract

One third of the world's population live in South Asia, an area that has lost 0.4 million people to earthquake deaths in the past 12 years, and more than 2 million in the past millennium when populations averaged one tenth of their present levels. The large multicentury earthquake deathtoll results from a broad collisional zone where earthquakes with Mw>7.0 are common inland. The purpose of this article is to examine some of the underlying reasons why populations are especially vulnerable to earthquakes in the region, and why a perceived disconnect exists between earthquake resistant engineering and those populations most at risk from earthquakes. The article notes that urban growth and changes in building styles have rendered urban populations more vulnerable than in the past, but that there exist numerous hidden factors within the structure of societies that act to thwart the best intentions of seismologists and engineers to apply ubiquitous earthquake resistance. More than 80% of all earthquake deaths worldwide have occurred in nations where the mean per capita income is less than $3200/year. The Gross Domestic Product of a country influences its level of education, its financial ability to implement earthquake resistance, and the efficiency of its laws to regulate the welfare of its people. Although all these factors contribute to the resilience of building stock to shaking from earthquakes, in many cases, the absence of code enforcement in the building industry is directly responsible for the collapse of structures. Contractors who are anxious to maximize profits in societies where corrupt practices are endemic, can avail themselves of numerous opportunities to circumvent not only earthquake resistant regulations, but common-sense safe-assembly guidelines, and the resulting dwellings frequently become the homes of the urban poor. For this reason many of the cities of Asia are disproportionately fragile, and can be expected to be the site of numerous future earthquake disasters.

Keywords: Earthquake Risk, Corruption, Historical earthquakes, Aggravated Risk, Building Codes South Asia.

1. Introduction: Hazard, Risk, and Aggravated Risk

It is well to introduce this chapter with a brief definition of terms. *Earthquake hazards* are historical observations of the effect, or potential effects, of earthquakes on society in a specified region. Earthquake hazards are quantified by the severity and duration of shaking produced by an earthquake (local accelerations, velocities and displacements), and the indirect effect of these accelerations at the earth's surface (landslides, tsunami and liquefaction). *Earthquake risks* are estimates of the effects of future earthquakes in specified regions, based on insights from a catalog of historical seismic hazards. The historical and recent record of earthquake hazards can be used to develop quantitative probabilities of future shaking that guide engineers in the design of structures that will resist damage during future earthquakes.

In this chapter I introduce the concept of *aggravated seismic risk*, a term invoked to embrace those elements of seismic risk that are caused by the flawed application of the products of seismic risk studies resulting from errors, overt manipulation or neglect.

Although earthquake risk can be reduced by human intervention, hazards cannot. But although hazards cannot be changed, the accuracy with which historical earthquakes can be quantified can often be improved by careful study. Sloppy studies of hazards can lead to exaggerated or underestimated estimates of risks. The world's written history is a fickle data-logger subject to human memory and perception, and considerable effort has been expended in re-assessing historical records of earthquakes.

Earthquake risk estimates provide the key shaking accelerations and durations used by engineers to construct buildings or structures (bridges, power-stations, dams and pipelines) to survive future earthquake shaking. The mandate of engineers is to construct buildings that do not collapse in earthquakes and therefore do not harm their occupants. A building can be constructed to withstand the strongest shaking, but the cost of a building increases with its resistance to collapse. Hence engineers are required to minimise the cost of a structure as a function of its use. Hospitals, schools and fire stations must be constructed to withstand the strongest shaking, and are expected to remain functional immediately shaking has ceased. At the other extreme it is possible to construct a building with minimal strength that will survive an earthquake permitting its occupants to escape injury, but which must be extensively repaired or torn down and rebuilt following the earthquake. The cost of a building immune to all earthquake damage may be ten times the cost of a building with minimal resistance that must be repaired after an earthquake. The cost of minimal earthquake resistance (i.e. sufficient resistance to guarantee occupant survival) is often less than 10% of the cost of the similar structure that would otherwise collapse without earthquake resistant features.

Earthquake risk is of major importance to insurance companies who must estimate their exposure to losses in regions where earthquakes are expected. Regions of higher risk require higher insurance premiums. For this reason insurance companies are eager to refine estimates of future risk.

In contrast, earthquake risk is rarely considered by home owners in cities or villages, or people renting dwellings and apartments. Many residents, even in high risk seismic zones, have zero knowledge of how their house or apartment was constructed. Some owners may have added to, or modified, their homes without thinking whether those changes have made their homes more, or less, resistant to future earthquakes. This is an example of *aggravated seismic risk*. A knowledge of future earthquake shaking may be known to parts of a society, but it is not reaching the user community.

More importantly, although construction guidelines exist in all parts of the world (and in many places these guidelines include codes related to earthquake risk), in most parts of the world these guidelines were, and still are, not considered important by contractors or by authorities responsible for regulating building construction. The reason for this disinterest is that contractors, builders and building inspectors have together, or in isolation, subconciously applied their own estimate of seismic risk to constructions for which they are responsible.

A few hundred years ago the non-implementation of building codes was not as much a problem as it is now, because populations were sufficiently sparse for most people to live in single-story structures in rural communities. However, in the past hundred years populations have not only increased by an order of magnitude, populations are now concentrated in cities. The dense packing of people in cities has required a change in city construction from single family homes to multi-family housing in multistory buildings made of concrete and steel. This has led to a change in construction methods that are more vulnerable to earthquake shaking.

A measure of our awareness of the present vulnerability of the world building stock is that when an earthquake occurs near a major city, within half an hour of the mainshock seismologists can calculate, using empirical methods, how many people are injured, how many are dead and approximately the cost of reconstruction (Wyss et al., 2006; Jaiswal and Wald 2010). Yet despite the rapidity of these empirical calculations, it often takes many days before survivors at the epicenter are able to count the dead and wounded, and many months or years before the true costs of reconstruction are known. This is not a success story - it is a measure of failure of two scientific disciplines (seismology and earthquake engineering), and in a broader context, a failure of a species to recognize that it inhabits a planet where some small fraction of its dwelling units will collapse every year due to earthquakes.

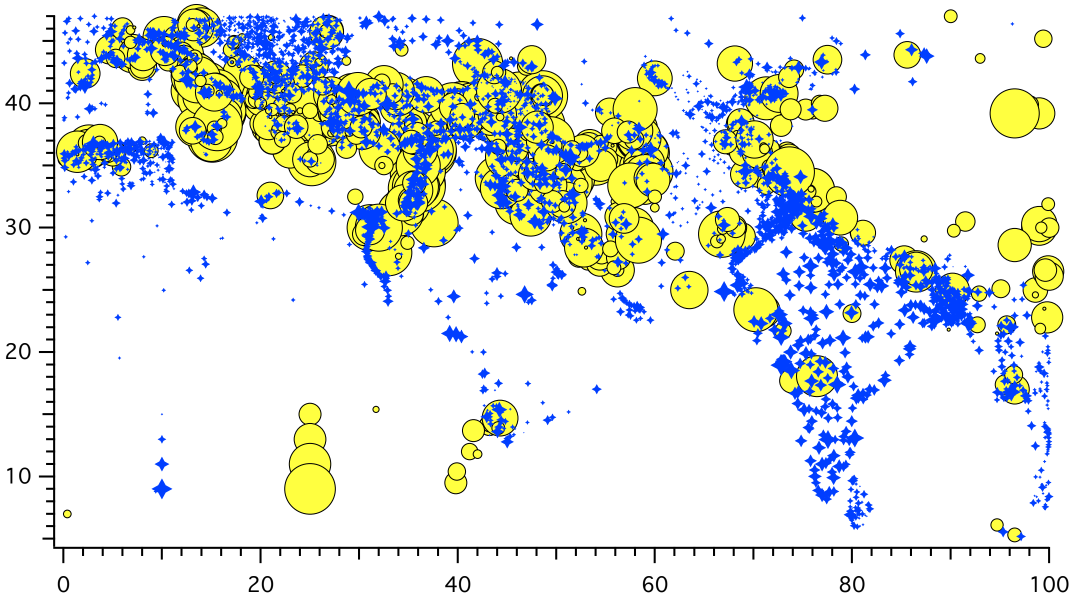

Figure 1 Earthquake deaths in the past 2000 years along the southern edge of the EuroAsian Plate compared to present-day centers of population. The shores of the Mediterranean, the River Nile, India and the Arabian continent are can be recognised by their population distributions. Deaths from earthquakes in the past thousand years are shown as yellow circles. Figure 2 highlights the post-1900 increase in fatality rate east of 47°E .

2. Statistics of earthquake fatalities

Many millions of people have died from building collapse in the past several thousands of years (Bilham, 2009; Holzer and Savage, 2013), but more than 80% of these deaths are recorded to have occurred in less than 12% of the world's land area. This region of high seismic risk is a broad zone that follows the Alpine/Himalayan collision zone along the southern edge of the EuroAsian plate (Figure 1). Earthquakes here result from the convergence of the African, Arabian, Indian, Australian and Pacific plates towards the EuroAsian plate at velocities of 1-10 cm/yr. The historically high deathtoll from earthquakes in the region is attributable to the high population density living within the collision zone (England and Jackson, 2011), that includes several of the earliest centers of civilization.

Although populations in this region prior to 1800 remained relatively low, since 1800 they have increased by an order of magnitude, and many former villages are now major cities with population densities two or more orders of magnitude larger. Numerous megacities (population>8 million) now host more people than the populations of entire nations two centuries ago. This change in demographics has inevitably increased the potential for a future earthquake close to a large urban population to result in an unprecendented deathtoll and economic cost (Hough and Bilham, 2006; Musson, 2012). This change in global and regional demographics has occurred in a time frame that is short compared to the recurrence intervals of earthquakes, especially in the broad collision zones of south Asia, and as a result the decadal loss of life from earthquakes has significantly increased since the 19th century (Figure 2), and is likely to continue to increase unless earthquake resistant construction is not adopted throughout the region.

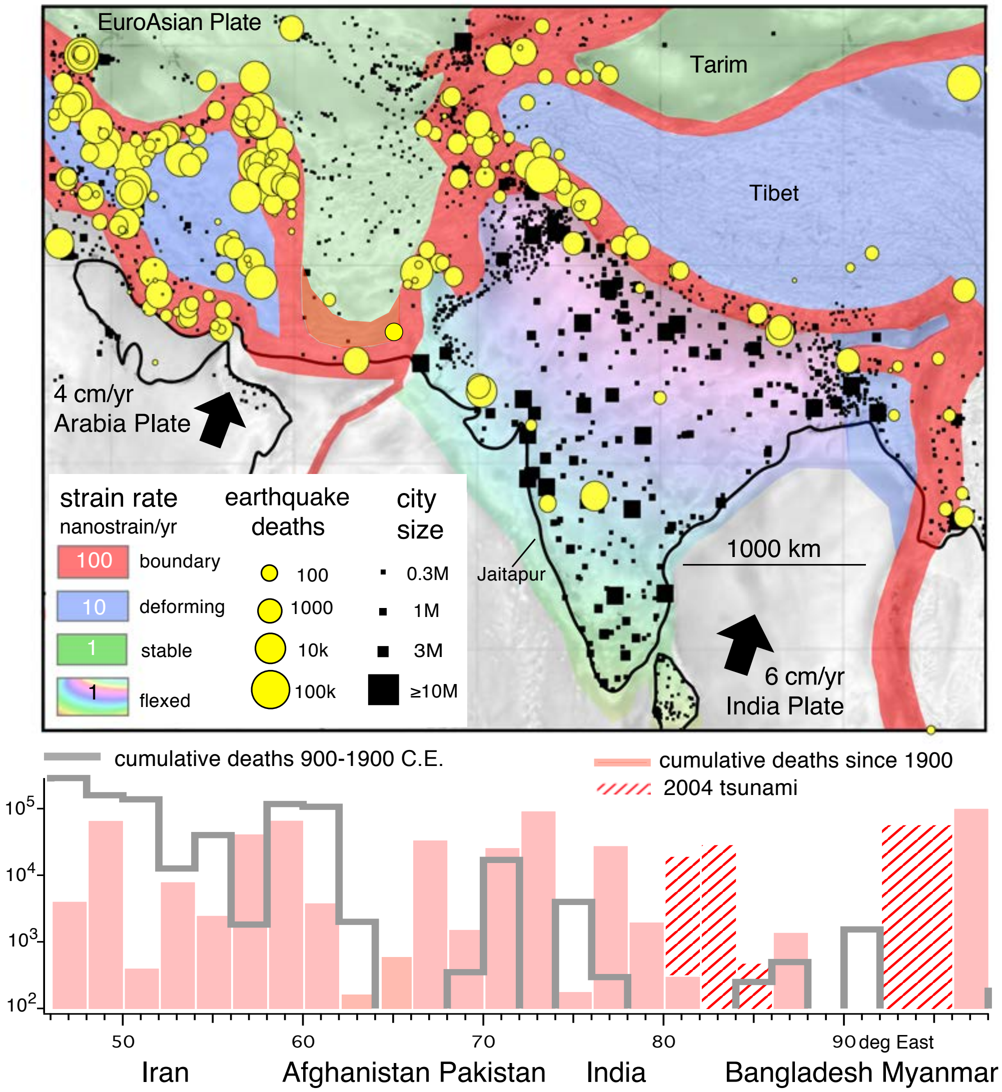

Figure 2. Earthquake fatalites in south Asia before and after 1900, showing current population demographics (updated from Bilham and Gaur, 2013). The figure illustrates plate boundaries and the breadth of the deforming regions of Iran and the Tibetan plateau, and the collisional flexure of the Indian plate responsible for mid-plate earthquakes in parts of India, Pakistan and Bangladesh.

A disproportionate number of earthquake deaths occur far from the ocean-continent plate boundaries where much of the global earthquake energy release occurs (Figure 3). Many of these deaths occur within the wide collision zone that borders the southern edge of the Eurasian plate between Turkey and Burma, amid which numerous mid-continent faults exhibit low levels of seismic activity. In the desert regions of Iran, villages are preferentially located near the edges of mountain ranges bordered by these faults, since it is in these regions where water supplies are usually abundant. (Jackson, 2006). Similar settings prevail in villages in Baluchistan (e.g. Quetta destroyed 1935) and the Pakistan Himalaya (e.g. Taxila near Islamabad destroyed 55 AD).

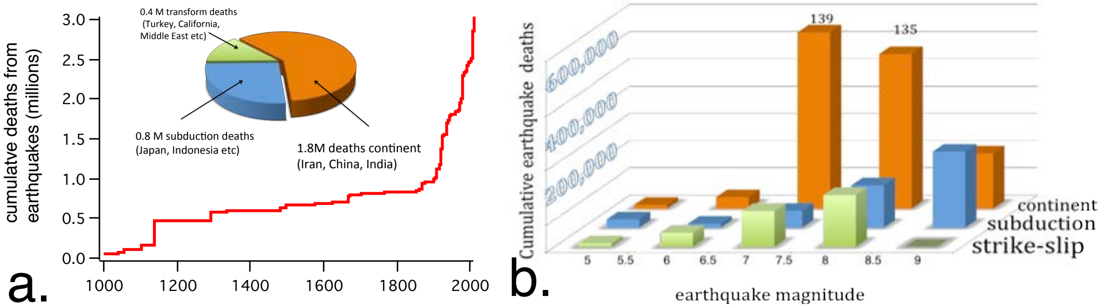

Figure **3a.** Teo-thirds of earthquake deaths prior to 2012 have not occurred on simple strike-slip or subduction zone plate boundaries where most of the world's seismic energy is released. **b.** most of these deaths occur in 6.5<Mw<8 earthquakes in the broad collisional zones interior to continents.

3. Problems associated with assessments of seismic hazards

The critical reader should be aware that a number of problems impede a precise knowledge of seismic risk based on traditional methods for evaluating seismic hazards. The following four approaches to assessing seismic hazards are particularly problematic in south Asia.

Instrumental catalogues: A common assumption in the interpretation of seismic catalogues is that the constants in the Gutenberg Richter relation for a region are invariant with time. Simply stated, in a given period of time, ten times more earthquakes occur with a magnitude of 6, than with a magnitude of 7, and one tenth as many with magnitude 8. The relationship is stated in the form $\log N = a - bM$ where N is the number of events with magnitude ≥M, and "a" is measure of seismic productivity (i.e. the total number of earthquakes considered = 10^a). "b" is often a constant close to 1.0. The utility of this relation is that if it is truly valid, a relatively short (40-100 year) period of instrumental data can be used to evaluate the probabilty of future less frequent larger damaging earthquakes in a region. The b-value is frequently invoked for its importance in estimating large future earthquakes that may be sparsely sampled by an existing regional instrumental or historical record. It can be tested for its ability to forecast the number of moderate earthquakes from the number of minor earthquakes, thus providing a measure of confidence to those that seek to view the future. However, the time invariance of the "a-value", which also contributes to this forecast, is rarely questioned. The a-value numerically indicates the total number of earthquakes available in a catalogue of finite length. In some regions where the historical catalogue is sufficiently long, the a-value has been shown to vary with time, as for example in Turkey, where seismic activity alternates between the northern and eastern Anatolian faults over hundreds of years (Ambraseys, 1970; 1971; 1975). In India a similar time variable trade-off in seismic productivity may occur between earthquakes in Burma and those in the Shillong plateau (Vernante et al., in press). Forward projections of seismic catalogues based on the b-value alone may thus underestimate (or overestimate) the potential for future damaging earthquakes.

An inadequate record of historical earthquakes: Although the Middle East, Turkey and Iran have extensive records of historical earthquakes in the past 2000 years, an incomplete or inaccurate seismic history is typical of many parts of the world, and in some south Asian countries (Afghanistan, Pakistan, India, Bangladesh, Nepal, Tibet, Bhutan and Burma) the historical record is surprisingly scant. This may arise from the absence of a historical tradition of archival retention, or an absence in continuity of governance resulting in the loss of records (wars, malicious destruction of archives etc). An example, is that many of the written histories of Assam, India, were sought and deliberately destroyed in the 18th century, by those in power because in some cases they showed a less than honorable family history. Thereby the sins of ancestors were erased along with information on destructive earthquakes. A written history of Sikkim was destroyed by an invading Nepalese army who used its wooden tablets as roofing tiles. The Jesuit archives of India's history were destroyed in the Lisbon earthquake, and duplicates in Goa were burnt on the dock by the captain sent to retrieve them, to make space for a more lucrative cargo.

More often, the absence of written history is directly related to the decay of written records due to dampness or insect infestation. As a result of this loss of written archives, damaging earthquakes may be missing from catalogues, or the scant surviving records bias the inferred location of major earthquakes. Place names may have changed and earthquakes assigned to inappropriate coordinates. Some undoubtably major earthquakes may be omitted or misrepresented because they are recorded at only one location. For example, a major earthquake occurred 3 January 1519 possibly in the Kunar fault in Afghanistan during the eastward march of Baber's army (Ambraseys and Bilham, 2003a). Its magnitude may have exceeded $Mw \approx 7.5$, because mainshock and aftershock shaking is reported to have persisted for half an hour. But because only one report exists, location and magnitude remain speculative, and it cannot be placed with any reliability in parameteric catalogs, and hence is omitted by most researchers. In contrast, some early compilations of earthquakes (e.g. Oldham, 1883) have erroneously listed storms or cyclones as earthquakes, as has occurred in Mumbai in 1618 and Kolkota in 1737 (Bilham, 1994; Bilham and Gaur, 2013). These early entries have been adopted uncritically in later compilations and persist in many recent catalogues.

Unmapped faults: Earthquakes occur on faults, and a profitable investigative approach has been to exhume their surface rupture to determine a history of slip, that in some cases has extended the local seismic record for many tens of thousands of years (e.g. the strike-slip faults of California and Iran) thereby permitting estimates of recurrence intervals and the variability of slip in sequential earthquakes. However, where strain rates are low and faults activated infrequently, faults may be obscured by erosion and deposition rendering their surface expression invisible. Worse still, subsurface faulting may be responsible for earthquakes that leave no local distinct expression of subsurface activity. The existence of unmapped faults in a region may thus render paleoseismic investigations impotent, and bias estimates of seismic risk downwards.

Low strain rates: In the absence of recent earthquakes or a history of slip on known faults it is common to invoke measurements of geodetic strain (GPS and Insar) to provide an estimate of potential seismic productivity. The underlying physics is that where strain rates are low, earthquakes will occur less frequently. However, low seismic productivity does not imply no seismic productivity. If an earthquake on a fault occurs every ten thousand years and the last one was 10,000 years ago, the earthquake could obviously occur soon. Observations of low geodetic strain rates in isolation may thus misleadingly lower estimates of seismic risk.

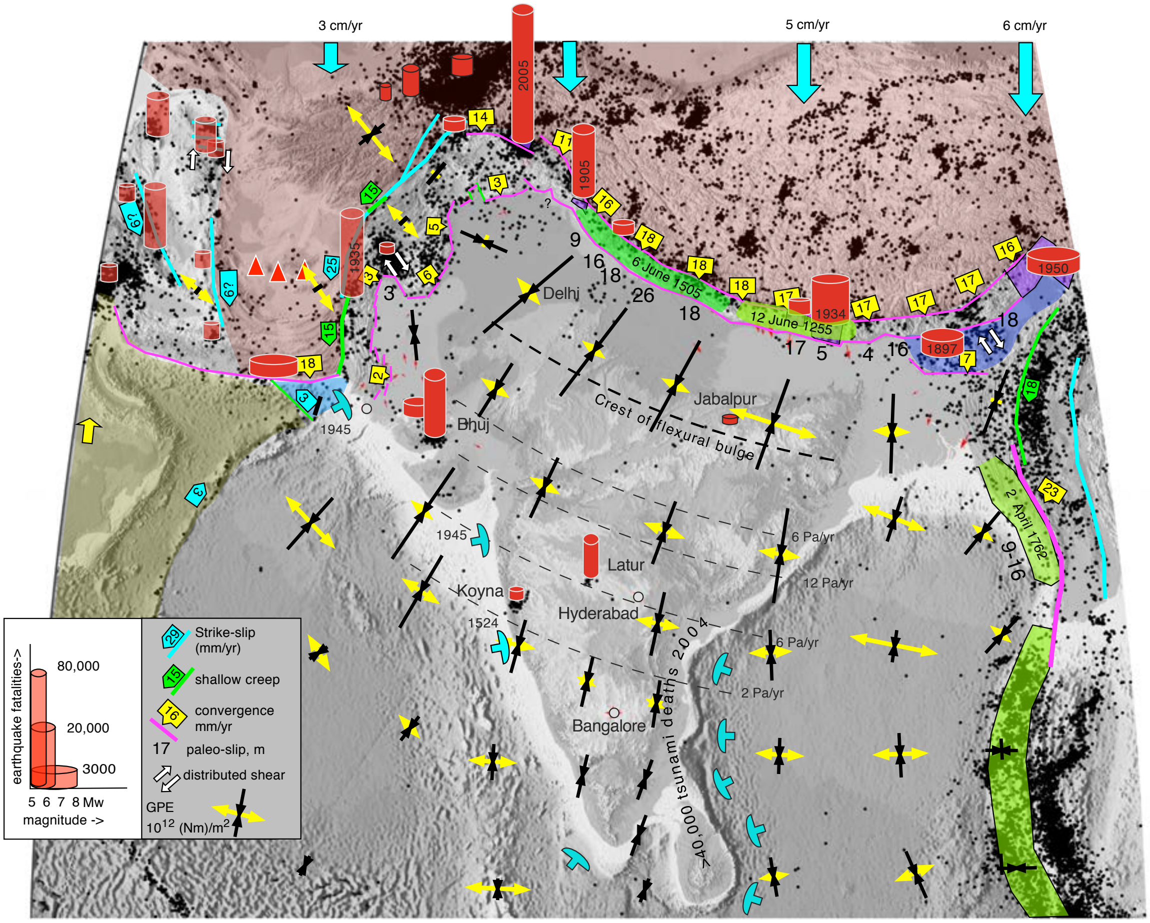

Fig. 4 Earthquakes, deathtolls, plate-boundary velocities and interplate stresses in the Indian plate. Inferred flexural stressing rates (dashed lines in Pa/yr, Bilham et al., 2003) and potential energy stress in the Indian subcontinent (Ghosh et al., 2006), with megaquake rupture zones (green), recent earthquakes (PDE), inferred GPS plate boundary vectors (arrowed tabs with numbers in mm/yr) (Socquet et al., 2006; Banerjee et al., 2012, Ader et al., 2012, Khan et al., 2008; Szeliga et al., 2012; Drukpa et al., 2012; Gahalaut et al., 2013), and Himalayan paleoseismic slip (black numbers adjoing collision zones in metres (Lavé et al., 2005; Kumar et al., 2001,2010; Jayangondaperumal et al., 2011; and Sapkota et al., 2013). Motion of the Ormara plate shaded blue near Karachi is quantified by Kukowski et al. (2000) and the consequences of rotation of the Shillong block (also blue) by Drukpa et al., (2012). Known tsunami are indicated by a blue hammerhead, with major earthquake deathtolls and magnitudes shown as vertical cylinders. Red triangles are volcanoes. Due to India's slow anti-clockwise rotation the velocities of collision increase eastwards, but the convergence across the Himalaya (yellow tabs in mm/yr) remains approximately uniform. Green tabs indicate observed creep rates on surface faults and blue tabs indicate strike slip velocities in mm/yr.

Low strain rates prevail in the Indian subcontinent – typically around 1 nanostrain per year (Paul et al., 1995; Banerjee et al., 2008). Thus if an earthquake has just ruptured at a failure strain of 100 microstrain, this tiny background strain rate would take 100,000 years to return the rocks in the nucleation zone back to a point close to failure in a future earthquake. But because India's collision with Asia has been ongoing for hundreds of millions of years, stresses are high everywhere. The forces involved are not just the north-south stress of collision, but are imprinted also with a combination of flexural and gravitational forces (Figure 4). The flexure comes from the bent northern edge of India as it is depressed under the Tibetan plateau (Bilham et al., 2003), and from the weight of the sediments deposited in the Arabian sea and Bay of Bengal by the great rivers of India. The gravitational stress arises from the forces resulting from supporting the great weight of the Tibetan Plateau, and the oceanic edges of the Indian continent (Ghosh et al., 2006).

The result of these stresses is that thoughout the Indian subcontinent, except where an earthquake has just occurred, the rocks may be close to rupture everywhere. The recent occurrence of M>6 earthquakes there has been attributed to the release of these large stresses by minor perturbations resulting from reservoir impoundment (Seeber et al 1996, Talwani, 1997). Viewed in terms of our ability to assess future seismic risk, reservoir construction for power and irrigation purposes is responsible for subtly raising the "a-value" in the Gutenburg-Richter relationship.

4. A summary of earthquake hazards in and surrounding the Indian plate.

The highest strain rates measured in the region (>100 nanostrain year) occur across plate boundaries. It is these regions that exhibit the highest seismic productivity for all ranges of earthquake magnitudes. Wrapped around the edges of the Indian plate are three distinct plate boundary settings where in the past 50 million years the Indian plate has been forcibly inserted into Asia at rates that once exceeded 10 cm/yr, but have now slowed to 3-5 cm/yr. To the west, the Chaman fault system between Karachi and Kabul permits the left edge of the Indian plate to slide past Baluchistan and Afghanistan. To the east the eastern edge of Indian plate, partly collides and partly slides past Indonesia and the Andaman islands along the Sagaing fault system through Myanmar to Assam. The northern edge of the Indian plate lies hidden beneath the Tibetan plateau several hundred km north of the Ganges, but the northern edge of the Ganges/Brahmaputra plain is truncated by a thrust fault slipping at roughly 2 cm/yr that marks the start of the Himalayan collision zone, a 2000 km long belt of seismicity that has hosted two Mw>8.4 earthquakes in the past 100 years, and more are considered overdue. In the following sections we discuss the history of earthquakes in each of these regions in detail, the structures that underlie these earthquakes, and the populations at risk in each setting.

Western edge of the Indian plate; Afghanistan, Pakistan and Baluchistan: The 1000-km-long Chaman fault system, a left-lateral boundary between the Indian and EuroAsian plates has an overall slip rate of 29 mm/yr distributed over a 100-400 km wide zone. It includes numerous branches, few of which are parallel to the slip vector between India and Asia ,but several segments exceed 200 km indicating Mmax (Maximum credible earthquake) capabilities exceeding Mw=7.5. The largest known earthquakes in the fault system (1935 Mw=7.7 Quetta; 2013 Mw=7.7 Arawan) occur at intervals of not less than 500 years given observed GPS rates. It is clear from Figure 5a that the historical record is remarkably incomplete prior to 1800, and many major earthquakes are probably missing from early earthquake histories in the region (Ambraseys and Bilham, 2003a;2003b).

Subparallel faults throughout the fault system share the burden of sinestral slip and partitioned convergence (note arrows on fold belts orthogonal to India's motion). Convergence evident in Figures 1 and 5 between the fold belts bordering the Chaman fault and the Indus Valley occurs at rates from 2-17 mm/yr, the fastest rate occurring in the southern Sulaiman range. Right lateral shear at 11 mm/yr occurs between the Sulaiman range and the fold belts south of Quetta, which is absorbed by slip on subparallel SW/NE trending sinestral "bookshelf" faults. In 2008 a pair of Mw=6.0 earthquakes occurred near Pishin on two contiguous faults.

A cursory view of Figure 5a&b suggests that a slip deficit exists between 32° and 34°N on the Chaman system. Segments of the fault system north of 32° are believed to be creeping although there is incomplete agreement on the depth to which the Chaman fault creeps. The presence or absence of creep on this part of the Chaman fault is important, because the fault here is a single strand for >200 km, and it could slip >10 m were it to rupture in a single earthquake (Mw≥7.9). Surface creep would reduce the slip potential to be released in a future earthquake, which would otherwise have a renewal time ≥500 years and would result in considerable damage in Kandahar and Kabul.

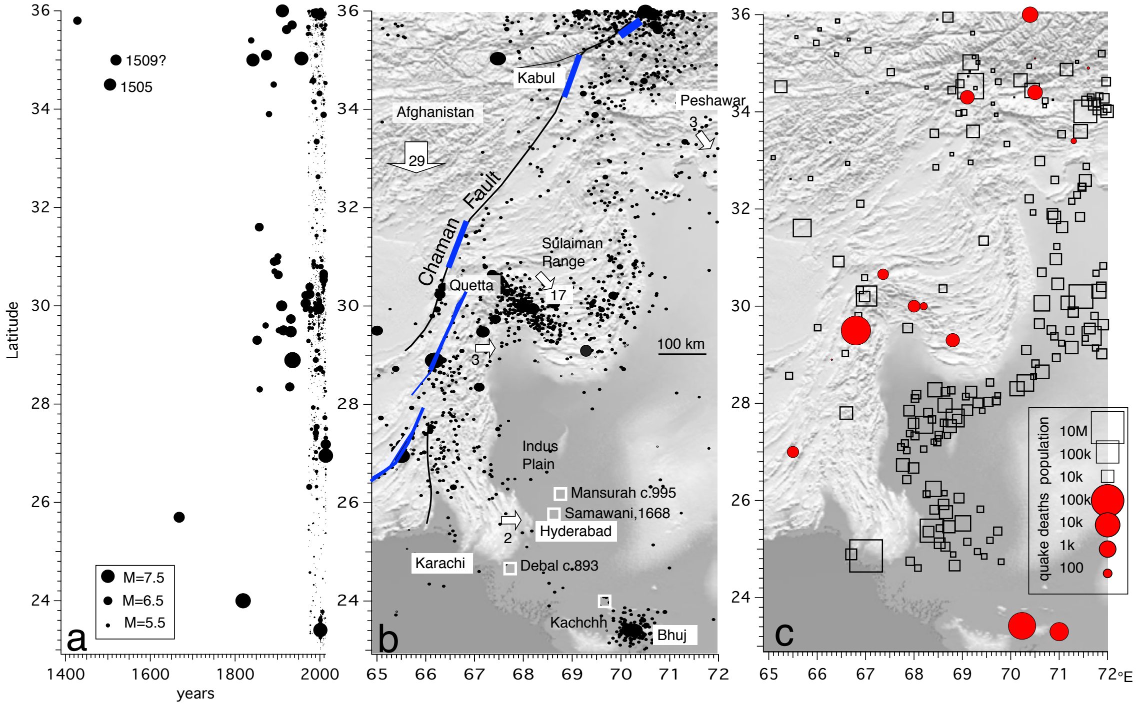

Fig. 5 **a.** Historical earthquakes 1400-2014 on the Chaman fault system and the western edge of the Indian plate, **b.** Pre-1900 earthquakes (Ambraseys and Bilham, 2003a,b; Bilham and Lodi, 2004) and instrumental earthquakes (pde and Centennial catalog), and **c.** populations and recent deaths from earthquakes. Blue = ruptured faults. Arrows indicate GPS velocities relative to the Indian plate (mm/yr). The obliquity of the plate boundary to the plate convergence direction (≈north/south) is responsible for the considerable thrust fault activity to the east of the Chaman fault. Despite two Mw≥7.6 earthquakes in the Bhuj region of India in the past 200 years, GPS rates in the 200 km region near Bhuj indicate deformation rates of less than 2 mm/yr. An east-west GPS convergence rate >2 mm/yr exists near Hyderabad north of Karachi which has been the locus of several damaging earthquakes (white squares).

Populations are sparse along much of the Chaman fault system, but building styles in villages (unreinforced masonry, adobe etc.,) are particularly vulnerable to damage from quite modest shaking. In Figure 5c it is clear that historically, fatality losses from earthquakes in the region have occurred where populations are thinly distributed. In the 1935 Quetta earthquake there was a high deathtoll (35,000) because it was a major town in a sparsely populated desert region, that took a direct hit from a nearby earthquake. In 1936, Quetta was unique among Indian cities for being the first city in what was then India, to rebuild with mandatory earthquake resistance. The largest densities of population near the Chaman fault system are Kabul (3.3 million in 2012), Kandahar(0.5M), Quetta(2.8M) and Karachi(with 24 million, Pakistan's largest city), all close to former earthquakes.

Recent earthquakes in the past century near Karachi have been minor, but segments of the fold belt upon which it is constructed are converging with the Indian plate at a rate of ≈2 mm/yr. Former damaging earthquakes in the Indus Valley within 200 km NE of Karachi have resulted in the historical destruction of several now-abandoned towns (Figure 5c). Hyderabad (current population 1.2 million) was relocated to its present location in 1768 following an avulsion of the river Indus following the 1668 Samawani earthquake (Bilham et al., 2007; Bilham and Lodi, 2010). Samawani is presently a small village. The destruction of Mansurah, the former Arab capital of Sindh, is approximately dated at 950 C.E. from the time of its abandonment some years after an earthquake. This earthquake (of unknown magnitude or precise location) destroyed major public structures in the city (also known as Brahmanabad, 25.881° N, 68.777° E) and survivors abandoned the city when the Indus shifted its course to the west, compromising its water supply and removing its commercial viability as a river trading station (Bilham and Lodi, 2010). It is likely that Debal (the archaeological site of Bhanbore at 24.751°N 67.521°E) was also abandoned when the river nearby, the westernmost distributory of the Indus silted up, rendering the town no longer viable as a port. Kovach et al., (2010) interpret a stone tablet discovered in Debal as indicating that the city was reconstructed after an earthquake in 893 C.E.

The southernmost Chaman fault (the Ornach Nal fault) enters the sea roughly 100 km west of Karachi at a triple junction between the Ormara plate (Kukowski et al., 2000), the Asian Plate and the Indian plate. No great earthquake is known between the 1945 Mw=8.1 Makran earthquake and the triple junction (Bilham et al., 2007), although there is currently no reason to suppose that this segment of the plate boundary could not have a Mw≥8.0 earthquake. The 2012 Mw=7.7 Awaran earthquake in Baluchistan released strain at shallow depths, and quite locally close to the fault, and hence the slip potential from Ormara/Asia plate convergence may currently be high. A great earthquake on this segment of the plate boundary would be potentially damaging in Karachi where earthquake resistance is largely non-existant, and where several critical facilities would be vulnerable to the resulting tsunami.

Northern edge of the Indian plate: The Himalaya from Kashmir to Arunachal Pradesh: The mean convergence rate across the central Himalaya is approximately 18 mm/yr (Ader et al., 2013) with lower rates observed near the western end of the arc - 11 mm/yr in Kashmir (Schiffman et al., 2013) and slightly higher rates (19 mm/yr) in eastern Assam (Drukpa et al., 2012; Vernant et al., 2014) (Figures 1 and 6). Several great earthquakes (M≥8.0) have occurred in the past 500 years along the Himalaya but the rupture areas of all of these earthquakes, even the most recent in 1950, have not yet been studied in detail. It is certain that the largest earthquakes nucleate beneath the high mountains of the greater Himalaya and rupture the entire 100 km width of a locked décollement. The along-arc rupture lengths of Himalayan earthquakes are not well defined. Even the 1934 earthquake whose mainshock location is known from instrumental records (Chen and Molnar, 1978; Molnar and Deng, 1984) and whose surface rupture has been partly exhumed (Sapkota et al., 2013) the mechanisms that initiate and terminate rupture are unknown.

Figures 6b and 6c demonstrate a striking complimentary asymmetry between sparse populations and widespread seismicity north of the Himalaya, and low seismicity and high population densities south of the Himalaya. The highest seismic productivity, and most of the known deaths from earthquakes have occurred within the Himalaya at the confluence of these two extremes , and all of the listed high fatality earthquakes have occurred in the past 200 years. The historical data base (Figure 6a) includes a handful of damaging earthquakes prior to 1800 but for these earthquakes we have no quantitative estimates of magnitude or location. The fatality counts most of these historical earthquakes are unknown or unreliable. There has been a tenfold increase in population, and a change in building styles since 1900 which suggests that future earthquakes in the Himalaya will be associated with significantly greater numbers of fatalities.

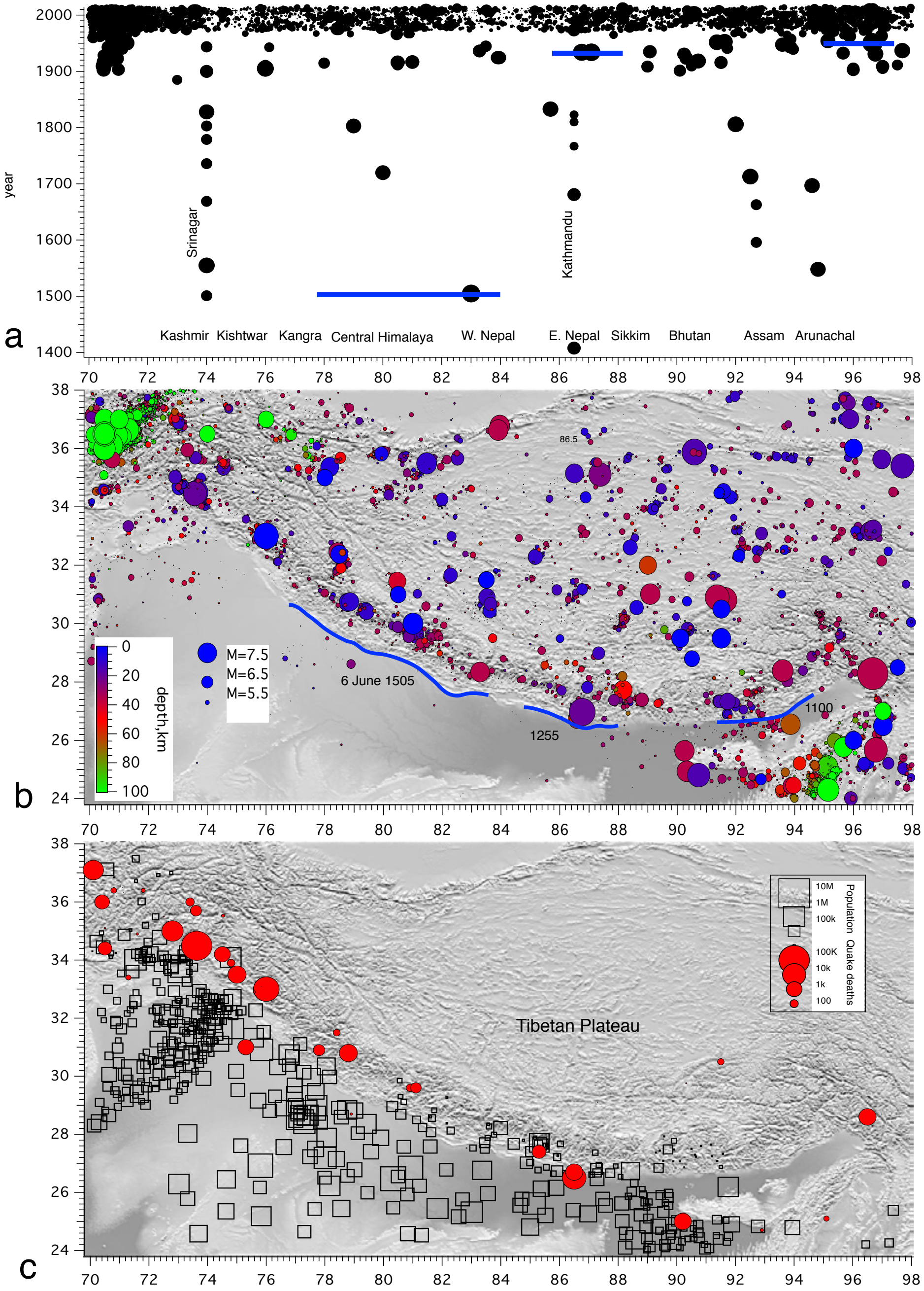

Fig. 6 Himalayan Seismic Hazards. **a.** Historical data base and inferred major ruptures. **b.** Distribution of seismicity with major surface ruptures. Deep earthquakes in green (>100 km) occur at the ends of the arc. **c.** Populations are dense in the plains of India, Pakistan and Bangladesh and sparse in Tibet.

From extant histories that have survived in the principal cities of isolated Medieval Kingdoms (Srinagar and Kathmandu) we know of numerous damaging historical earthquakes, but not their magnitudes or precise locations. Neither Kashmir nor Nepal are potentially higher in seismic productivity than elsewhere in the Himalaya, and Figure 6a suggests that had similar histories survived elsewhere along the arc the figure would now be densely populated by many more damaging earthquakes. The question of concern in seismic risk studies is the future recurence of the most damaging earthquakes in the Himalaya. To answer this question we would need to know the timing and location of, say, future Mw≈7 earthquakes that now occur at several decade intervals somewhere along the arc, and to know the recurrence interval of infrequent Mw≥8 earthquakes (every few centuries) along the arc, since these, with their large footprint, can damage the cities in the Ganges plains south of the Himalaya.

An often neglected constraint in assessing seismic hazards in the Himalaya is that a Himalayan loading rate of 18 mm/yr, means that each 100 km segment of the Himalaya could host a Mw=7.8 earthquake every 100 years (100km x 100km x 1.8 m. Thus in any given century twenty Mw=7.8 earthquakes should occur on a segment of the Himalayan arc, i.e. one every 5 years. The actual rate exceeds 50 years. The inescapable conclusion is that Himalayan stress is not being released in these smaller (but nonetheless damaging earthquakes), and is instead building up stress that will be released in larger ones. If we assume that Mw≈8.5 earthquakes are the norm for the Himalaya (1950 Assam Mw=8.6, 1934 Nepal Mw=8.4 see discussion below), and these occasionally rupture the Himalaya in seven 300-km-long segments, they could do so every 300 years with 5.4 m of slip. We might expect 2-3 of these great earthquakes to occur every hundred years somewhere along the Himalayan arc. Coincidentally, this is about the rate we have seen in the past century, but from what little we know of the history of these very large earthquakes (Figure 6a), it appears that no Mw=8.5 earthquakes occurred in the previous 100 years, or even the past 400 years, that fits this pattern. We therefore conclude that some Himalayan earthquakes are much larger than Mw=8.5, and that they occur very infrequently, possibly at intervals of a thousand years or more.

One such earthquake occurred at dawn on the 6 June 1505 (Ambraseys and Jackson, 2003) and may have had a magnitude of Mw=9.0 (Figure 6b). Evidence for its magnitude comes not so much from the distribution of recorded intensities, which are sparse and imprecise, but from paleoseismic evidence. Several trenches across the Himalayan frontal thrust between 77°E and 84°E revealed offset sediments containing detrital charcoal dated at about 1400 CE (Wesnousky et al., 1999; Kumar et al., 2004). The causal earthquake must have thus occurred after this date and many are now of the opinion that these trenches have sampled a single earthquake corresponding to the June 1505 earthquake along at least 550 km of the arc. Although not a certain indication of a single megaquake, it is suggestive, and consistent with the broad felt area of damage in the 1505 earthquake (Joshe et al., 2009). Slip of as much as 23 m has been inferred in some of these trench investigations (Lave et al., 2005; Kumar et al, 2001;2010) and scaling laws suggest that such large slip requires a correspondingly along-arc ruptures (Stirling et al., 2014).

In segments of the Himalaya where the slip in metres and the date of the most recent great earthquake and the convergence rate (see Figure 4) are all known, it is possible to infer the approximate time to the next earthquake (an important assumption is that a future earthquake will slip the same amount as the previous earthquake). Applying this reasoning to the 6 June 1505 earthquake and a time invariant convergence rate of 18 mm/yr (Ader et al., 2012), a 1000-1300 year time between earthquakes must elapse, and hence an identical repeat of this earthquake cannot occur for a further 500-700 years. There are inherent observational difficulties that attend this calculation because it is not certain how well point measurements of paleoseismic slip characterize the mean slip in an earthquake (i.e. is observed slip representative of mean slip), or whether the large observed slip exposed in trenches crossing the fault represents the slip in one earthquake, or from several major earthquakes that occurred years or decades apart.

Even were these uncertainties overcome, the problem with this approach is that we would typically like several historical demonstrations that Himalayan earthquakes indeed recur with the kind of regularity implied by this type of time-predictable renewal process, a regularity that depends upon not just the strain at failure, but also upon the friction and strength of the rock-rupture process being replicated in consecutive earthquakes. Examples of repeating earthquakes elsewhere in the world show this regularity exists only in a statistical sense, with large variations in intervals between earthquakes.

No statistics for the recurrence interval of earthquakes in India exist. In the Himalaya, and in fact throughout India, we know of only two regions where earthquakes have repeated – the 1255 and 1934 Mw>8 earthquakes in eastern Nepal (Sapkota et al., 2012) and, possibly the 1999 Chamoli and 1803 Mw<7 earthquakes in the central Himalaya. In Gujarat two nearby Mw>7.6 earthquakes, in 1819 and 2001, did not occur on the same fault and cannot be considered repeats of one another.

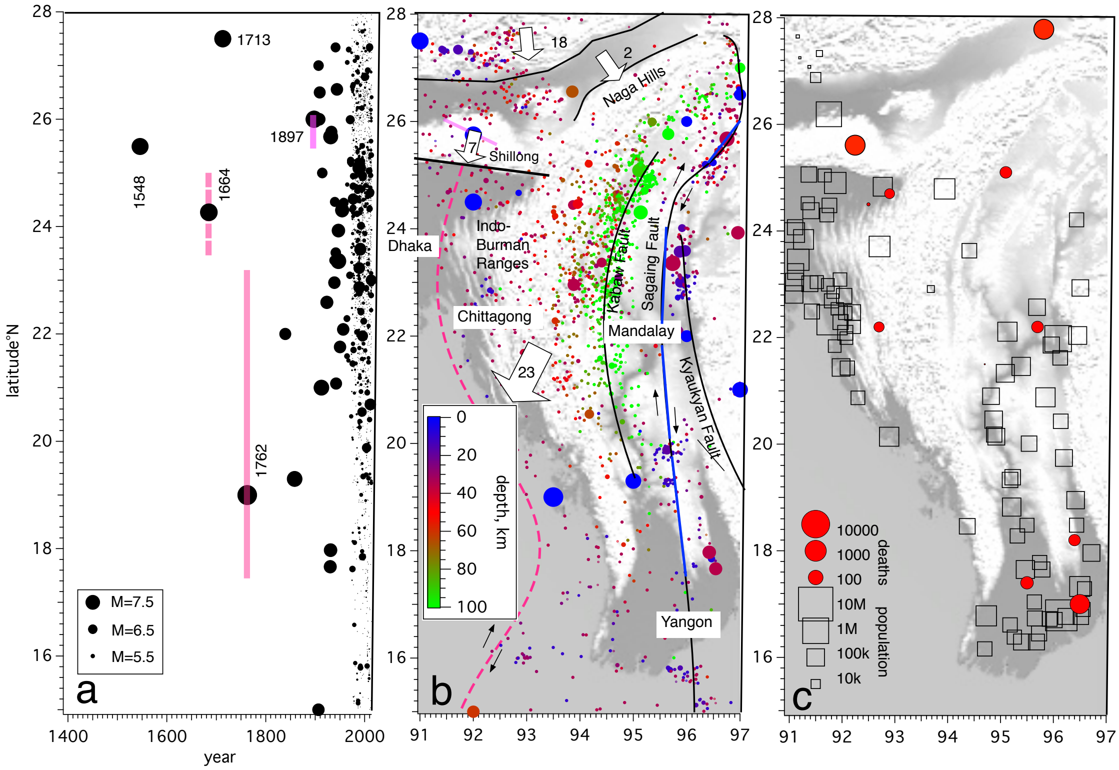

Fig. 7**a.** Historical earthquakes, **b.** earthquake distribution and GPS velocities relative to Indian plate, and principal surface faults, **c.** populations and fatality losses from historical eathquakes Bangladesh and Mynmar. Population data are spatially incomplete.

Eastern boundary of the Indian plate: The disastrous Indian Ocean tsunami resulted from the rupture, in the time span of ten minutes, of a 1600 km long segment of the eastern plate boundary from 2°N to 15°N (Lay et al., 2004; Chlieh et al., 2007), twice as long as the inferred 1505 central Himalayan earthquake discussed above. Previous tsunamigenic earthquakes (e.g. 1881 Ortiz and Bilham, 2003; 1945 Bilham et al., 2005) had been described before the earthquake and evidence for earlier tsunami have since been documented (Malik et al., 2011). North of the Andaman Islands, rupture in 2004 terminated near 15°N where the plate boundary veers to be subparallel to the slip vector. In Myanmar, north of 18°N, northward slip of the Indian plate is accommodated on the right-lateral Sagaing fault system and subparallel faults, and the east west component of convergence with the Burma plate is absorbed by a subduction zone whose central segment slipped in a great earthquake in April 1762 (Cummins, 2007; Wang et al., 2014). The shorter segment between 22°-25°N may have slipped in 1664, for which there are several authentic accounts (Iyengar et al., 1999; Ambraseys, 2004). An earthquake in 1548 is repeated in numerous popular media as affecting Sylhet, and by implication Dhaka and most of Bangladesh, but original accounts of this event are brief, and its location is probably in the Naga Hills bordering the Brahmaputra Valley (Iyengar et al., 1999).

The Indian plate dips eastwards beneath the Indo Burman ranges (Satyabala, 1998) to depths exceeding 100 km with a Benioff zone (figure 7B) defined by moderate and occasional major earthquakes (e.g. Mw=7.4 1954). Earthquakes at shallow depths above this east dipping zone are associated with east-west compression and folding (Steckler et al., 2008; Wang et al., 2014). In the past century sufficient earthquakes on contiguous segments of the dextral strike-slip Sagaing fault system have occurred to identify gaps where future earthquakes are now probable (Wang et al., 2014). Numerous population centers follow the active faults of south central Myanmar (Figure 7c), and there is considerable concern that future M>7 earthquakes will occur near major cities (e.g. Wyss, 2008).

5. Conservatism and denial as aggravated risk

In the foregoing sections I provide a brief summary of the seismic hazards that follow the western, northern and eastern plate boundary regions of the Indian plate. These provide the input that have been used by individuals, governments and global organisations such as GSHAP and GEM as input to maps of seismic hazards, which in turn form the basis of numerical estimates of seismic risk. A glance at the figures is enough to show that numerous population centers are at risk from earthquakes in each region, and that the number of historical "hits" represent a small fraction of potential future "hits" from earthquakes. In this context a "hit" is the occurrence of a major earthquake close to a major population center, an example being the 1935 Quetta earthquake with its 35,000 human fatalities.

The left-hand (a.) panels of each figure reveal the burst of seismic information that occurs after the installation of seismometers around 1900 and the yet greater increment that occurs following the deployment of the standardised seismic network in 1960. The corollary of these data-rich improvements in knowledge is the extraordinary incompleteness of historical information about earlier earthquakes. From time to time new earthquakes are added as a result of the discovery of an as-yet unexamined history of a region, or increasingly, as paleoseismic investigations of surface faults yield information extending our knowledge of earthquakes to prehistory. It is my opinion, however, that the historical record is likely to remain in its present incomplete state for many years.

I now return to the theme of aggravated seismic risk. This section introduces the notion that seismic risk can be aggravated by interpretative denial. Because historical data are interpreted by so-called experts, it is possible, and indeed expected, that expert opinion will form a diversity of conclusions based on these available data. If a damaging earthquake is deleted from the historical record it can effectively reduce future seismic risk, thereby relaxing local building codes; if one is added it will increase assessments of future risk, and lead to stronger building codes. Often these diverse opinions can be incorporated into so-called logic-tree calculations of risk where extreme views are considered and assigned probabilities. The consequences of these considerations are not academic, they affect human safety and often have enormous economic consequences. For example, a conservative view of the historical earthquake record in a specific region may permit the construction of a nuclear power plant at half the cost of one that incorporates a more cautious interpretation of these same data.

It is important to understand why expert opinion would wish to err on the side of a conservative interpretation of earthquake histories.

Unsensational science vs. banner headlines : Scientists, in general, know the perils of sensationalising their results. Unnecessary alarm is counterproductive since it de-sensitizes the listener to real alarm. Its consequences are exemplified by the story of the young shepherder who cried wolf when there was none, knowing that he would grab the attention of the concerned community, only to be ignored by the community when a real wolf appeared. The problem for the earthquake scientist is that the historical seismic record describes the past imperfectly, and the future only in a probabalistic sense. When findings indicate that the seismic risk of a region has been hitherto underestimated it is common for scientists to report their findings to each other in the vaccuum of academic discourse - at scientific meetings, in learned articles and in conversations in corridors - but it is difficult to convey this information to the public without the information being considered sensational. This is partly due to the substantial reporting differences between scientific and journalistic reporting. Science procedes by building hypotheses that can be refuted. Journalists write what they consider to be confirmed truths that they hope (if they are honest) are beyond refutation. Words spoken at a scientific meeting sound very different on prime-time news.

Four recent examples of the gap between scientific knowledge and implementation are noted, of several that have occurred in recent years.

- The L'Aquilla disaster in Italy followed from difficulties in communicating the statistical uncertainty of a damaging earthquake. When a fatal earthquake occurred scientists involved in assessing the significance of foreshocks were accused of providing "incomplete, inaccurate and contradictory" statements (Hall, 2011; Nosengo, 2012).
- A few years prior to the Tohuko 2011 tsunami, scientists knew that a previous tsunami had swept ashore with similar amplitude and reach (Satake, 2008; Tajima et al., 2013) but mechanisms to communicate these new data to those responsible for coastal defenses were unavailable. Attempts to convey this information through media outlets would have been characterized as alarmist.
- In the years preceding the the 2010 Haiti earthquake Eric Calais and his colleagues approached government officials in Haiti with their findings that geodetic strain was close to being renewed following two 18th century earthquakes that had destroyed the former city of Port au Prince (Manaker et al., 2008). Officials listened but were unable to act.
- In June 2004 an invited talk was given at a scientific meeting in Bangalore, sponsored in part by NSF and NASA, on the natural hazards of southern India. During the talk graphical views of potential tsunami runup along the east coast of India were presented, based on historical tsunami in the Nicobar and Andaman islands (Ortiz and Bilham, 2003). Neither the speaker nor the audience had any intention of releasing these findings to the press, or persuading coastal authorities to implement tsunami warnings. The speaker was me, and the tsunami that occurred six months later was far worse than I had calculated.

The problem scientists face is that the transition from a tentative, or certain, scientific finding to a news release is a quantum leap. There is no smooth transition from abstract hypothesis to headline news. Societal infrastructure responds not to the scientist but to the megaphone of the journalist. Scientific findings may be important to societal planning, but societal action frequently requires the litmus test of banner headlines, a course of action which scientists are loathe to invoke.

Denying the unprecedented - a Mw=9.0 earthquakes cannot occur in the Himalaya: The Mw=9.1 earthquake that occurred along the submarine southeastern boundary of the Indian plate in 2004 had no historical precedent. The largest known historical earthquake at the time was the 1881 Mw=7.9 Car Nicobar earthquake. The parallels between Himalayan seismicity and the length of the plate boundary prompted speculation that the 1505 earthquake in the central Himalaya may have been a similarly large earthquake (Bilham and Wallace, 2005). To qualify as a Mw=9.0 the earthquake had to satisfy an area and slip combination that was unprecedented in the historical record of the Himalaya - but the arithmetic was, and is, plausible - a rupture length of 600 km, a down-dip width of 100 km and a slip of 20 m yield a magnitude Mw=9.0.

Yet to some scientists the conclusion is unacceptable. A litany of objections has been assembled, similar to the response of the scientific community to the proposition by Alfred Wegener of his theory of continental drift. The arithmetic that leads to the conclusion that Mw=9 earthquakes must be considered possible in the Himalaya is simple, but the three quantities that go into the sum can each be questioned, as can the historical record itself.

A recent article by Srivastava et al., (2013) criticizes the weaknesses of the historical record (Figure 6A) but then uses it as a template to conclude that the Himalaya are unable to sustain earthquakes larger than Mw=8.6 in the east or Mw=7.6 in the west, with a range of intermediate magnitudes in between, as exemplified by the past century of earthquakes. The authors deny that the Himalaya can sustain ≈600-km-long ruptures, and propose that the region is too segmented to permit long ruptures to propagate. To overcome the inadequacy of historical earthquakes to keep pace with the known seismic-deficit accumulation rate, they invoke an as-yet unidentified creep process on the Himalayan décollement. Most certainly creep is currently absent (Avouac, 2003; Ader et al., 2013). Historical accounts of collapsed temples in Tibet and damage to Agra in 1505 are attributed to a modest earthquake in the region and local amplification effects. Paleoseismic slip > 20 m reported in trench investigations of the Himalayan Frontal Thrust are dismissed as unreliable. Age dating of detrital carbon is considered questionable. All these arguments are a fundamental component of scientific refutation, but for none are compelling arguments provided that refute the fundamental observations.

Other authors have questioned the magnitude of Himalayan earthquakes in the past millennium (Rajendran et al., 2013, and previous articles cited therein) based on specific observational data. These authors place considerable emphasis on the survival of Medieval masonry structures as indicative of the absence of great earthquakes. However, the findings presented are qualitative in that they provide few numerical estimates for the maximum accelerations and shaking durations implied by the survival of these monuments. For example, accelerations in the Andaman islands did not exceed Intensity VII in the 2004 Mw=9.1 earthquake. Their findings are of interest since numerous examples of repairs to temples have been discovered that supplement our knowledge of historical earthquakes. The survival of ancient structures is enigmatic in that those that have survived tell us little about those that have succumbed to shaking (Ambraseys, 2009). In Kashmir several structures assembled c. 800 CE are known to have survived Intensity VII shaking, and occasional Intensity VIII shaking (Bilham et al., 2010, Bilham and Bali, 2013), each successive earthquake resulting in incremental damage but incomplete collapse.

National pride and the need to protect the public from alarm: The populations at risk from a Mw≥8 earthquake in the Himalaya are considerable because of the anticipated high accelerations and long shaking duration of great earthquakes. Scenario studies undertaken to assess the deathtoll from large earthquakes predict huge losses. For example, Wyss, (2006) estimated a fatality count of 29-56,000 for an Indian Kashmir earthquake. Hitherto, India's reaction to the recognition that great earthquakes are inevitable in northern India (e.g. Bilham et al., 2001) has been inconsequential, however, in 2012 a series of scenario projections of damage from Mw=8 earthquakes along the Himalaya were initiated by the India's National Disaster Management Authority. Early results indicate that a repeat of the 1897 Mw=8.2 earthquake could result in 600,000 deaths in Assam, and Mw=8-related death tolls elsewhere could reach 800,000. The simulation model for the Mandi region (≈76-77°E) is based on a line source model (Sinha et al., 2012) and forecasts Intensity IX shaking over a 10,000 km^2 epicentral region. In previous Himalayan earthquakes Intensity IX shaking has been observed in quite limited (≈100 km^2) regions (Ambraseys and Bilham, 2003c; Ambraseys and Douglas, 2004).

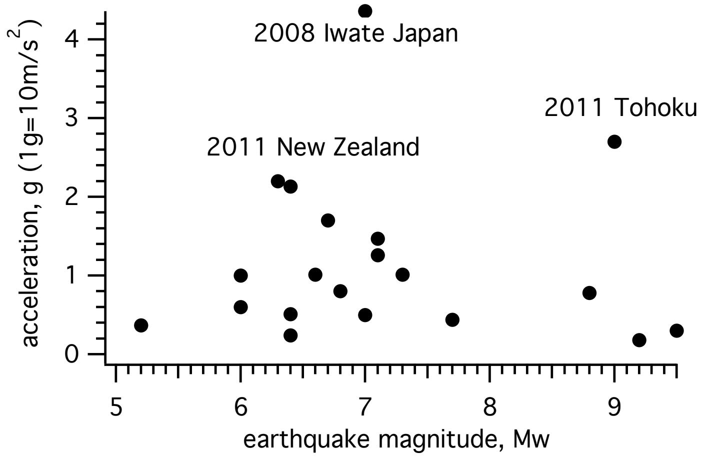

Fig. 8. Magnitude vs maximum shaking intensity for some recent earthquakes.

However, resistance to the notion of a Mw=9 earthquake remains, and one reason is thought to be that such earthquakes are intriniscally "off-scale". The global headlines following the 2004 and 2010 Mw=9 headlines would be unthinkable to be associated with Delhi or Srinagar, or Gauhati, or Agra. Local reactions to an assessment of possible scenarios for future earthquakes in Kashmir by an international team in December 2011 (Jones, 2011) understandably resulted in concern, panic and denial by local officials. It is possible that denial comes from an unjustified assumption that earthquake shaking intensity rises with magnitude. As mentioned earlier, the recurrence of such megaquake in the central Himalaya is not anticipated for ≈700 years as calculated from the renewal time for ≈20 m of slip. In Kashmir Mmax has in fact been calculated to be Mw=9 based on the unlikely contiguous rupture of a 180-km-wide, 300-km-long segment length between the Kangra 1905 and the Kashmir 2005 earthquakes, one of a dozen scenario ruptures (Schiffman et al., 2013). Although shaking duration increases with great earthquakes, there is no evidence to suggest that the accelerations during Mw>8.5 earthquakes may be significantly larger than those associated with Mw<8.0 earthquakes. In general the stress at failure, and proximity to the fault rupture, determines local acceleration, but the elastic energy released in an earthquake is stored in a volume of rock surrounding the fault and there is a corresponding increase in mass upon which these accelerations act. Observational data confirm an absence of trend in Mw vs. measured peak surface acceleration (e.g. Figure 8). As an extreme example consider the 2011 Tohuko Mw=9 earthquake in which accelerations locally exceeded 2g. In the same year similar peak accelerations were recorded during the Mw=6.3 and Mw=6.4 Christchurch, New Zealand earthquakes that released 0.01 of the energy. During the 2004 Mw=9.1 Indonesian/Andaman earthquake, shaking intensities in the Andaman islands did not exceed MSK VIII (<0.65g) above the rupture zone. Such considerations are of little comfort to populations at risk in and near the Himalaya, since accelerations of the order of 1 g will prove disastrous to infrastructure and typical constructions in cities in the Ganges plains to their south where shaking durations and amplitudes are expected to be amplified by basin resonances (Hough et al., 2005a,b). The denial of the possibility of the future occurrence of a great earthquake by those responsible for public safety should be accompanied by irrefutable evidence to support such opinions. Insubstantiated claims aggravate the assessment of seismic risk..

Jaitapur: "all apprehensions raised have been considered"

Jaitapur (16.6°N,73.3°E) is a small village on the west coast of India far from the boundaries of the Indian plate. The Nuclear Power authority of India has been advised that it is an ideal location to site the largest nuclear power station in the world.

This apparent perfection, however, is marred by the observation that a significant fault scarp is mapped near the planned powerplant. No earthquake has occurred closer than 44 km, but two earthquakes in the past century at similar latitude indicate that stresses in the Indian plate are sufficently high to sustain moderate earthquakes: in 1967 a Mw=6.7 earthquake occurred at Koyna (17.4N, 73.8°E) 110 km to the north, and in 1993 a Mw=6.3 at Latur (18.1°N,76.5°E) to the NW (Figure 4). The origin of these stresses released by these earthquakes are related to India's collision with southern Tibet, which flexes the Indian plate into a several hundred km undulation and compresses it in a north-south sense (Lyon Caen and Molnar, 1983; Bilham et al., 2003), and to the gravitational potential energy of the large range in topography, from the sea floor to the 5 km elevations of the Indian plate (Ghosh et al., 2006). The existence of a substantial deviatric stress in the Indian plate accounts for the faint background of microseismicity manifest throughout India in small and sometimes damaging earthquakes. The larger earthquakes occur on faults with dimensions of tens of km, at intervals of many hundreds if not many thousands of years. Hence the existence of any fault near Jaitapur, given the history of moderate earthquakes at these latitudes, is of concern to characterising seismic hazards in the region. (Bilham and Gaur, 2011, Gaur and Bilham, 2012).

Usually the faults of southern India are subtly expressed, and many of them are concealed in the subsurface, but a glance at the Google imagery south of Jaitapur reveals a 35-km-long, 20-m-high step in the marine terrace on which the power plant will be constructed. There is no disagreement among geologists that this is the scarp of a tectonic fault (the Vijaydurg fault), and were this in Europe, Japan or the USA it would have been the subject of extensive paleoseismic trenching investigations to determine when it last slipped. Its on-land length exceeds 35 km, and its NNW projection offshore passes within 10 km of the site an unknown distance to the north. The dimensions of the fault suggest that if it slipped in a single earthquake it could do so with 6.5<Mmax<7.5 depending on its offshore extent, which is currently unknown. The site report and a recent article (Rastogi, 2012) asserts that the fault is inactive - incapable of slipping in a future earthquake - based on a surface inspection of the fault scarp. The site report (not released publicly as of January 2014) indicates no trenching has been undertaken and no offshore mapping has been undertaken. In the USA a capable fault is defined as one that has slipped once in the past 35,000 years, or slips with a recurring nature in the past 500,000 years. Such questions have not been addressed at Jaitapur.

The issue is not so much that a local fault may potentially slip in an earthquake near a planned nuclear power plant, since a power plant can be built to withstand accelerations of

1 g or more (although the design of a nuclear plant potentially 10 km from the epicenter of a Mw=7.5 earthquake would be challenging and costly). At issue is the absence of transparency in the site review process, and the apparent absence of many of the geological investigative techniques currently available to quantify fault activity both onshore and offshore (Gaur and Bilham, 2012). Perhaps of greatest concern is the overt attempt to stifle scientific discussion concerning seismicity near Jaitapur (Bagla, 2012). Government suppression of the discussion of seismic hazards must surely aggravate objective assessments of future seismic risk. It is of little value claiming that "all apprehensions raised have been considered" (Rastogi, 2012), without quantitative and transparent evidence supporting such claims.

6. Earthquake knowledge and its application

In the above account I consider aspects of earthquake hazards, an imperfect knowledge of which in most cases underestimates earthquake risk. I avoid the presentation of seismic hazard maps, since these are maps of an imperfect earthquake history, not of a possible seismic future (Nikolic-Brzev, 1999). I also omit a discussion of the extensive probabilistic calculation of earthquake risk from the best available information of seismic hazards. The remainder of this chapter assumes that accurate estimates of seismic risk are available, and focusses on the imperfect transfer of this knowledge to the user community.

Earthquake risk has been discussed for more than 100 years and the developed nations have responded by incrementally improving the guidelines and reach of recommendations for earthquake resistant construction. In wealthy industrial countries such as Japan and in regions of the USA where earthquakes occur, earthquake risk is recognized as a problem with a simple solution - quantify the risk and design structures accordingly (FEMA, 1995). Earthquake resistant design is typically considered in a cost benefit analysis, and for civic structures is mandatory where the risk has been quantified. Earthquake resistance in historical public structures (retrofits) are introduced where existing earthquake resistance is considered inadequate, but is left to the home owner in older housing. New housing starts in California must comply with earthquake resistant design recommendations before a planning permit is awarded, and at each step in construction, compliance is verified before the next stage in construction can be undertaken. Thus to a large degree the public in developed nations is protected from unexpected home fragility, or the collapse of civic structures such as schools, fire stations and hospitals, or from earthquake damage to city infrastructure such as harbours, pipelines, bridges and roadways.

In the developing world where most of the population increase in the past century has occurred, earthquake resistance has not been an important factor in the assembly of dwellings (Jain 2005). Earthquake resistance has been ignored through ignorance or poverty. In some cases earthquake resistance has been deliberately avoided in order to maximize construction profits.

Adobe mud buildings with thick mud roofs are still common in Iran (Berberian, 1979; Manafpour, 2008). The use of undressed field-stones cemented with mud to assemble walls proved fatal in the Latur earthquake in India. In contrast, some traditional construction methods are inherently resistant to earthquake shaking. In the Kachchh region of India adobe mud walls surmounted by thatch survived the Bhuj earthquake. In Kashmir, Sikkim and Ladakh traditional stone and masonry buildings are intercalated with wooden beams that absorb shaking energy (Langenbach, 2009; Tessman, 2012). In Assam and in villages in Kachchh, wattle-and-daub or bamboo lightweight dwellings (Das et al., 2012) once common and resistant to earthquake shaking, are now shunned by those that can afford concrete and steel structures. In some case villagers spurn traditional construction methods in favor of the perceived prestige attending the adoption of buildings that have adopted new methods of construction.

The demise of wooden construction in most parts of Asia due to the depletion of forests means that some traditionally earthquake resistant buildings can no longer be considered by villagers. Increasingly, the only materials available for new construction consist of bricks, cement and steel. In nearly every settlement, village, town and city, new construction is based on these three materials. When they are of adequate quality and correctly assembled they can provide safety from shaking in an earthquake. When the bricks or cement are weak, or if the steel is brittle, or of insufficient quantity with inadequate internal connectivity, the assembled buildings are prone to collapse in an earthquake. This is particularly the case in cities where space is at premium and the need to house many families requires buildings with three or more storeys, resulting in higher loading stresses during earthquakes.

In the major cities and megacities of the south Asia the current building stock is fragile and is an easy target for earthquake damage (Bilham and Gaur, 2013). A measure of the fragility of structures in south Asia is the frequent occurrence of buildings that collapse spontaneously, but the percentage of substandard construction is unknown. A well known example is the collapse of a garment factory on 24 May 2013 in Dhaka that killed 1123 people, and injured 2500 others. Although the largest of these disastrous collapses are reported internationally, local news reports of building collapse suggests that it is far more common than realized. During the year 2012 in India, 2,737 instances of structural failure (including bridges, walls and buildings) resulted in 2651 dead and 850 injured (Chalabi, 2013). In Pakistan the statistics have yet to be gathered, but a cursory survey of collapse reports in Karachi, Islamabad and Hyderabad reveals that collapse in "zero intensity" shaking is not uncommon. Almost on an annual basis a building collapses in Karachi killing or injuring occupants. After 21 were killed in August 2011 the Sindh Building Authority indicated that they had issued notices to occupants to leave 200 buildings considered in a dangerous condition. Despite warnings occupants rarely emptied the buildings, and in 2013 Karachi witnessed the spontaneous collapse of buildings in January, April and August.

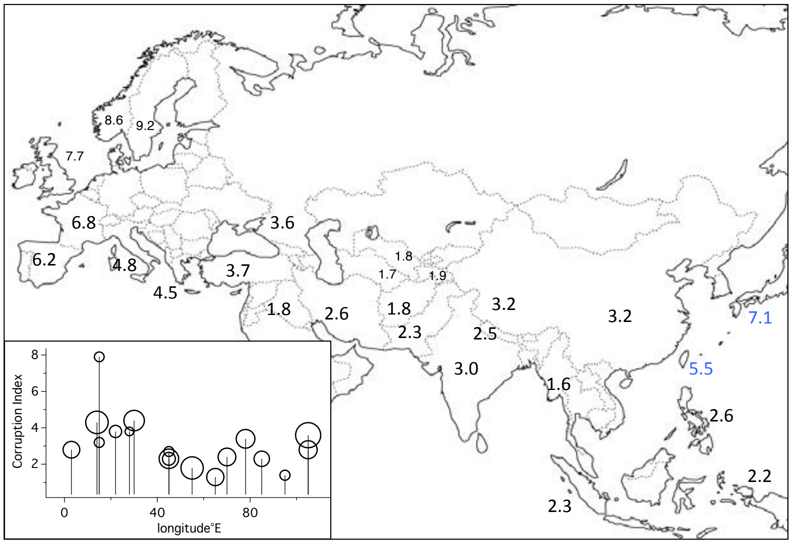

Fig. 9. Perceived Corruption Index since 2002-2012 declines eastward along the Alpine Himalayan collision zone to low values between Iran and Mynamar. Ten is not corrupt (transparent with no bribes) and 1 is very corrupt (opaque with rampant bribery). Inset shows a weak relationship between corruption index and cumulative fatalites (circle size is proportional to log cumulative earthquake deaths since 1900).

Wealth, Ignorance and corruption: An essential feature of civic institutions in cities with moderate population density is the presence of an engineering/planning facility responsible for ensuring the wise design of city infrastructure and the safe assembly of public structures and private dwellings. The collapse of buildings due to shoddy construction thus speaks to a breakdown in the responsibilities of these planning departments. To varying degrees the fragility of construction methods in a city is related to disfunction in the inspection process and Ambraseys and Bilham (2010) hypothesize that this weakness is in part related to the prevalence of corruption in a country (Figure 9). Corruption statistics (CPI= Corruption Perception Index) are taken from Transparency International (2013). The association is not simple because corruption, income levels and education are to some degree related to each other. But although poor countries are generally more corrupt than rich countries, , some countries are more corrupt than others with similar income levels, and this has been quantified numerically as an *expectation index*. The striking conclusion is that more than 80% of global earthquake fatalities have occurred in nations that are more corrupt than predicated by their level of poverty (Figure 10). The difficulties associated with examining the intertwined global statistics of corruption and poverty are addressed by Asquer(2011).

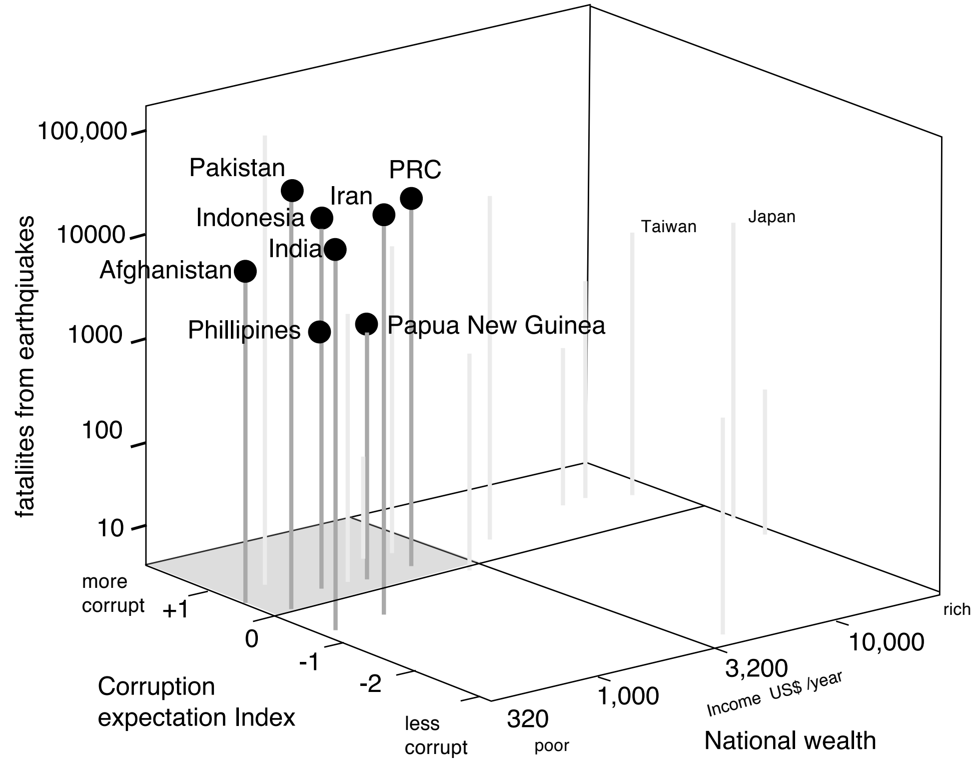

Fig. 10. Global deaths from earthquakes as a function of national wealth and corruption expectation index. Selected Asian countries are highlighted with bold circles. The expection index is a measure of the observed corruption perception index (CPI) above or below the mean CPI anticipated from a nation's average income level (see Ambraseys and Bilham, 2010). Of the 20 countries in this plot, one third lie in south Asia. The grey area on the NW side of the base of this 3-D plot indicates low average-income countries with higher than expected levels of perceived corruption, where more than 80% of all deaths from earthquakes have occurred in the past century.

Corruption and its many forms in the building Industry: The ≈$10 trillion per year building industry is the most lucrative component of the global economy: roads, dams, bridges, civic structures, schools and housing. The basic ingredients of construction concern real-estate, steel and cement. Their manipulation requires the participation and skillfull organisation of numerous engineering trades: architects, civil engineers, demolition experts, excavation and soil engineers, transport planners, assembly contractors, water and waste engineering, electrical distribution and public safety.

The enormity of the funds available and the complexities of completing construction projects over periods of several months offer many opportunites for dishonest elements of the building industry to participate and to maximize profits where possible. The most common form of dishonest practice is to use substandard materials and or assembly methods, and to conceal these shortcuts invisibly within the structure. The term *cover-up* originates in the building industry. At few points during the incremental progression from planning, to foundation, to structure, and to a final coat of paint, are retroactive tests of structural integrity possible, hence in the industrial nations a rigid sequence of building inspections has been introduced.

It is important to distinguish between engineered and non-engineered construction. Engineered construction includes the official construction of civic structures and major buildings that require architectural and engineering design and are subject to mandatory supervision by experts during assembly. In contrast, non-engineered construction applies to buildings that are assembled by contractors and home-owners without supervision by engineers. Many dwelling units in the large cities of south Asia are non-engineered structures. Both forms or construction are nominally subject to inspection, and both forms of construction are, or should be, required to adhere to local earthquake resistant construction guidelines.

Although it is self-evident that earthquake resistance will be considered essential by an engineer aware of local code requirements, a rural contractor may be unaware of earthquake resistant codes, or may consider them irrelevant unless an earthquake has occurred recently nearby. A city building inspector will expect adherence to earthquake resistant codes, but a rural building inspector, even when aware of earthquake resistant codes, may judge them inappropriate especially when persuaded by visible hardship, or a small payment to turn a blind eye to their absence.

The circumvention of inspections during the construction process is the most common form of corruption in the building industry in south Asia (Bilham, 2009; 2012). Permits are required to initiate construction and the issuance of these permits can often be influenced by bribes. Code avoidance can occur at the planning stage (construction in environmentally protected land), at the foundation level (inappropriate location in regions of unstable ground), at the design stage (avoidance of earthquake resistant elements), in the construction stage (avoidance of appropriate materials or incorporation of substandard assembly practices), and at the final approval stage (ignoring known non-compliant elements in the building). Each of these corrupt practices enhanced construction profits for the builder, and income for the inspectors who accepted these bribes.

A substantial number of structures are assembled without any kind of planning or construction oversight by user/owners, some on illegally occupied lots. Once built the structure becomes part of the landscape and other illegal structures follow in time encroaching on contiguous areas. Occasionally authorities will react and demolish such structures, but all too often they remain and become part of a city's building stock. A remarkable example of corrected encroachment recently occurred in Kathmandu when authorities ordered all buildings encroaching on main throughfares to be truncated at their legal lot lines. The truncated buildings exposed half rooms and severed hallways and were considerably weakened by the removal of shear walls, requiring substantial retrofits to retain building integrity.

7. Discussion - who gains, who loses

A curious feature of world-wide housing is that few buildings can be purchased or rented with any kind of a guarantee of their structural integrity, or resistance to shaking, yet it would be unthinkable to purchase a motor vehicle that did not adhere to the most stringent safety criteria. While this is unlikely to change in the foreseeable future, earthquake risks remain a societal problem that can be managed only by the resolve of the State. The collapse of hundreds of schools in the 2005 Pakistan earthquake, for example, reveals that the State itself may be unaware of its responsibilities for code awareness and enforcement. Home-owners and apartment-renters are not seismologists, nor are city planners, contractors, developers and engineers intrinsically aware of earthquake risks. In the absence of a recent earthquake, knowledge that buildings must be assembled to resist occasional strong shaking must come from the collective wisdom of a small group of historians, geologists and seismologists familiar with the geological structure and seismic history of a region. Knowledge of these earthquake hazards must be transferred to, and acted on, by the State if it is to effectively reduce earthquake risk to its citizens. Numerous societal impediments, however, act to prevent the successful application of this knowledge (Bilham, 2009). Seismologists are adept at describing hazard and at quantifying risk, but are ill equipped to see the conversion of quantified risk to safe housing. The "unkindest cut of all" is the circumvention of the collective knowledge of seismology, engineering and state laws during the assembly of a structure by an ignorant or corrupt contractor (Bilham, 2012).

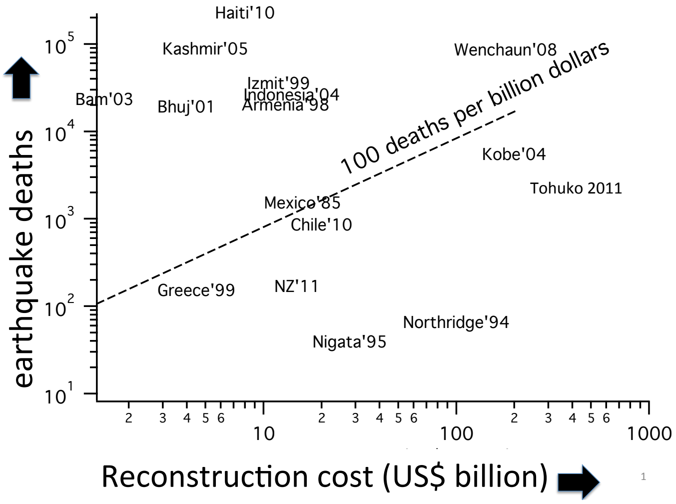

Fig. 11 Dollar losses vs. fatality counts in recent earthquakes

The cost of earthquakes to society is considerable. In recent earthquakes the costs of reconstruction have exceeded $500 billion in the industrial nations and deaths have exceeded 0.5 million in the developing nations (Figure 11). A line approximately divides the poor nations from the industrial nations with a slope of 100 deaths per million dollars. *Transparency International* has estimated that the cost of corruption in the building industry results in worldwide construction costing the public 15% more than it would were corruption absent. Engineers indicate that the incorporation of earthquake resistance to a building may add less than an additional 10% to its total cost. Global earthquake resistance would appear to be less expensive than the costs to society of corruption.

The doubling and redoubling of SE Asia building inventories in the past four decades represents a lost opportunity to construct safer cities. Instead the building boom was undertaken at minimal cost, leaving many cities intrinsically fragile. Construction was undertaken largely with indifference to earthquake resistance, and in many cases without construction code adherence of any kind. The true state of building fragility in a region is often revealed only during earthquakes, and numerous examples have occurred in the past decade to remind us that deaths in urban earthquakes can exceed 12% of an urban population. Clearly this state of affairs should not continue, but it is unlikely to change if the disconnect between earthquake hazards/risks and safe construction is not firmly addressed. In many countries national earthquake resistant codes exist, but their implementation is applied without rigour. The challenge for future seismologists and engineers, is perceived to be one of education: to educate the State of the certainty of future earthquake disasters given current policies, and to educate the public that construction short-cuts by contractors who assemble their dwellings are unacceptable.

Several mechanisms are available to politicians and developers who are willing to place progress ahead of considerations of safety. In the case of the Tehri Dam, disagreements among scientists with different views were exploited to demonstrate a lack of consensus, and to select a result favorable to government designs (Gaur and Valdiya, 1993). In the case of the Jaitapur nuclear power plant investigation, and estimates of Mmax for Kashmir, it was considered necessary for the Indian Government to banish from India the US coauthor of studies attempting to quantify these hazards (Bagla, 2012). A trickle-down effect also exists that goes far beyond initial conflicts of interest. Once a scientific study has been touched by political controversy, young scientists are discouraged from investigating the issues raised for fear of government reprisals in the form of restrictions in future research funding, or threats to job security and future promotion.

8. Conclusions

The implementation of earthquake resistant construction in south Asia depends not only on the objective evaluation of the history and probable future of earthquakes in the region, but also on the transfer of this knowledge to an appropriate user community. The seismic history of India's plate boundaries are incomplete, but in some locations they are adequate to form probabilistic estimates of future risk for regions of high seismic productivity in India, Pakistan, Bangladesh, Nepal, Bhutan and Myanmar. In contrast, the short historical record of intraplate earthquakes renders the characterisation of seismicity in central and southern India very uncertain. The probability of supplementing the written historical record is low everywhere, but there remains hope that paleoseismic studies of surface faults will extend the record of major earthquakes back several thousands of years along plate boundaries, continental margins, and in the interior of the plate.

The development of a reliable historical data base and from it estimates of seismic risk and regional code guidelines is considered insufficient to guarantee that building codes are applied ubiquitously to civic and private structures. Corrupt practices prevail throughout the building industry that can prevent engineered structures from performing according to design. Where private dwellings are assembled by contractors, a mix of corrupt practices and ignorance can lead to structures that are unsafe even without earthquake shaking.

Despite competence in the geophysical and engineering communities of south Asia, numerous societal pressures are at work in India that in the past have tended to downplay seismic hazards. Instead of seen as a necessary prelude to safe engineering design, studies of seismic hazards are often perceived to constitute a threat to progress, with the potential to delay or cancel plans for major engineering works. It is almost impossible to believe that any public organization would justify attempting to influence objective assessments of seismic hazards, but circumstantial evidence demonstrate that this indeed occurs. Political influence of the scientific method is a form of high level corruption.

Various forms of aggravated seismic risk are identified. Seismic risk is high in many locations in south Asia due to large populations located on the wide collision zone that follows the southern margin of the EuroAsian plate. Political pressures to bias seismic hazards to a level favorable for inexpensive construction of major engineering works, do not reduce seismic risk. Instead, they aggravate the potential for future disaster. Whereas the development of building code guidelines based on seismic hazard mapping is successful where seismic productivity is high, largely because the historical data base is short in south Asia and is best sampled where earthquake recurrence intervals are short. In other regions, building code guidelines are likely to be misleading because maps of seismic hazard reflect recent earthquakes, which may not at all be where future earthquakes will occur. Earthquake zoning maps in some mid continent regions may aggravate seismic risk, since they lull design engineers into a false sense of seismic stability. Finally, and perhaps most importantly, the combined efforts of seismologists, historians and engineers to implement safe dwellings and civic structures to protect future societies from harm in earthquakes, may be failing to reach those most in need of this protection - in the low cost housing in villages and cities in south Asia where more than two billion people live.

Acknowledgments

The research was funded by NSF EAR 0739081. Its findings are trhe results of discussions with numerous colleagues in Pakistan, Iran, India Nepal, Bhutan and Bangladesh.

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