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From global seismotectonics to global seismic hazard

Robert Muir-Wood
BEQE, Newbridge House, Clapton, Glos, U.K.

Abstract

The concept of globally consistent seismic hazard has two central and inter-related problems: first in achieving a uniform hazard methodology, and second in ensuring that there is consistency in the availability and use of seismotectonic knowledge. Seismotectonics and seizmic hazard are two parallel «worlds» that do not simply correspond. Seismotectonics concerns the science of earthquake origins. Seismic hazard is a set of judgements made about earthquake recurrence and earthquake ground motion based on the available seismotectonic knowledge. The two worlds comprise different philosophies, different concepts and different terminologies. This paper reviews the key elements of seismotectonic understanding and presents a rational way in which seismotectonic data can be transformed into a seismic source model. Seismotectonic audits are proposed to allow the knowledge base to be assessed and graded, thereby providing confidence limits on the resultant hazard maps. As hazard modelling is determined by the state of seismotectonic knowledge no single hazard methodology can be universal.

1. Introduction

In 1846 a young Irish civil engineer, Robert Mallet, set out to create a science of earthquakes for which he coined the name «seismology» (Mallet, 1848). He designed the first seismographic recorder, performed experiments in seismic resistant architecture and the propagation of seismic waves, undertook the first scientific field-study of the nature and distribution of damage in a major earthquake and created the first world map of earthquake effects (Muir-Wood, 1988). He also explored the causes of earthquakes to try to understand their locations. Robert Mallet was motivated by a desire to employ scientific means to lessen human suffering in earthquakes. Ever since the work of Robert Mallet, the determination of future earthquake effects has involved a creative tension between two fields of endeavour: mapping the effects of past earthquakes and constructing a scientific theory to explain their origins.

The first attempt at constructing earthquake zoning maps was initiated in the Soviet Union by the Moscow Institute of Physics of the Earth in 1937. More detailed maps were prepared in 1957 and incorporated into a building code (Lomnitz, 1974). Regulatory zoning was subsequently updated in maps published in 1968 and 1978, with the hazard indicated in terms of the peak intensity to be expected over some unspecified time-period. These maps gained the status of official documents of the state, and the mapped hazard-level became employed for all aspects of seismic design, including design of nuclear power plants. In 1976 the credibility of this map became tested when a magnitude 7 earthquake at Gazli in Uzbekhistan produced intensity IX where the map showed a maximum intensity V to VI. Architects continued to believe the earthquake was a fluke and the buildings were reconstructed to the old codes before being destroyed once again by another intensity IX earthquake in 1984. Finally on December 7th 1988, the town of Spitak in Armenia was destroyed by an earthquake reaching MSK intensity X, where the map showed only intensity VIII.

The state had decreed one thing and the earth did not obey. The state was shown to be fallible. The popular response to this failure of the central authorities, led to the closure of the nuclear power station in Medzamor, Armenia and the ending of construction on another nuclear complex in the Crimea, where the authority of the map was also being challenged from palaeoseismic observations (Muir-Wood, 1989). Earthquakes had provided one of the several contributory factors that undermined the authority of the old Soviet Union and led to its disintegration.

The Soviet Union had been caught out, not because it was irresponsible with respect to its understanding of seismic hazard but because it is so big: the largest country in the world, one sixth of the Earth's land surface. Many other countries continue to define their seismic hazard on the basis of a few hundred years of historical observation in an identical fashion to that of the USSR. It is no more than a matter of probabilities, with respect to their relative land areas, that a large earthquake has not already arrived in an «unexpected location» in Western Europe. In 1985 the world's second largest country, Canada, experienced earthquakes almost one magnitude grade higher than were shown on the contemporary seismic zonation map, although fortunately in a remote and unpopulated area of the North West Territories (Wetmiller *et al.*, 1988). These are salutary reminders of the frailty of the decisions made in seismic zonation. How can one make seismic hazard maps that are not to be torn up at the next unforeseen earthquake? How can one make seismic hazard maps that through oversight could be held to be responsible for the deaths of future citizens?

2. The generations of seismic hazard

One can trace the evolution of seismic hazard in the form of a series of five methodological generations.

a) *Historical determinism.* The first generation of seismic hazard involved mapping the maximum intensity of earthquake effects recorded in the known historical period. These were assumed to represent the highest intensity to be expected in the future. The method was very simple, took no account of the duration or completeness of the historical record, and required no knowledge of earthquake causes. «Modified» first generation hazard, as employed for critical facilities, involved adding some «ad hoc» factor to the mapped intensity (typically one or two intensity grades) to obtain a more extreme hazard.

b) *Historical probabilism.* The second generation of hazard took the historical record of seismicity and considered it in terms of its duration to achieve some kind of annual probability of the recurrence of earthquake effects. This could be the annual probability of exceeding an intensity, or some other ground motion parameter calibrated with intensity. The annual probability of more extreme effects is simply extrapolated. Modified second generation hazard employs some conversion to translate historical earthquakes into magnitudes and then, through the use of an attenuation relationship, computes the recurrence of some magnitude-distance related ground motion parameter within a simple seismic source model. Many seismic hazard cultures remain at this stage.

c) *Seismotectonic probabilism.* Third generation seismic hazard recognizes the danger of relying solely on the historical record of past earthquakes and incorporates geological evidence, including the prehistoric record of palaeoseismic ground motion and neotectonic surface faulting, as well as the scientific seismotectonic understanding of earthquake causes. These different data sources can only be combined through a seismic source model. In recognition of the uncertainty and judgement involved in determining the input parameters of such a model, all parameters are assigned in the form of a weighted range of values, through a logic tree.

d) *Non-Poissonian probabilism.* Fourth generation hazard is time-dependent. The more that is learnt about earthquake recurrence the more it becomes clear that major earthquakes are not located randomly in time. The occurrence of any major earthquake will affect the likelihood of other events in its vicinity and in particular the repeat of the same event. Time-dependent hazard models have been explored in a number of the most seismically active regions. The hazard has to be computed through the use of fully probabilistic seismic source models employing non-Poissonian earthquake recurrence. As seismotectonic knowledge increases, non-Poissonian hazard models will become employed in medium and even low-seismicity areas. Initially concerned with time-dependence, such models are now evolving towards the full spatio-temporal properties of earthquake activity.

e) *Earthquake prediction.* Fifth generation hazard is earthquake prediction. Where sufficient knowledge is accumulated to indicate that an earthquake is imminent the concept of seismic hazard enters a new phase — concentrating on the probability of constraining the time of the earthquake, as well as its size and location.

These hazard generations blur into one another. Different regions of the world exist in different generations of hazard. Some countries have become stuck in first generation hazard for political reasons, others because there has never been the initiative or funding to attempt anything better. A number of researchers in plate boundary regions are strongly involved in developing and implementing fourth generation time-dependent hazard models (see for example Working Group on California Earthquake Probabilities, 1990).

These hazard generations can make profound differences to seismic hazard estimates. One can follow their implications for hazard by comparing two cities lying above subduction zones: Valdivia in Southern Chile, and Portland, Oregon. The city of Valdivia has been destroyed four times (1575, 1737, 1837 and 1960) by major plate boundary earthquakes since it was founded by the Spanish in the mid 16th century (Lomnitz, 1975). In contrast the city of Portland has suffered no serious earthquake damage since it was founded in the mid 19th century.

Second generation hazard assigns a very high hazard to Valdivia and a very low hazard to Portland (see fig. 1). On reaching third generation hazard the subduction zone setting of Portland, and the evidence for major coseismic land-level changes and tsunami sand deposits along the neighbouring coast, indicate that the hazard is much higher than is suggested by historical seismicity alone (Atwater, 1987). However this averaged hazard remains below that of Valdivia as the Cascadian convergence between the Juan da Fuca and North American plates is slower than that between the Nazca and South American plates, and the recurrence of major earthquakes appears to be 400-600 years in Cascadia, in contrast to 100-200 years in Southern Chile. However on reaching fourth generation hazard, the position becomes reversed: the last major subduction zone earthquake in Valdivia was in 1960, while on the Washington State coast to the west of Portland it was around 1690 (Heaton, 1990). Hence the seismic cycle in the region of Portland is becoming mature; that close to Valdivia is very immature.

Any attempt to achieve a global seismic hazard programme has to attempt to bring all regions up to a third generation hazard culture. However for some regions of the world it may prove impossible to move beyond second generation hazard while at a number of plate boundaries the hazard culture has already moved into the fourth generation, from which it cannot be returned. For the mid 1990s global seismic hazard has inevitably to be a mixture of third and fourth generation philosophies. Hazard methodology is defined by the state of seismotectonic knowledge. Hence it is not possible to employ a single uniform model of earthquake hazard globally. Fifth generation earthquake prediction hazard remains a much debated drawing-board research programme that is taking a long time to fly.

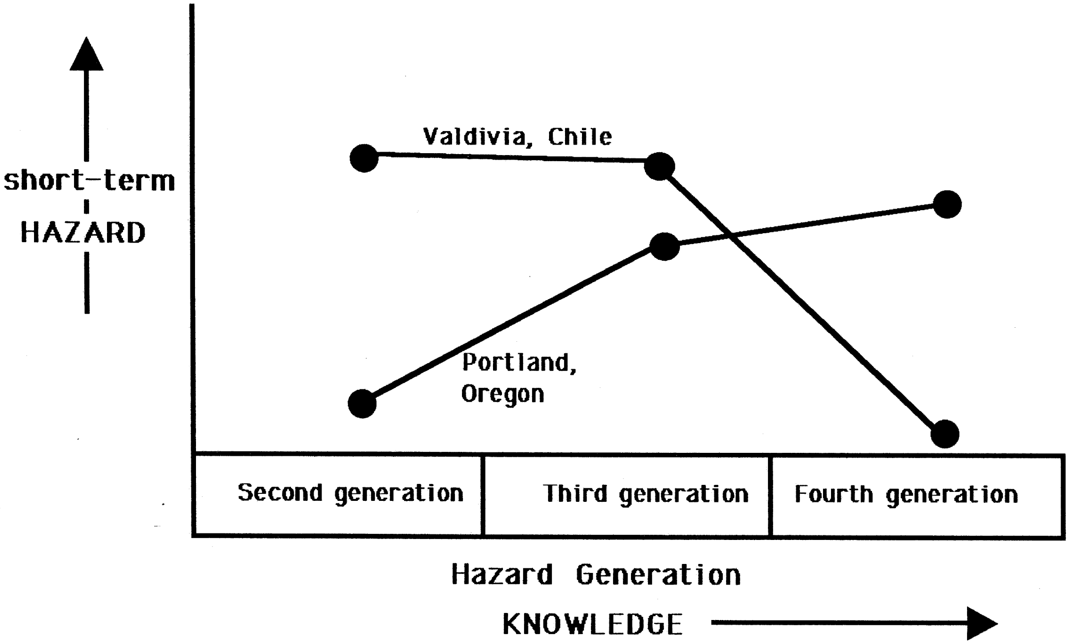

Fig. 1. Variation in short-term seismic hazard vs. hazard generation.

3. The science of seismotectonics

Seismotectonics (defined here as the science of earthquake origins) has developed as a result of empirical observation, theoretical understanding and modelling. Earthquake phenomenology: scientific investigations in the aftermath of major earthquakes provide some of the most important components of this understanding. Good summaries of seismotectonic science are to be found in Scholz (1990) and Wallace (1986). We can try to reduce this knowledge and experience from neotectonics, active fault investigations and historical and instrumental seismology into some simple principles relevant to hazard.

— The very large majority of earthquakes are generated by the rupture of faults: planar breakages in the rock. This is demonstrated from waveform studies of energy release, focal mechanism studies, and for a small proportion of events: surface fault rupture. Hence the study of earthquake hazard is the study of the potential for fault rupture. This allows geological and seismological evidence to be combined to obtain an overall understanding of earthquake generation.

— Displacement to length ratios of long-lasting faults are typically in the range 10^{-2}-10^{-3} (Walsh and Watterson, 1988) whereas displacement to length ratios of individual fault rupture events are in a range typically of 10^{-4}-10^{-5}. Hence faults must undergo repeated displacement events. This simple observation provides the justification that history offers an insight into the potential for earthquakes in the future.

— Many faults that show recent displacement also reveal one or more episodes of past displacement within the past few thousands or tens of thousands of years. Other faults can be shown to have undergone no displacement in the past few millions of years having been the locus for crystal failure at earlier periods. This strongly suggests that certain «currently sensitive» faults repeatedly fail, as the shear-strain in the surrounding crust reaches some critical value.

— Many faults do not break surface and can only be seen from boreholes, geophysical evidence, or from distributed surface deformation. In particular reverse faults are prone to show no fault rupture even at magnitudes of 7 (Muir-Wood, 1984) and even some continental normal fault earthquakes have shown no surface fault rupture at such magnitudes (Valensise and Pantosti, 1992). Subduction zones comprise a range of hidden earthquake sources, either along the shallow dipping plate boundary interface, or within the downgoing slab (Byrne *et al.*, 1988). Hence there are very significant differences from one tectonic setting to another, in the potential for a geological exploration of earthquake recurrence, the most optimal settings being zones of active rifting.

— Crustal deformation is chiefly driven by mantle convection. The top of the convection cells forms the oceanic lithosphere and the forces associated with upwelling at spreading ridges, sinking at subduction zones, and subplate traction, play the chief role in regional deformation. These driving mechanisms have very long time-constants. A consistent set of boundary forces implies a repeated pattern of fault movements. There is expected to be a fairly simple relationship between the regional rate of deformation (where it is known) and the recurrence interval of major displacement events along faults (Gilbert, 1909).

— Earthquakes involve the release of shear strain accumulated by regional deformation in the surrounding rockmass. Hence large earthquakes are expected to affect the accumulation of shear strain on other neighbouring faults. The occurrence of any one major earthquake will therefore influence the occurrence of any other earthquake within the same region. The «influence volume» increases with increasing earthquake size. This interdependence has important implications for models of earthquake recurrence and also for assumptions that a historical population of earthquakes (preceding or following a major earthquake) will necessarily be representative of near-future seismicity.

— The population of earthquakes within a given region shows a very simple scaling relationship or power-law known as the Gutenberg-Richter relation, typical of fractal sets. The activity rate (*a*-value) and gradient (*b*-value) of this relation show regional variations. Experiments have shown that the *b*-value varies according to the degree of heterogeneity in the rockmass, and also that a decrease in *b*-value accompanies an increase in applied stress. A high *b*-value is found in aftershocks. A high *b*-value can also be shown to provide full three dimensional crustal deformation without requiring high magnitude earthquakes. The emergence of a power law of earthquake sizes is predicted by the general model of spatially extended dissipative systems developed by Bak *et al.* (1988), that evolves to a state of self-organized criticality.

— For some outcropping faults, typically high angle normal or reverse faults, there is good geological evidence that fault ruptures of the same approximate size have been replicated. The earthquake associated with the repeated rupture of the fault is termed «characteristic». Such situations offer confidence to the belief that the future hazard is indicated by the latest earthquakes. Characteristic models of earthquake recurrence have been proposed in which the population of large earthquakes is more frequent than would be predicted by the simple extrapolation of the magnitude frequency relation established for smaller earthquakes (Schwartz and Coppersmith, 1984). All attempts to compile geological and seismological data on earthquake recurrence are however problematic, in particular where there is evidence for non-periodic fault rupture.

— For the largest plate boundary strike-slip and subduction zone faults, there are good historical data on earthquake recurrence from regions such as Chile or Southern Honshu, where interplate fault rupture can be explored through three or more seismic cycles. Different segments of these plates have tended to rupture separately, although the rupture of one segment has often ruptured adjacent segments within the same event. Multiple block mass-spring-slider models provide useful analogues for such behaviour (Nussbaum and Ruina, 1987). Areas not broken in a previous rupture are likely to be more prone to rupture the next time round. This understanding has important implications for hazard modelling. While the concept of some quasi-periodic recurrence of major earthquake occurrence is supported, the next plate boundary fault rupture is likely to be very different in size and extent to the latest event. In such plate boundary settings seismic hazard cannot simply be represented by considering a recurrence of the latest earthquake.

— Away from subduction zones a simple relationship can be established between the maximum depth of earthquakes and the temperature gradient, both in continental and oceanic crust (Chen and Molnar, 1984). Beneath some limiting depth rocks will behave plastically in response to applied stress. Above that depth brittle deformation and fault rupture will dominate. The difference in the dominant mineralogy of the crust (quartz-feldspar) and mantle (olivine) means that in areas of low heatflow the brittle-plastic transition zone may be encountered twice in passing through the lithosphere leading to two distinct depth ranges of earthquakes (Kusznir and Park, 1987). Earthquake size shows a relatively simple dependence on rupture area and therefore the largest earthquakes occur where a fault extends for the greatest area within the brittle crustal regime. Such faults are close to horizontal and are found along the shallow plate-boundary interface in a subduction zone. Deep earthquakes (>100 km) are only found in association with subduction zones.

— One can consider three potential physical constraints on the limiting size of earthquakes within a region. The first is the restriction imposed by the largest size of available, suitably oriented, fractures. This might suggest that largest earthquake sizes will be reduced in any region involved in a completely new deformation state. However as some fault ruptures have demonstrably jumped from one fracture plane to another and may rupture through sections of previously unfaulted material, this constraint does not appear very reliable. The second constraint is provided by the volume over which the deformation field is coherent. This in turn may be influenced by topography, changes in the rheological behaviour of different crustal units, etc. Thirdly, along transcurrent or subduction zone plate boundaries, there may be some limiting aspect ratio of rupture length to width. This in turn will be controlled by the style of faulting and the temperature gradient. However on such plate boundary megafaults it is difficult to be confident that fault ruptures could not extend the full length of the San Andreas Fault, or the full length of the Andean subduction zone, in the very rare circumstance that interseismic deformation had reached a similar stage of maturity along the full length of the boundary.

— Plate tectonics is a theory of earthquake geography. Earthquakes tend to concentrate in narrow corridors along plate boundaries involving oceanic crust although continental plate boundaries tend to be broad and diffuse. A small proportion of deformation is also accommodated internally within plates. There is no entirely effective terminology for determining and classing different tectonic provinces according to their deformation rate. A project to construct a series of *World Strain Maps* would achieve many of the principal scientific objectives of a global seismic hazard initiative. Strain-rates would have to be defined over a range of distance scales and time-periods. The detail of the map would gradually resolve itself through time, and fundamental differences between geodetically determined strain-rates, geological strain-rates and seismic strain-rates would be revealed.

— Not all earthquakes are a response to tectonic deformation. Earthquakes have been induced both by changing vertical stresses, and increasing pore-fluid pressures, in processes such as oil-field secondary recovery, mining, reservoir impounding, etc. The most important and largest scale non-tectonic causes of crustal strain and modifications of the stress-state are associated with ice-sheet loading and unloading. Observations of vertical rates of land-level changes and models of rebound show that in North America and Northern Europe, even far beyond the limits of the ice-sheets, crustal deformation continues to be influenced by the movement of the underlying mantle material back into the former centre of the ice-load (Gasparini *et al.*, 1991). Hence in all these regions the current strain-state and crustal seismotectonics are likely to be affected by postglacial recovery.

4. Grades and sets

In order to translate diverse sources of seismotectonic information on past earthquakes and fault displacements into a form suitable to be employed in seismic source models for seismic hazard, it is necessary to develop formal procedures for the treatment of uncertainties and incompleteness. An earthquake catalogue is simply a collection of surviving observations that cannot be utilized statistically without some treatment of completeness thresholds. Similarly a geological or neotectonic fault map is inevitably an incomplete and partial interpolation of available data. In order to employ all these different types of imperfect data sources it is necessary to develop procedures to handle all forms of seismotectonic data in terms of «grades» and «sets» (Seismic Hazard Working Party, 1988).

4.1. *Grading*

Grading concerns the exploration and ranking of uncertainty. All forms of data and all parameters are assigned a quality grade, ranked according to some scale of uncertainty. This is first applied to all forms of primary data such as an intensity assessment, the location of an earthquake, its depth and its magnitude. As data become assembled, so the quality ranking of each parameter travels with the data. For example if an earthquake has a level of uncertainty of its hypocentral location beyond some limit then no attempt is made to attribute it to a mapped fault, because the uncertainty of such attribution would be too great.

Grading can also be applied to geological data. For example in Western Europe, many publications claiming neotectonics are partial and incomplete. A scarp has been observed or some unexplained sedimentary deposit encountered in a borehole and this has then been published as a claimed instance of neotectonics. However very often a fault offset has not been observed and a superficial explanation cannot be discounted. Such claims can be graded according to a set of criteria as to how likely the observation is to reflect neotectonics. Only credible claims should be employed in a regional seismotectonic analysis.

As data with different grades is collated so the grading continues to affect the distribution of specific parameters within the whole population. The grading finally becomes employed for assigning weights within the logic tree of a seismic source model as a measure of uncertainty.

4.2. *Setting*

Setting concerns assigning thresholds of completeness to any data-set. For all statistical analysis only sets of data can be employed that over some time-period and above some threshold are demonstrated to be complete.

For historical seismicity, thresholds of catalogue completeness should be derived from historiography: the study of how historical information is recorded and preserved. For instrumental observations historiography involves the exploration of noise levels, station spacings and interruptions in recording. Alternative «internal» explorations of temporal variations in the population of events of different sizes can provide an internal check on observational completeness but inevitably have to assume some constant rate of seismicity that may not be valid. There are very profound variations in the duration of the historical record of significant earthquakes around the world (fig. 2) as well as the threshold of catalogue completeness through history (fig. 3).

Geo-historiography, the study of how geological evidence is recorded and preserved, provides an opportunity to explore the time-periods and degree to which the geological record of palaeoseismicity, or faulting, can be considered complete (relative to the severity of ground motion or the dimensions of surface

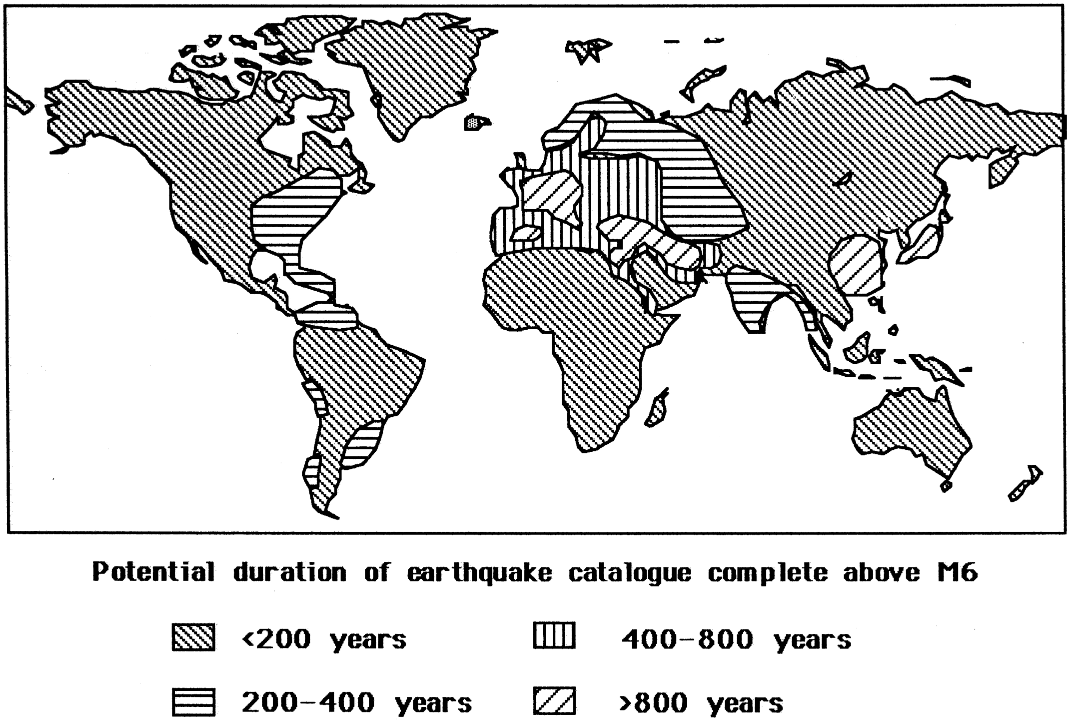

Fig. 2. Schematic world map of the duration of historical record of earthquakes in excess of magnitude 6.

fault rupture). Such completeness thresholds may be far higher than is generally assumed. For example the two largest recent surface fault scarps so far discovered in Northern Europe and Eastern North America: the 26 km long, 5 m high Meers Fault scarp in Oklahoma, and the 165 km long, 12 m high, Parvie Fault scarp in Northern Sweden were both discovered serendipitously in regions that had already been intensively mapped several decades previously without the scarps being noted (Gilbert, 1983; Lundquist and Lagerback, 1976). A map showing the potential extent of the neotectonic record of observations is shown for the British region in fig. 4. On the margins of the former Pleistocene ice-sheets the variations in the duration of the potential record of surface faulting and palaeoseismicity span more than two orders of magnitude: a far greater range of observations than is ever encountered in regional variations in the historical record of earthquakes.

4.3. *The knowledge base*

Different regions of the world have very different seismotectonic «knowledge bases». This knowledge base can be reduced to a very simple factor: the duration of the record of past earthquakes divided by the duration of the seismic cycle (defined as the major earthquake recurrence interval). This factor is termed **R**. The highest ratio of **R** (fig. 5) is encountered in Southern Honshu where the plate margin has ruptured six times in the historical period. In Southern Chile the plate margin has ruptured four times. Ratios in excess of 1 are also found along the North Anatolian Fault. For simplicity zones of deforma-

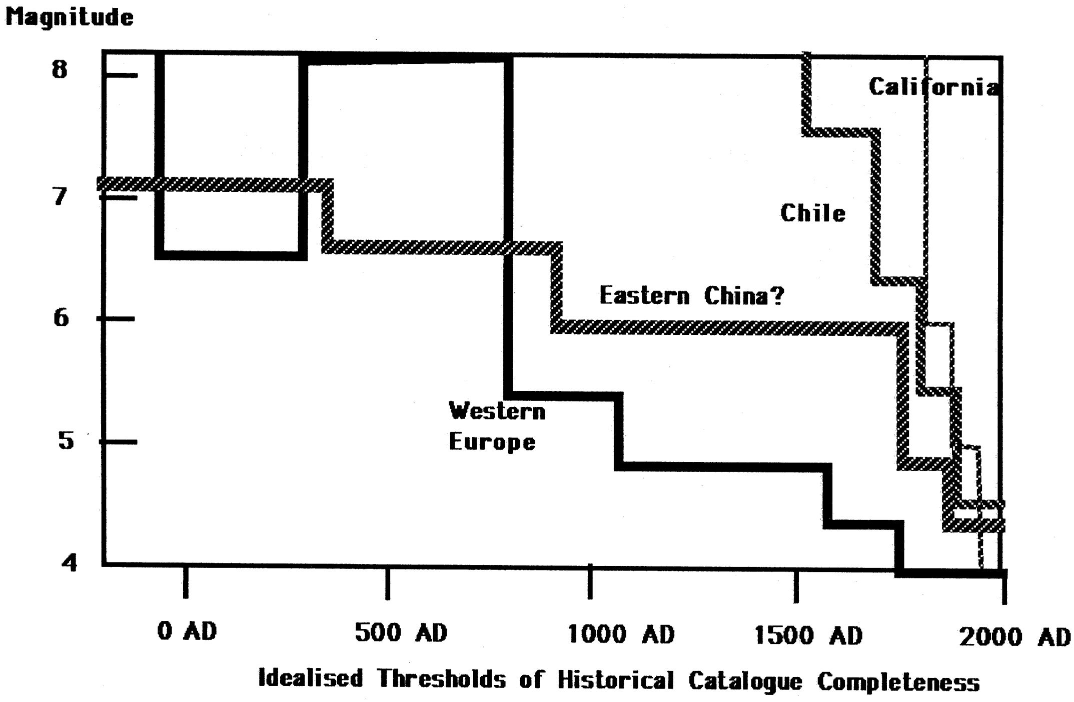

Fig. 3. Schematic thresholds of historical earthquake catalogue completeness.

tion have been divided into four categories: fast plate boundaries, slow plate boundaries, regions of rapid continental deformation and regions of slow continental deformation. For the zones of rapid rifting in Western Turkey, Greece and Italy, with a very long historical record, **R** is probably closer to 1 than for a number of slow plate boundary areas. However for the very large proportion of the world **R** is less than 1; in stable continental areas probably substantially below 0.01, as for example in Oklahoma where the Meers Fault was shown by Crone and Luza (1990) not to have ruptured over the 120 000 years prior to the 5 m displacement event that occurred about 1200 years ago. However in some areas, in particular areas of active rifting, high quality geological information on fault displacement recurrence allows the historical period to be extended into prehistory, allowing the knowledge base ratio **R** to climb above 1 again.

From fig. 5, one can see that certain regions of the world that may have little in common tectonically share similar states of the knowledge-base with respect to earthquake hazard.

Paradoxically there is no simple relationship between the value of **R** and the quality of a third generation hazard assessment as any region in which **R** approaches 1, will inevitably move towards a fourth generation, time-dependent, seismic hazard methodology.

5. The seismic source model

The creation of a seismic source model demands translating seismotectonic information into a spatial approximation of earthquake localization and recurrence (see paper McGuire: this volume). It should always be remembered that none of the elements of a seismic source model is intended as an exact representation

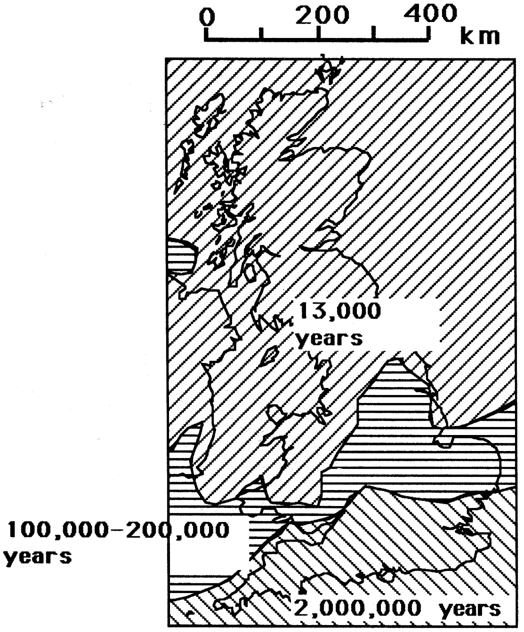

Fig. 4. Variations in the duration of the potential geological record of palaeoseismicity and surface faulting in Britain.

of reality. Instead these are construct, simplifications, chosen to reduce knowledge into a form that can readily be employed for computation. The terminology of the seismic hazard model sometimes implies a scientific meaning and this in turn leads to confusion and misunderstanding. This is particularly true of the terms «zone boundary», «maximum magnitude», «active fault» and «fault seismicity».

— Zones of uniform seismicity employed in a seismic source model are of course artificial. The choice of zone boundaries should be based on an examination of the statistical distribution of earthquakes. A boundary should only be shown where differences in the spatial density or properties of earthquakes can be demonstrated. Within any source zone it should be possible to demonstrate statistically that any further subdivision is unjustifiable. However, zonation is a primary element of expert judgement, a dialectic between the urge to lump seismic sources together and the tendency to further subdivide.

— Maximum magnitude is the term given for the upper limit truncation of the magnitude frequency distribution employed in defining a specific earthquake source. Maximum magnitude is a construct and should not be confused with some seismotectonic equivalent, such as the «largest possible earthquake». From everything that has been discovered about the physical restrictions on earthquake size and the empirical observations of plate boundary earthquake recurrence, scientifically the largest possible earthquake can probably only be defined with respect to some annual probability of occurrence. Very rare combinations of faults rupturing concurrently could conceivably create earthquakes above an assumed maximum magnitude. The term maximum magnitude itself has an implicit annual probability of exceedance.

— The term «active fault» is so familiar that most researchers assume it must have a complete scientific definition. While it is possible to have a practical definition of the scientific active fault (a fault observed to undergo rupture) «sufficient» definitions for the purpose of defining future hazard, have persistently eluded earthquake hazard regulators. In an attempt to avoid the impasse new modelling constructs such as the «capable fault» have been devised. The problem of the sufficient definition of the active fault is one of time-scales. When can a fault be defined as not active? The only non-arbitrary time-period to search for an absence of displacement is the duration of the current tectonic regime in which the fault is located and by which it is motivated (Muir-Wood and Mallard, 1991). In hazard terms an active fault is one that has more than a negligible probability of being the locus of fault-rupture in the near future. This probability («the active status weighting factor») may in turn need to be assigned a weight in the seismic source model.

— Of all the elements of the seismic source model, fault seismicity is perhaps the most unrealistic. This is because any genuine determination of the seismicity of a fault is simply a matter of attribution. Both earthquakes and faults always have some spatial uncertainty as to their precise sub-surface location. Hence the decision to consider any earthquake as forming part of a population associated with a fault involves a judgement as

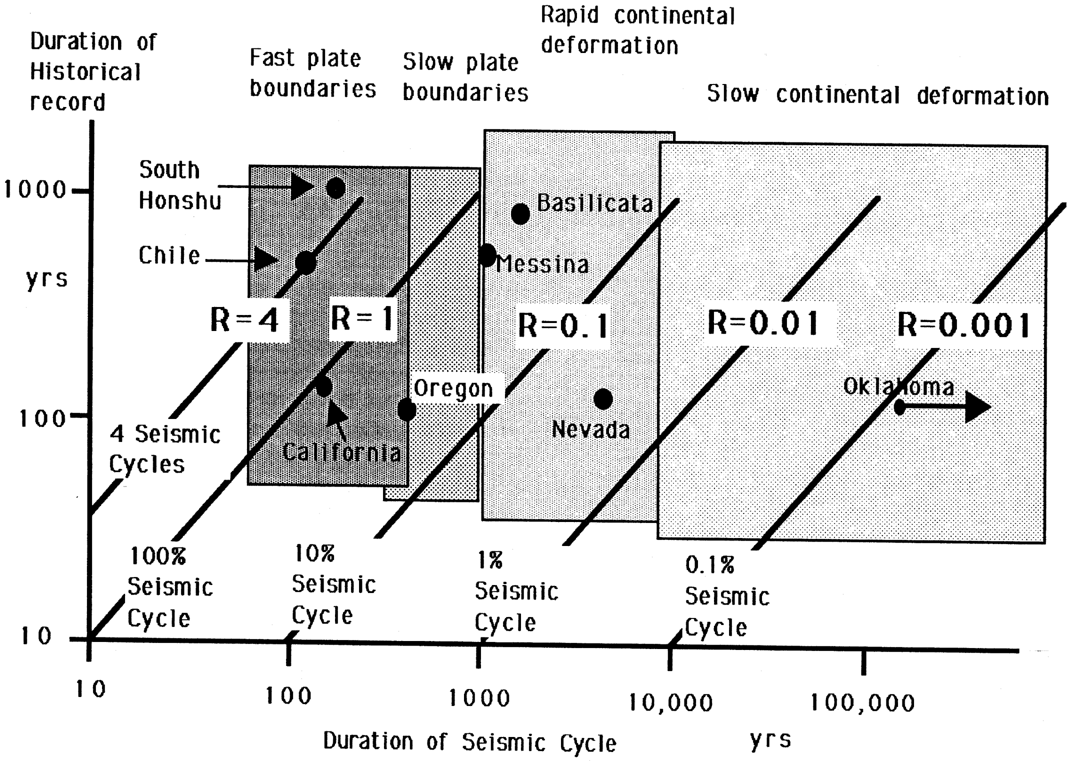

Fig. 5. The seismotectonic knowledge base defined in terms of duration of historical record of seismicity vs. duration of seismic cycle.

to what width and degree of locational uncertainty to accept. As it seems probable that most major faults rupture in characteristic earthquakes the non-characteristic seismicity that is associated with a fault may simply be seismicity that is occurring on faults in its immediate vicinity, although these in turn may owe their existence to the presence of the major structure. The so-called «fault-source» is therefore likely to be no more than a narrow zonal source centred around a fault. The *b*-value of such a source will chiefly be determined by the width or uncertainty band over which earthquakes are assumed to be assigned to the fault.

6. The exercise of judgement

Seismic hazard can be defined as the exercise of judgement concerning seismic sources, recurrence and attenuation on the basis of available knowledge. Seismic hazard is only undertaken for special social, planning or engineering objectives. All seismic hazard studies have to freeze an evolving knowledge base at the particular moment when the results are required. Hence for three fundamental reasons all seismic hazard studies are provisional and become outdated: first because knowledge increases, second because the occurrence of earthquakes physically alters the controls of future activity, and third because the fundamental philosophy of seismic hazard, its methodology and self-definition, evolves.

6.1. *The implicit time-scale of interest*

Whether explicitly stated or not, the definition of seismic hazard always includes some implicit future time-period of concern. Within fourth and fifth generation seismic hazard this time-period becomes central to the concept of hazard itself. The reason that the time-period is not more clearly stated in second or third generation hazard is because most seismic hazard is undertaken for engineering or planning decisions which share a common lifespan of perhaps 30-50 years. However there are other users of seismic hazard who will operate over very different time-scales. An insurance company sets premiums and estimates risks annually. Dams or tunnels are probably intended for a life-time of centuries, far longer than the officially stated period for the recovery of capital costs. Underground nuclear waste repositories inevitably concern a time-scale two or three orders of magnitude longer. The time-span of interest is certain to affect the results of a fourth generation hazard model but even in a third generation model, uncertainties increase the longer the time-span extends into the future.

6.2 *The politics of hazard*

As a set of judgements made on available data, seismic hazard is no different to the vast range of expert opinions that are encountered in economic modelling, environmental assessment or predictions of global change. All these worlds of expert judgement are potentially inter-related to social decisions. Seismic hazard may not itself be political in nature, but there is no natural frontier between seismic hazard and politics. In many countries planning decisions concerning critical facilities, such as nuclear power plants, have been founded on crude seismic hazard studies that may be more than twenty years old. Once made these engineering decisions not only become almost impossible to reverse but there may exist considerable personal and political inertia to obstruct a redefinition of hazard. Hence there is a paradoxical situation that seismic hazard in many developing countries (in particular in Western Europe) has been sustained in a far more primitive state than in some developing nations.

6.3. *Who should make the judgements?*

As seismic hazard has evolved, so different professionals have become involved in making the judgements. In first and second generation seismic hazard almost all the professionals involved were seismologists, initially relying on highly imperfect catalogues of historical seismicity. As long as judgements were left to seismologists alone hazard could never advance into the third generation. (There are now even parts of the world where it is possible to construct seismic hazard almost solely from geological information.) For a country or community of research seismologists that has previously achieved only a first or second generation seismic hazard methodology, participation in the third generation seismic hazard philosophy intended for GSHAP cannot be achieved without an intervening period of education and collaboration with other relevant geoscientists.

It should be the job of anyone involved in seismic hazard to pursue scientific information, to be an expert in seismotectonics, seismology, earthquake strong motion, or palaeoseismicity and to be prepared to freeze their knowledge base at the moment when some external agency demands a seismic hazard assessment to be completed. However between seismic hazard assessments (and using the funding available from seismic hazard) those involved should continually seek better data and an improved seismotectonic understanding. Seismic hazard is a continuing creative battle between engineers needing an answer and scientists pursuing research, an argument between scientific innovation and engineering conservatism.

No one country can hope to provide sufficient experience to explore the full seismotectonics of hazard. Learning is most usefully achieved through mistakes. Typically the most important advances in seismic hazard methodology follow when an earthquake occurs with a location or severity unpredicted by pre-existing hazard models. Sites of unexpected earthquakes provide the most important lesson for other regions that may share similar characteristics and where, as a result, seismic hazard is at present underestimated.

6.4 *Calibrating judgement*

It is important to calibrate the expertise involved in seismic hazard studies to explore how different individuals confronted with the same data-set choose to make decisions. An archetypal problem for such calibration concerns the presence of a single large «rogue» earthquake in the historical record of a region with only moderate seismicity.

There are four principal seismic hazard strategies that can be adopted to take account of this circumstance:

a) uniform: seismicity is considered uniform and the rogue earthquake is given an equal chance of occurring anywhere in the region;

b) rerun historical: seismic hazard is considered simply to be a re-run of history, the highest hazard is mapped where the large earthquake occurred;

c) seismic gap: on the basis that strain energy has already been relieved in the vicinity of the large earthquake, such an earthquake is given an equal weight of occurring anywhere except where it actually occurred;

d) causative: a causative explanation is offered for why the large earthquake occurred where it did (as on a particular style, orientation or intersection of faults) and comparable locations are assumed to have a similar potential for such an earthquake.

Of all these models the one that is in general most acceptable to politicians and the public is model b). It is the hallmark of a first or second generation hazard map that the locations of isolated large earthquakes show up as «bull's eyes» on the hazard map. There is even scientific investment in model b), when seismological centres become established in the vicinity of major historical earthquakes. Research funding may then become predicated on sustaining the earthquake threat at that location. Clearly model d) is most convincing if the explanation is correct, but many explanations offered for the localization of large earthquakes may be incomplete or even wrong. The choice between these hazard strategies will commonly be based on non-scientific judgement: such as personal conservatism; the regulatory perspective; implications of the result for sustaining a development, or for challenging a pre-existing hazard decision.

7. The seismotectonic audit

It is far easier to plan a uniform (even if hybrid) global approach to the computation of seismic hazard than to ensure that there is consistency in the availability and use of seismotectonic knowledge. Without such consistency global seismic hazard will not be meaningful.

One way in which to explore the depth and reliability of regional seismotectonic knowledge is to perform a *seismotectonic audit.* Such an audit can explore how much these variations depend on intrinsic differences in the facility with which such knowledge can be quarried and how much on differences in the amount of research that has so far been undertaken? The results of the audit should be used to determine the uncertainty inherent in seismic hazard estimation, the ability of those involved in making seismotectonic judgements as well as to define future research objectives.

An audit can be undertaken through the pursuit of a series of simple questions, such as:

— Has the historical catalogue of earthquakes been thoroughly re-researched and individual events re-mapped, returning to *primary* earthquake sources, employing modern (post-1970) methods of analysis?

— Have regional calibrations been established between earthquake felt areas and magnitudes to allow event sizes of historical events to be known. (Correlations attempted between peak intensity and earthquake size are inevitably suspect).

— Has a historiographic programme been undertaken to establish thresholds of catalogue completeness throughout history?

— What is the state of instrumental seismic monitoring in the region? What are the thresholds of current observational completeness?

— Has the current instrumental catalogue been analysed for errors in location, size, fake-earthquakes etc.

— What is degree to which geological deformation and earthquake sources can readily be mapped at surface outcrop?

— How intensively have active faults or fault scarps been searched for? How many of these have been investigated and dated in natural or artificial exposures?

— Is there any alternative plate tectonic, or geodetic route for assessing regional deformation-rates?

— Is there scientific consensus as to the current seismotectonic state?

— What is the level of geological analysis of recent deformation?

— How does historical seismic moment release correspond with the rate of regional deformation as estimated a) from plate boundary constructs, b) from geological evidence?

— What is the probable duration of the recurrence of major fault displacement in the region? What is the relationship between the duration of the historical record to this duration?

For any region of the world the seismotectonic knowledge can be graded as to the degree to which it fulfills certain criteria. In parts of the developing world this grading may chiefly reflect the current state of scientific research. In the developed world it will be determined by the facility with which current tectonic deformation can be resolved. For example, despite intensive investigation it is intrinsically far more difficult to identify seismic sources in a region of blind reverse faults such as Los Angeles, than among the well-exposed extensional faults of Nevada or Utah. This uncertainty should itself be shown on maps of seismic hazard.

8. Conclusions

Seismic hazard maps are always working documents, provisional judgements on future

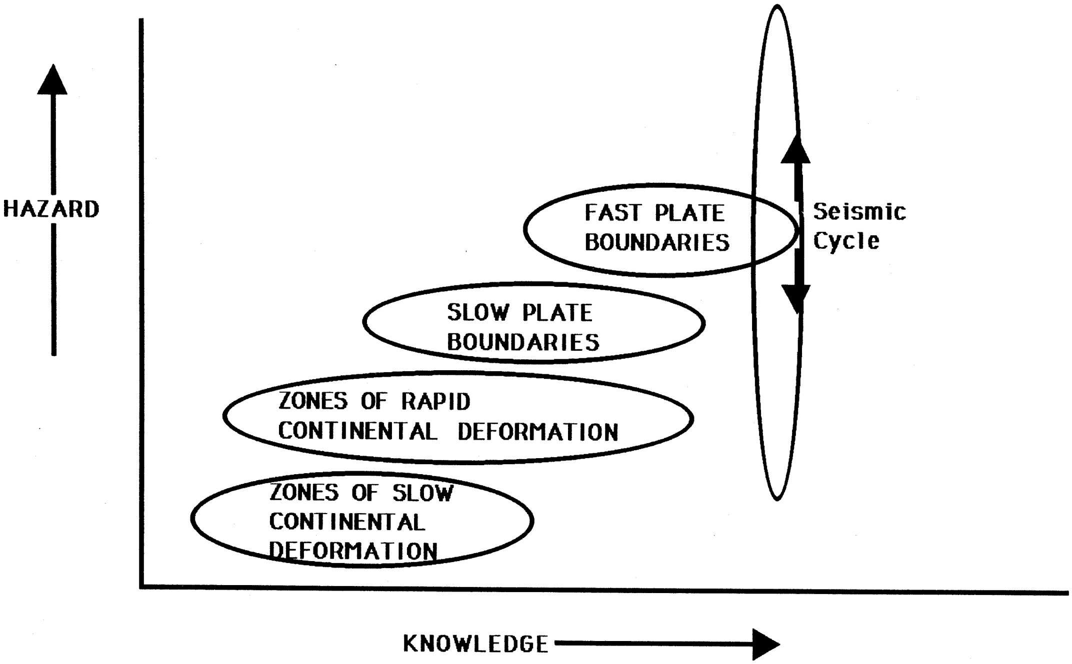

Fig. 6. Generalised relation between level of hazard and level of knowledge-base.

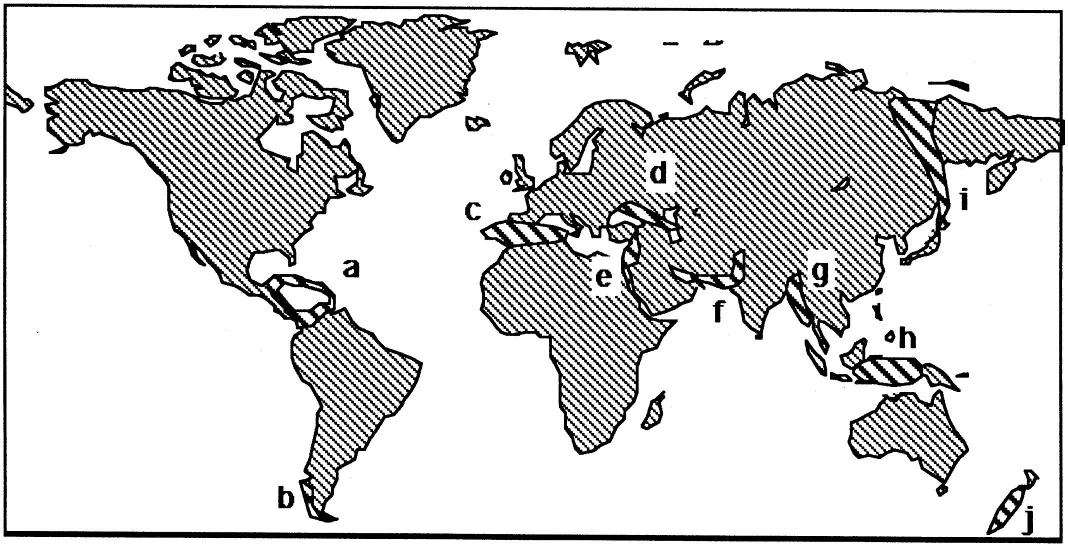

Fig. 7. Key problem areas for seismic hazard: slow plate boundaries: a) Caribbean; b) Chile south of 47S; c) Western end of Africa-Eurasia collision zone; d) Caspian- Caucasus-Black Sea; e) Syria-Lebanon-Israel; f) Pakistan and Southern Iran; g) Burma; h) Eastern Indonesia; i) Sakhalin and Eastern Siberia; j) New Zealand and Macquaries.

earthquake activity. Seismic hazard, in particular in areas of moderate or low seismicity, is inevitably based on imperfect knowledge. The level of hazard shows a general correlation with the knowledge-base (fig. 6). In fast plate boundary setting, hazard is high, but knowledge is also advanced and fourth generation time-dependent hazard models may be applicable. It is at slow plate boundaries, in particular those involving plate convergence, where earthquake recurrence cannot readily be retrieved from geological evidence that there may be relatively high hazard, but as yet poor seismotectonic knowledge. As one among a number of examples (fig. 7) in the area around the slow (4mm/yr) Africa-Eurasia collision zone, to the south and south-west of Iberia, historical seismicity probably shows little relation to near-future hazard. It is in these areas that GSHAP can hope to make the greatest contribution to improving the crude second generation hazard models that are now current, through exploring seismotectonic knowledge.

Seismic hazard maps for the USSR did not endure more than a few decades before they had become discredited by the appearance of unexpected earthquakes. From the relative area encompassed, a project to map seismic hazard for the whole world is almost inevitably going to become assailed by a major «unexpected earthquake» perhaps within a single decade. The project should prepare for this eventuality, focussing on problem areas, such as slow plate boundaries, and offering new ways to display uncertainty. The quality of a seismic hazard map is determined by the degree to which seismotectonic knowledge has been pursued. Long after the maps themselves have been superseded, future generations will judge the Global Seismic Hazard Assessment Programme by the degree to which it inspired and focussed further seismotectonic (most critically palaeoseismic) research, especially in the developing world.

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REFERENCES

Atwater, B.F. (1987): Evidence for great Holocene earthquakes along the outer coast of Washington State, *Science*, **236**, 942-944.

Bak, P., C. Tang and K. Wiesenfeld (1988): Self-organized criticality, *Phys. Rev. A.*, **38**, 364-374.

Byrne, D.E., D.M. Davis and L.R. Sykes (1988): Loci and maximum size of thrust earthquakes and the mechanics of the shallow region of subduction zones, *Tectonics*, **7**, 833-857.

Chen, W.-P. and P. Molnar (1984): Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere, *J. Geophys. Res.*, **88**, 4183-4214.

Crone, A.J. and K.V. Luza (1990): Style and timing of Holocene surface faulting on the Meers Fault, southwestern Oklahoma, *Geol., Soc. Amer. Bull*, **102**, 1-17.

Gasparini, P., R. Sabadini and D.A. Yuen (1991): Deep continental roots: the effects of lateral variations of viscosity on post-glacial rebound, in *Glacial Isostasy, Sea Level and Mantle Rheology*, edited by R. Sabadini *et al.*, Publ. Kluwer, Dordrecht, pp. 21-32.

Gilbert, G.K. (1909): Earthquake forecasts, *Science XXIX*, pp. 121-138.

Gilbert, M.C. (1983): The Meers faults of southwestern Oklahoma - Evidence for possible strong Quaternary seismicity in the midcontinent, *EOS*, **64**, 313.

Heaton, T.H. (1990): The calm before the quake?, *Nature*, **343**, 511-512.

Kusznir, N.J. and R.G. Park (1987): The extensional strength of the continental lithosphere: its dependence on geothermal gradient, and crustal composition and thickness, in *Continental Extensional Tectonics*, edited by M.P. Coward, J.F. Dewey and P.L. Hancock, Geol. Soc. Spec. Publication No. 28, London, pp. 35-52.

Lomnitz, C. (1974): Global tectonics and earthquake risk, *Developments in Geotectonics*, **5**, Elsevier, New York, pp. 320.

Lomnitz, C. (1975): Major earthquakes and tsunamis in Chile during the period 1535 to 1955, *Geologische Rundschau*, **59**, 938-960.

Lundquist, J. and R. Lagerback (1976): The Parve fault: a late-glacial fault in the Precambrian of Swedish Lapland, *Geol. Foren., i Stockholm Forhandlingar*, **98**, 45-51.

Mallet, R. (1848): On the dynamics of earthquakes: being an attempt to reduce their observed phenomena to the known laws of wave motion in solids and fluids, *Trans Roy. Ir. Acad.*, **31**, 50-106.

Muir-Wood, R. (1984): Problems of estimating earthquake recurrence from geological investigations in thrust fault terrains, in *Proc. Int. Conf. on Seismic Microzonation*, Ech Cheliff, Algeria, vol. 1, 147-159.

Muir-Wood, R., R. Mallet and J. Milne (1988): Earthquakes incorporated in Victorian Britain, *Earthquake Eng. and Struct. Dynamics*, **17**, 107-142.

Muir-Wood, R. (1989): After Armenia, *Terra Nova*, **1**, 209-212.

Muir-Wood, R. and D.J. Mallard (1991): When is a fault «extinct»? *J. Geol. Soc. London*, **149**, 251-255.

Nussbaum, J. and A. Ruina (1987): A two-degree of freedom earthquake model with static/dynamic friction, *Pageoph.*, **125**, 629-656.

Scholz, C.H. (1990): *The Mechanics of Earthquakes and Faulting*, Cambridge University Press, Cambridge.

Schwartz, D.P. and K.J. Coppersmith (1986): Seismic hazards: new trends in analysis using geologic data, in *Active Tectonics, Studies in Geophysics*, National Academy Press, Washington, pp. 215-230.

Seismic Hazard Working Party (1988): *A Review of seismic hazard assessment methods, and their adaptation for Britain*, vol. 3M CEGB, UK.

Valensise, G. and D. Pantosti (1992): A 125 Kyr-long geological record of seismic source repeatability: the Messina Straits (southern Italy) and the 1908 earthquake (Ms 7 1/2), *Terra Nova*, **4**, 472-483.

Wallace, R.E. (Chairman) (1986): *Active Tectonics, Studies in Geophysics*, National Academy Press, Washington D.C.

Walsh, J.J. and J. Watterson (1988): Analysis of the relationship between displacements and dimensions of faults, *J. Struct. Geol.*, **10**, 238-247.

Wetmiller, R.J., R.B. Horner, H.S. Hasegawa, R.G. North, M. Lamontagne, D.H. Weichert and S.G. Evans (1988): An analysis of the 1985 Nahanni earthquakes, *Bull. Seismol. Soc. Amer.*, **78**, 590-616.

Working Group on California Earthquake Probabilities (1990): *US Geol. Surv. Circ.*, **1053**.