

Geology 4 Deformation Processes option essay:

An Assessment of the Predictability of Earthquakes.

Bruce Lamond 9653742.

Introduction.

The general public here in the United Kingdom usually have little concern with the occurrence of earthquakes, and until fairly recently in this century, were pretty much oblivious to them. In other parts of the world of course this is far from the case where earthquakes can be a regular occurrence at the small scale and may cause catastrophic disruption at the large scale to large communities, on the timescale of decades or longer. Massive loss of life and destruction of man-made structures has meant that scientists have been very keen to study means of how to predict such events. Recent reports in the media based on 'hard scientific fact' have claimed that the metropolitan area of Tokyo expects an imminent large magnitude earthquake, as does Los Angeles. A question arises: 'what is the basis for these predictions?'. It stands to reason that if these really were factual claims, then the spatial accuracy inherent in the claims should be applicable globally, presuming earthquakes occur according to similar phenomena i.e. the Kobe and Mexico City earthquakes of recent should also have been expected. This clearly was not the case and so there is a problem with the scientific modelling of earthquake prediction. I propose to examine this problem and hope to highlight the reasons in the light of ideas about the response of the Earth's crust to stress, problems with the actual definition of 'prediction', difficulties in establishing methods of prediction, and sociological considerations pertaining to prediction. Hopefully this will lead to a different understanding of earthquake prediction than that popularly advanced by the media at the present time.

Crustal Response to Stress.

An understanding of how the Earth's crust responds to stress should enable testable theories and observable results about earthquakes, but as the following illustrates; there are two views current amongst scientists pertaining to crustal response, with very different implications for prediction. The first seems intuitively accurate based on a little knowledge of plate tectonics, but appears to fall short when compared with the second more complex contemporary idea.

With the advent of the models of plate tectonics and sea-floor spreading in the mid-sixties, it seemed intuitively likely that these would provide the scientific community with a solution to the problems of how, when and where earthquakes might occur (Geller, 1997). Following Reid's elastic rebound model the Earth's crust is seen as a homogeneous material. As a result of large-scale tectonic movements, shear strain builds up over time throughout the area surrounding a zone of weakness or fault. When this has accumulated to a level where local shear stress exceeds local strength, rupturing of the crust occurs propagating catastrophically through the whole strained region of the fault. This is manifested as an earthquake and corresponding relief of accumulated stress over the region.

This model seems to explain the patterns of deformation seen after many quakes fairly well but does not explain several factors:

- aftershocks show that not all of the stress has been released.
- the occurrence of pairs of large earthquakes show that the underlying mechanism is more complicated than this.
- measurements based on the ratio of energy radiated to seismic moment and of the heat flow in the neighbourhood of faults shows that only a small fraction of the stress is liberated (Evans, 1997).

The model suggests that strain will build up until stress on the fault is at some threshold, resulting in an earthquake. This process then repeats until a similar magnitude earthquake occurs, in a cyclic manner. Such thinking has led researchers to look for a cyclicity in temporal occurrence and magnitude in consistent fault segments, but with little success. An alternative idea associated with this is the thought that some phenomena might have acted as triggers not associated with the general regional tectonic accumulation of stress, such as earth tides and the passage of distally initiated seismic waves from other earthquakes. Few examples of tidally triggered earthquakes, and one largely statistical example of seismic wave passage triggering (the Landers earthquake) have been highlighted (Evans, 1997).

Models concerning how precursors might occur are built on the presumption that stress and strain are increasing throughout some initial volume preceding an earthquake. It is therefore proposed that this volume and perhaps also the duration of stress accumulation are related to the energy liberated during an earthquake. Consequently stress can be related to some parameter subsequently, such as seismic velocity, surface strain or tilt, electric potential, gas release

The contemporary and much favoured model for crustal response to stress is the model of self-organised criticality (SOC) which is more complicated but ultimately seems to advance a more viable picture.

The key idea, which is in contrast to the previous model, is that stress, strain and strength distribution in the upper brittle part of the crust are uniformly heterogeneous at all scale, so that the behaviour of

the system is such that there is no preferred length scale (scale invariance) (Leary, 1997). Figure 1 shows examples of similar fault patterns produced naturally and by experiment at vastly different scales. Interestingly, the patterns all show marked similarity except for the scale of each. It is also postulated that feedback processes maintain the system with (shear) stress distributed close to the local fracture strength everywhere.

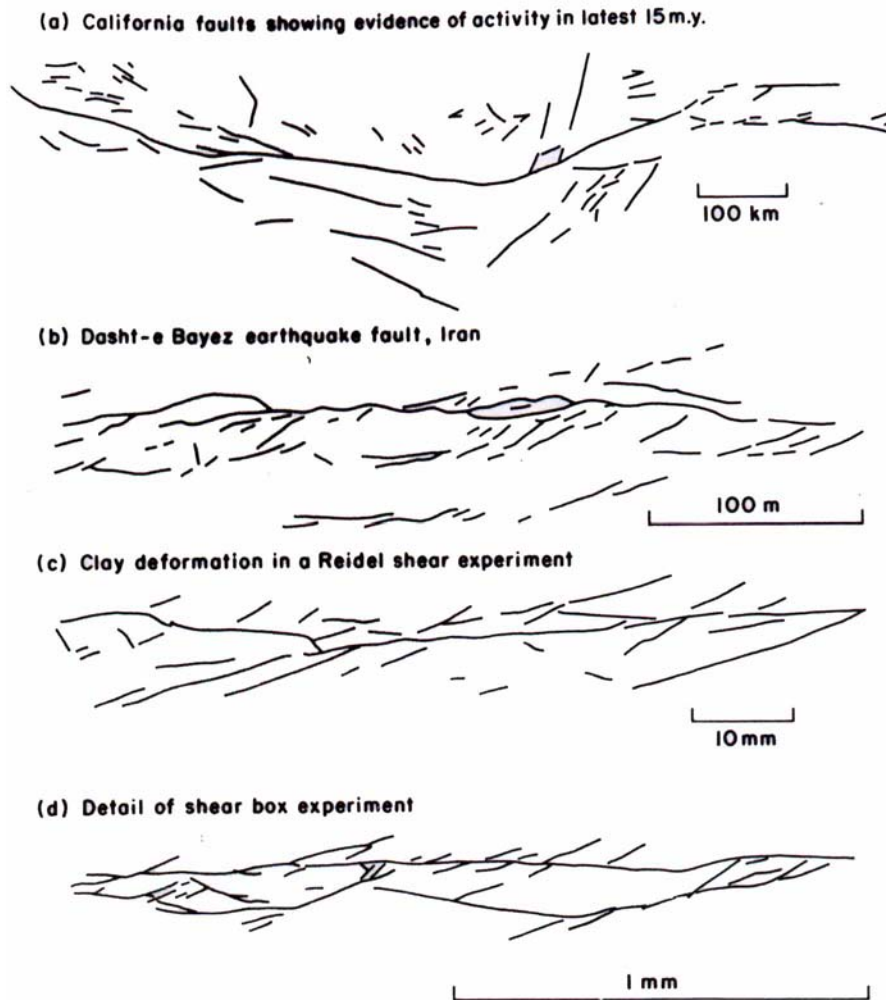


Figure 1. Traces of fault populations on a range of scales, from laboratory experiments (c & d) to plate rupturing faults such as the San Andreas (a). The fault patterns appear to be scale-invariant since they show similar patterns except for the scale (after Main, 1996).

'Criticality' implies that the system lies at the boundary between two behavioural regimes (ordered and chaotic), and 'self-organised' as suggested above means that the system maintains itself in a specific condition. Figure 2 shows the sandpile model commonly used to illustrate the concept.

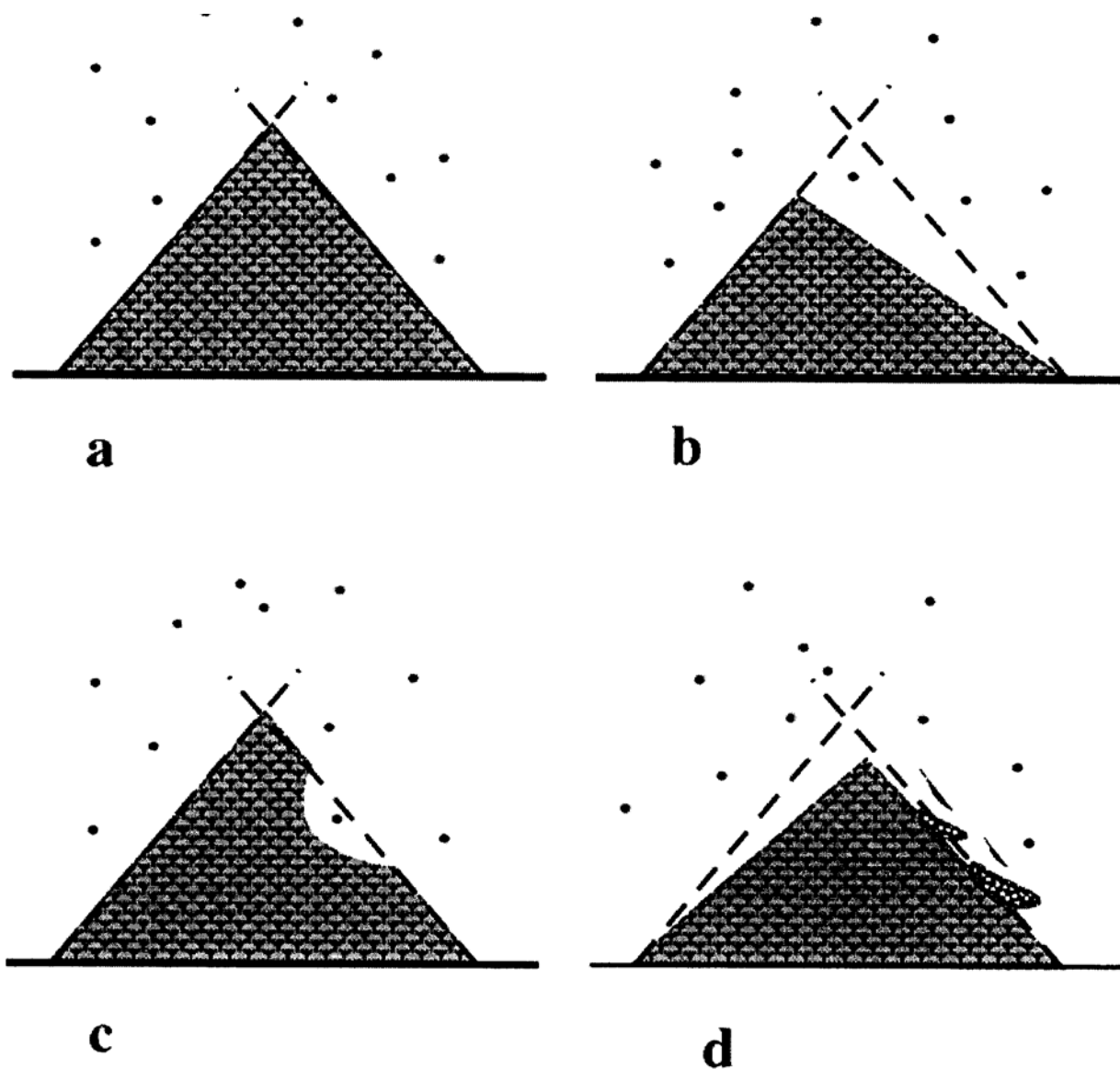


Figure 2. The sandpile model of self-organised criticality. The pile is built by a rain of sand and, when the sides reach the critical angle of repose, landslides of all sizes begin to occur. If we focus now on only one sector of the sandpile, there will occasionally occur a system-sized landslide which brings the local slope well below the angle of repose. No landslides can then occur until the slope is built back up to the angle of repose. It is this prediction which is the goal of long-term prediction.

Within the SOC system, an arbitrarily selected volume subjected to a stress change will show a predicted response in a statistical sense only, at any scale down to the subcrystalline level. Thus the behaviour of the volume as a whole is dictated by myriad distributions of stresses and strains within (Evans, 1997).

An understanding of the way a critical state Earth might respond to stress and also the crucial role of the interactions between stress and strength can be had by considering four possible cases:

a) an 'ideal' uniform elastic cube. This responds to a small (shear) stress by exhibiting uniform (shear) strain following Hooke's Law.

b) a uniform elastic cube except for a throughgoing lubricated fracture in the plane of shear. This exhibits sliding across the crack with shear strain concentrated in the crack. Displacement continues until the stress is removed.

c) a similar cube but this time the fracture is not lubricated. In this case, if the stressing force is above the Coulomb friction value then the components behave as in b). If the stressing force is below the Coulomb value then the components behave as in c).

d) a heterogeneous unfractured cube. This develops a fracture system and accordant behaviour as in b) or c) depending on lubrication and stress orientation.

Using these 4 types of behaviour we can now consider a system composed of many smaller elements of types a)-d), perhaps containing consistent inter-related fractures and all pre-stressed below the individual limits of fracture or frictional sliding. Then increase the system stress by a small amount. Obviously each element will respond somewhat differently. The elements near the limit may fail or slide, and part or all of the stress on them will be transferred to neighbouring elements which may in turn fail or may not. In this way a variety of behaviours is possible for the system, ranging from elastic to large-scale failure.

Out of all the possible configurations of elements, there may be some in which a large number of elements experience fracture or sliding, and a major redistribution of stress occurs, but for most configurations the overall system will respond in a near elastic fashion with only localised fracturing or sliding (Evans, 1997; Leary, 1997).

The system described above exhibits the behaviour associated with the idea of criticality, but is not necessarily self-organising. After a few cycles of this system, it can diverge from a state where the stress is near the local fracture limit throughout, to one where the whole collection acts as one big elastic block or one big single fractured block. This is because the system as it stands contains no feedback systems necessary to maintain the critical state. However, in the real crust, rocks exhibit a number of time-dependent properties which contribute to such feedback: strain softening and especially circulation of fluids in faults and breccias which act to reduce local strength in areas of high strain concentration. Conversely, when deformation rates are low, upper crustal rocks are able to heal by the process of mineral deposition in fractures (Leary, 1997).

At the largest scale the Earth's lithosphere acts as a composite material and ductile mechanisms in the lower crust and upper mantle transfer stress continuously to the brittle upper crust. At the smallest scale, microfractures in stressed rocks tend to elongate and coalesce eventually forming larger points of failure, leading to delayed fracture. Thus as a result of stresses induced by mantle convection on the

whole lithosphere, and high local stress leading to time-dependent failure, the Earth's upper crust can be seen to be in a state of constant readjustment.

The theory developed to describe this system leads to a number of conclusions which correspond to many observed features of earthquakes and seismicity. So far however, no complete model has yet been established for the Earth's brittle crust as a self-organised critical system and so the precise role of the various mechanisms in maintaining that criticality is not understood (Leary, 1997). Neither is it possible to say how far the components may deviate from critical behaviour (Evans, 1997).

The idea can be related to the issue of earthquake prediction. Within a critical system any small rupture is in principle capable of growing arbitrarily and of becoming a large earthquake. That small rupture may have been caused by an exceedingly small change in the regional stress regime as in the description above, or even by no regional change at all, as in stress-induced weakening. The state of the system is in constant evolution so that there is no guarantee that the same initiating failure would result in the same outcome if it occurred at a slightly later time, or that the same regional stress increase would result in failure at a later date. So here we can see that the timing of large-scale ruptures seems to be largely a matter of chance. In principle, the behaviour is mathematically predictable but involves knowing the stress and strength distribution throughout the whole of a region down to a subcrystalline level at any one time, and so is extremely unlikely and certainly impossible at the moment. So the theory of SOC tells us that deterministic prediction is impossible, but statistical estimation of earthquake hazard is entirely feasible (Main, 1996).

Definition of Prediction.

In the previous section we have a glimpse of the problem of the perception of what earthquake prediction means. The possibilities are that earthquakes are either (effectively) random or they are predictable to some extent. It is useful to define a scale of predictability, with four measurement points:

- 1) Time-independent. This means that earthquakes are random in time according to a Poisson distribution, and the best results that can be achieved are through the combination of the historical occurrences of earthquakes and active fault motions from plate tectonic and satellite data to evaluate an assessment of the behaviour of earthquake populations. In this way an estimate of seismic hazard for any area can be given (Main, 1999). This makes sense, as to denounce this would mean that you think Britain has the same risk as California (Michael, 1999). Such calculations are commonly used in the construction and insurance fields. Figure 3 shows a hazard map for the Northwest Pacific.

2) Time-dependent. This infers that a degree of spatial and/or temporal predictability is possible, and represents a distinct improvement over time-independent estimation. Aftershocks are usually associated with a set of earthquakes and larger ones can be catastrophic. Viable estimates of aftershock occurrences could be used to appropriate aid to afflicted regions. The recognition of foreshocks is even more desirable. This would require the creation of linear theories, revealing an increasing hazard, or the recognition of typical earthquakes from palaeoseismology (Main, 1999). At present joint foreshock and aftershock probabilities are released by authorities in America after earthquakes over magnitude 5, as well as in other countries (Kagan, 1997; Michael, 1999).

3) Forecasting. This level would require some feature of an earthquake to be predicted, implying that a precursor exists. Although a prediction would still be probabilistic to some extent, it would offer more accuracy than the clustering afforded by time-dependent prediction. This would have practical utility; knowing the likelihood of an impending event would allow evacuation of areas at risk well in advance, while problems would include public acceptance of a percentage of false alarms.

4) Deterministic prediction. This would require that the magnitude, date, and location of an impending earthquake be known within narrow limits, enabling a planned evacuation to occur.

At present as illustrated by the idea of SOC in the Earth's crust, all major experts in the field of seismology hold that deterministic prediction is an impossibility (e.g. Main, 1996, 1999; Geller, 1997; Jackson, 1999), and time-independent hazard analysis has been in use for over 3 decades (Main, 1999). It seems that any controversy regarding prediction lies somewhere around or between points 2 and 3 on the scale defined above. It is useful to examine factors pertaining to short-term prediction to clarify why problems exist.

Prediction Methods.

A basic premise of any short-term prediction scheme is that it has the ability to perform better than simple chance (the null hypothesis), although there is even disagreement on a suitable definition of the null hypothesis. The most frequently employed test (which would seem to make sense) is to test the performance of a prediction method against a simple Poissonian model of seismicity. This should result in a significance measure of the method, however this idea is flawed because as described above,

Northwest Pacific Forecast, 1977-94: Eqs in 1993-94 (blk), 1995-96 (white)

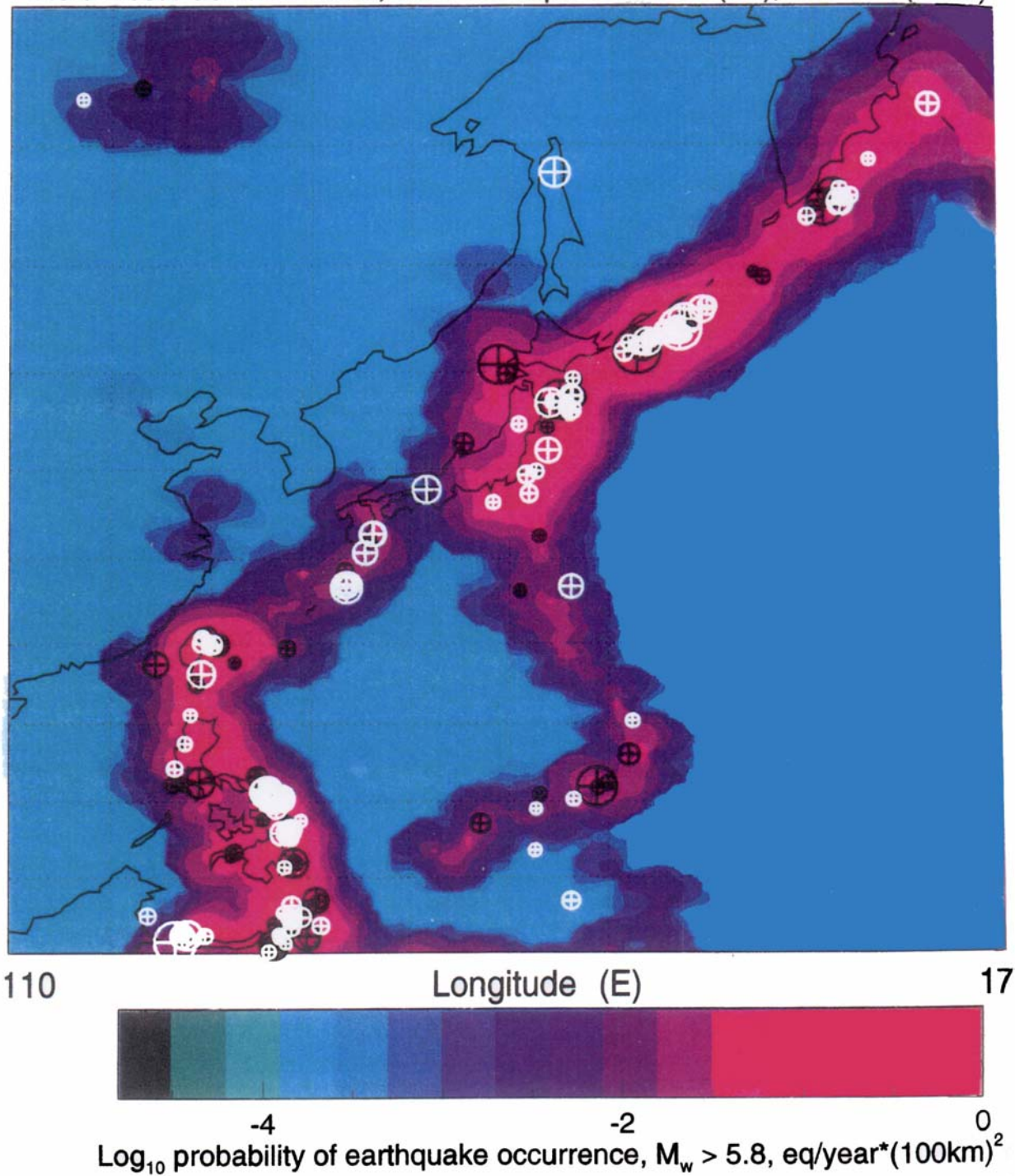


Figure 3. Northwest Pacific seismicity forecast: grey tones show the probability of earthquake occurrence calculated using the Harvard 1977-1994 catalogue. Earthquakes in 1993-1994 are shown in black; earthquakes in 1995-1996 are shown in white (after Kagan, 1997).

earthquake occurrences do not follow a Poissonian model (Stark, 1997). Other prediction methods utilise selections of best pairs of events together with the most effective time lag between them, discarding poorer results. This retrospective approach uses a positive result as starting point, thus introducing bias into the study. When discarded results are included, the statistical significance of the results drops dramatically (Mulargia, 1997). Even though the distribution of earthquakes in time is not Poissonian, standard statistical tests cannot be employed *a posteriori* because the large number of candidate possibilities considered are bound to throw up some correlations. This means that the process of searching itself needs to be modified, and should be used subject to specification in advance as to what is being predicted (Mulargia, 1997; Kagan, 1997).

Sociological Considerations.

At the present state of advancement, it is interesting to consider what effects, if any, that predictions have had for communities, as after all this is a goal of prediction. As Matthews (1997) notes, in order for a prediction to have any pertinent level of success it must be very reliable, even to warrant the issuing of an alert a prediction must have a level of accuracy much higher than even the best present day meteorological forecasts.

Recent claims were made by a Greek group suggesting that they had successfully predicted two earthquakes in Greece in 1995. However analysis of the original predicted magnitude issued (in the case of the first) and the predicted location issued (in the case of the second) suggested that these predictions were technically incorrect (by the groups own adopted rules). The psychological, economic and political impacts of such erratic predictions are poorly understood in the absence of successful prediction, the quality of which is extremely difficult to assess anyway. The only public alerts which seem to have worked up to now are those afforded naturally by a series of strong foreshocks, enough to generate sufficient fear among the populous to leave their habitation (Bernard, 1997).

It is further surmised that the effectiveness of issuing even fairly accurate short-term predictions is limited due to factors such as apathy and authoritative distrust in evacuation of urban centres, lead time between prediction and effect being too short for effective action, and less than 5% of sizeable earthquakes cause significant disruption (Stiros, 1997). Stiros argues that funds presently expended on prediction would be better spent on structural improvements (the main cause of loss of life) costing less money to save more lives than the at best erratic results obtained from prediction.

Conclusion.

It can be gleaned from the preceding chapters that very little seems to be considered to be hard and fast fact in the field of earthquake prediction. Not only does a basic underpinning model for the behaviour of the Earth's crust not exist, but the whole idea of what earthquake prediction implies lacks formal definition. A great deal of study has been undertaken into the possibility of different kinds of precursory phenomenon existing in association with seismic activity, but contemporary experts do not seem to be able to come up with even the shortest of lists of likely candidates. With the passing of time and very little progress in short-term prediction, frustration with the apparent waste of resources for little return, and surfacing ideas on the futility of such prediction anyway, mean that other systems for seismic hazard mitigation are coming to the fore. It may be that earthquake prediction can only be a valid consideration in the sense of evaluation of spatial seismic hazard, with perhaps the possibility for a small improvement in the resolution of probabilities of temporal clusters of earthquakes. However it appears that the prediction of individual earthquakes is impossible.

References.

Bernard, P., Pinettes, P., Hatzidimitriou, P.M., Scordilis, E.M., Veis, G., Milas, P., (1997). From precursors to prediction: a few recent cases from Greece. *Geophys. J. Int.***131**, 467-477.

Evans, R., (1997). Assessment of schemes for earthquake prediction: Editor's introduction. *Geophys. J. Int.***131**, 413-420.

Geller, R.J., (1997). Earthquake prediction: a critical review. *Geophys. J. Int.***131**, 425-450.

Jackson, D. (1999). The status of earthquake prediction. Nature webpage debate on earthquake prediction: http://helix_nature.com/debates/earthquake/equake_14.html.

Kagan, Y.Y., (1997). Are earthquakes predictable? *Geophys. J. Int.***131**, 505-525.

Leary, P.C., (1997). Rock as a critical-point system and the inherent implausibility of reliable earthquake prediction. *Geophys. J. Int.***131**, 451-466.

Main, I. (1996). Statistical physics, seismogenesis, and seismic hazard. *Review of Geophysics*, **34:4**, 433-462.

Main, I. (1999). Is the reliable prediction of individual earthquakes a realistic scientific goal? Nature webpage debate on earthquake prediction:

http://helix_nature.com/debates/earthquake/equake_contents.html.

Matthews, R.A.J., (1997). Decision-theoretic limits on earthquake prediction. *Geophys. J. Int.***131**, 526-529.

Michael, A. (1999). How well can we predict earthquakes? Nature webpage debate on earthquake prediction: http://helix_nature.com/debates/earthquake/equake_4.html

Mulargia, F., (1997). Retrospective validation of the time association of precursors. *Geophys. J. Int.***131**, 500-504.

Scholz, C., (1999). Earthquake prediction: feasible and useful? Nature webpage debate on earthquake prediction: http://helix_nature.com/debates/earthquake/equake_5.html

Stark, P.B., (1997). Earthquake prediction: the null hypothesis. *Geophys. J. Int.***131**, 495-.

Stiros, S.C., (1997). Costs and benefits of earthquake prediction studies in Greece. *Geophys. J. Int.***131**, 478-484.