OPERATIONAL REQUIREMENTS FOR AN EARTHQUAKE FORECASTING PROGRAMME FOR NEW ZEALAND

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ABSTRACT

This paper reviews considerations attendant on introducing an operational forecasting scheme in New Zealand. A background section summarizes the current views on the scientific basis of earthquake forecasting and the progress of empirical studies on New Zealand data. Further sections examine the likely form and time-scale of earthquake forecasts, technical resources required for different aspects of developing the forecasts, the need to identify and work with users of forecast information, and the protocols and procedures for issuing regular and ad hoc forecasts. The need for integrating the development of a forecasting programme within a coordinated framework of natural hazard mitigation is emphasized.

1. INTRODUCTION

Over the last twelve months, a number of new studies (see [1]-[4]) have been undertaken with the aim of assessing the applicability to New Zealand data of a variety of proposed earthquake precursors. The results are varied but sufficiently promising to raise for serious discussion the possibility of initiating a regular, on-going programme of earthquake forecasting. For the foreseeable future (meaning here a framework of around 10 years) such forecasts are likely to be highly uncertain, and best stated in terms of risk levels and probabilities. Even so there is now an arguable case that planning for such a programme should not be further postponed. The purpose of this paper is to summarize the current situation, and to initiate discussion on the issues that need to be addressed if such a proposal is taken seriously. It is something of a paradox that scepticism concerning the feasibility of earthquake prediction seems to have reached its climax at just the point where for the first time the quality and quantity of current data makes such a programme look distinctly more plausible. (An assessment of the New Zealand data base from this point of view is given later in the article.) This paradox may represent a change of paradigm, a belated recognition that the initial dream of deterministic earthquake prediction, even with some errors attached, has to be replaced with the lesser ambition of defining regions of greater or lesser transient risk*. At that point the goal of the research needs restating. The main task should be seen as improving the quality and usefulness of probability forecasts, starting from the estimates of background risk currently used in engineering design considerations, and refining these in the light of the accumulating information provided by catalogue and other data.

As soon as this task is examined in detail, it becomes clear that what is involved is not a single type of forecast or

procedure, but a family of interlocking procedures on different time scales, starting from preliminary indications of regions where large earthquakes might originate in the next decade or longer, and proceeding all the way to real-time warnings of approaching tremors; moreover the task does not finish with the event itself but extends beyond the event to the prediction of damage centres and immediate post-event hazards such as landslides and aftershocks. From this arises, as we feel strongly, the need to integrate the development of earthquake forecasting into a coordinated programme of earthquake hazard mitigation. Within such a programme, different users will have different requirements, and will be able to take advantage of predictive information on different time-scales and at different levels of risk enhancement. Attempting to identify those requirements, to match them to current scientific capabilities, to communicate the predictive information effectively to users, and also to the general public, are likely to be major challenges for the next decade, possibly even overshadowing new developments in the science itself.

The sections which follow cover, in sequence, brief reviews of the current state of knowledge concerning earthquake genesis and empirical studies; the progress of current work in New Zealand; the likely format of future forecasts on different time scales; the technical resources required develop

* The term "risk" is used here and throughout to mean a probability of occurrence per unit time and area, rather than in the insurance sense of an expected loss (probability times value). Note this differs also from the meaning of "hazard" in such phrases as "hazard reduction", or the "earthquake hazard" as distinct from the "volcanic hazard".

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an on-going forecasting programme; the needs of potential user groups; procedures and protocols for making available forecast information.

2. CURRENT UNDERSTANDING OF EARTHQUAKE PROCESSES

In this and the following section we give a bird's eye and somewhat personal view of current research concerning earthquake prediction. Readers interested in more complete accounts and alternative viewpoints may consult any of several recent review papers such as [5]-[8].

In the years following the San Francisco earthquake of 1906, the American geologist and engineer, H.F.Reid, studying the realignments of survey points before and after the earthquake, was led to formulate the elastic rebound theory of earthquake occurrence: for large shallow earthquakes, the crustal material beside a fault is deformed (strained) until a point is reached when the accumulated stress overcomes the friction along the fault. Then the stored elastic energy is released in a sudden readjustment of the crustal blocks on either side of the fault, and a new state of temporary equilibrium is reached. This elastic rebound theory dominated thinking about earthquake mechanisms during the many decades during which the primary attention of geophysicists was on the use of earthquakes as a means for probing the structure of the earth's interior. Since the advent of the plate tectonic theory in the 1960's, however, the situation has radically changed. During the last two decades, in particular, the actual processes of earthquake occurrence have taken a much more central role. In part this has been due to revived interest in the possibility of earthquake prediction, but another major factor has been the enormously improved quality (and quantity) of earthquake data made available since the development of modern seismic instruments and associated methods of data analysis. Even in a relatively small network such as that operated by the New Zealand Seismological Observatory, many thousands of events are located each year. The earthquakes which wreak havoc on a human scale are only the largest in a process of almost continual minor readjustments and small fractures.

The occurrence patterns revealed by modern networks are highly intricate. Their details are poorly understood, although their broad features confirm vividly the predictions of plate tectonic theory - beneath Wellington, for example, the occurrence patterns clearly reveal the descending Pacific plate, at a depth of some 15-20 km beneath the city, and perhaps two or three kilometres thick.

Attempts to better understand the details of the process of earthquake formation are now in the front line of current research. Many studies emphasize non-linear aspects, the ability of complex systems to adjust themselves to external forces (self-organizing criticality, phase transition analogues). In a loose sense, the continual readjustments to changing stresses taking place within the crust have been likened to turbulence, e.g. [9]. Like turbulence, the earthquakes are a means by which energetic processes operating on a large scale are broken down and made

manifest on smaller scales. Features such as self-similarity, long-range correlations, and power-law (scaling) distributions are characteristic of both fields. As with turbulence, however, a fully satisfactory physical theory has yet to emerge, and (judging by that experience) may take many decades to develop. Yet with turbulence this has not prevented major scientific and engineering advances being made through largely empirical studies, or a combination of empirical and theoretical work.

There are, however, two factors which make progress in earthquake studies even more difficult than in turbulence. The first is that solids, particularly highly inhomogeneous material such as rock, are complex objects by comparison with fluids. This difficulty besets all studies of fracture. With earthquakes, an additional level of difficulty arises because the processes take place deep within the earth's crust, on a scale and in temperature and pressure conditions which are hard to emulate in a laboratory.

The current wave of pessimism in regard to earthquake prediction may be attributed, in part at least, to a belated recognition of these fundamental difficulties. A case in point is the recent debate (see, for example, [10], [11]) as to whether the initial stages of a large earthquake can be distinguished from the initial stages of a small one. The debate is continuing, but recent studies tend to favour the view that there may be no such differences - a large earthquake is just a small one that happens to find favourable circumstances for further propagation. These studies have been used by the pessimists [6] as further evidence that prediction is physically impossible. In fact, the idea in itself is hardly new; it is inherent in virtually all stochastic models for earthquake fractures, especially those based on branching or percolation theory ideas, e.g. [12]-[14]. This does not mean, however, that no form of prediction is possible. As in the case of branching models for nuclear fission, the crucial point is to determine the factors influencing the probability that a small event grows into a larger one. This depends on the state of the environment: the percentage of fissionable material in the surrounding medium in the case of a nuclear reaction, the stress environment and local fault geometry in the case of earthquakes.

Granted such an interpretation, the scientific problems are to better understand the physical processes of stress accumulation and concentration in the earth's crust, and the varied signals, generally ambiguous and indirect, which may indicate that such stress changes are taking place, or have already occurred. Almost all the precursors we shall discuss can be interpreted as indicators that some part of the crust is in a state of changing or anomalous stress. The problems are to localise these, and determine the scale and structure of the region affected. Any such localisations are likely to involve considerable uncertainties, and therefore to require statement in probabilistic terms. Moreover, initial studies are likely to be partly or largely empirical, and forecasts based on such studies will be subject to all the uncertainties and imprecisions inherent in the empirical approach. Indeed, in the earthquake context, it may be preferable to avoid the word "prediction", with its implications of a clearly identified future event, and to talk rather in terms of risk

enhancements and probability forecasts. Again, this is hardly a new idea, having been foreshadowed more than two decades ago in early papers by Vere-Jones, Evison and others [15],[16].

In summary, there is as yet no fully formulated or widely accepted mode for the genesis and development of an earthquake fracture. For the foreseeable future, models are likely to remain partly or largely empirical, and predictions are likely to be in the form of statements of enhanced or reduced risks. The basic tenet of this paper is that, even within these limitations, there is still scope for a practical, useful programme of earthquake forecasting, the more so if it is integrated into an overall programme of hazard reduction and mitigation.

3. EMPIRICAL STUDIES, WITH ESPECIAL REFERENCE TO NEW ZEALAND

In the last few decades, a large number of proposals, based on many different types of observations, have been put forward as possible bases for earthquake prediction or probability forecasting schemes. Before any such procedure can be considered for incorporation into a forecasting programme for New Zealand, its effectiveness must be assessed directly on New Zealand data. Indeed, the FRST contracts, with which the authors are currently associated, have a systematic review of such procedures as one explicit aim. Here we briefly review those procedures which, in our current assessment, have the potential to contribute usefully to improved estimates of transient risk within New Zealand. For this purpose the procedures have been roughly classified into three groups. The first two groups are concerned with catalogue-based procedures, roughly differentiated according as to whether or not sufficient experience and information is available to be able to provide initial estimates of the risk enhancement factors they might provide. The third group consists of procedures based on physical variables not recorded in standard earthquake catalogues, and requiring additional monitoring before they could be brought into an on-going risk-assessment programme. The procedures vary greatly in terms of the time scales and the sizes of the spatial regions to which they apply. Rough indications of these scale factors are given, alongside any estimates of the corresponding risk enhancements (ratio of occurrence probabilities per unit time and area, with the numerator conditioned by the precursory information, and the denominator based on an estimate of the background (Poisson) rates).

Group 1. Catalogue based procedures for which risk enhancement factors can be roughly estimated

- *Precursory swarms.* In different versions, this is perhaps the most extensively trialled of all proposed precursors in New Zealand, see e.g. [17],[18]. As with other examples, the main difficulty in practice is to identify the precursor before the event. Here, the precursor is a swarm with tightly defined characteristics. Given such a

swarm, the probability of a future event within specified spatial, time and magnitude boundaries is enhanced by at most two orders of magnitude. For a precursory swarm corresponding to a future event with magnitude around 7, the time window is of the order of 20 years, starting about 5 years from the occurrence of the swarm; the spatial window has a radius of around 50 km. Partly because of the relative paucity of such events, rigorous trialling of the method is still proceeding.

- *Foreshocks.* An early study by Smith [19] showed that approximately 25% of large New Zealand earthquakes were preceded within a short period by foreshocks emanating from the future focal region. Unfortunately this is a very different ratio from the probability that a particular small event will turn out to be a foreshock. The difficulty again is that a foreshock does not distinguish itself in any unambiguous way before the event. The critical proportion is thus the number of events which might be foreshocks (essentially all isolated events, i.e. those not identified as being part of an aftershock sequence by a standard declustering routine) which in fact turn out to be foreshocks. A recent study by Rupp [2], following the methodology of Savage and de Polo [20], showed that approximately 4.5% of isolated New Zealand events with magnitudes between 3.5 and 6 were followed within 5 days and a radius of 30 km by an event at least half a magnitude greater. Although the proportion of successes here is small, the risk enhancement factor is quite large (again of the order of several hundred), because of the tight space and time constraints involved. Further attempts to characterise the statistical properties of foreshocks relative to other types of earthquake clusters are given in [21] and [22]). Studies of the New Zealand data are in progress.
- *Regional excitation (e.g. M8).* The M8 algorithm is one of a family of procedures (including also studies of earthquake frequencies, mean magnitudes (*b*-values), and accelerated moment release) which use different measures of enhanced seismic activity as indicators of increased risk. The general premise is that large events tend to appear in, or be preceded by, periods of heightened regional activity. For example, Smith [23] suggested fluctuations in *b*-values (increases in mean magnitude) as a possible precursor of this type. We take M8 as a representative of this family, mainly because it is part of our current project.

The M8 algorithm combines several features indicating enhanced activity. It takes the information from a series of 7 parallel time series, uses this information to predict times of increased probability (TIPS) for different sized events. The size is related to the size of the region surveyed, in the style of self-similarity. To forecast events of magnitude 7, for example, the M8 algorithm surveys regions of some 280 km radius, and proposes a period of enhanced risk which extends for up to five years. By covering the country with overlapping circles of this size, fluctuating risks over the whole country can be monitored. Initial studies in California and New

Zealand both produced results suggesting that the risk enhancement achieved over such circles was of the order of 10-15 [24],[25],[1]. The method, like many other catalogue-based procedures, is highly vulnerable to changes in network coverage and processing, which become confounded with real changes in seismicity. More carefully controlled studies are currently in progress, both in New Zealand and overseas. Two key technical problems in this type of study are to find the best indicator(s) of enhanced activity within a region, and to quantify the link between the indicator and the probability of a large event. M8 itself remains somewhat controversial, although it has played an important role in shaping alternative paradigms for prediction methods. Overall, it is difficult to dismiss the evidence outlined earlier that probabilities of large earthquakes are increased at times of regional activation; however, identifying the scale and character of the region affected is still an exercise fraught with difficulty.

- *Stress release models and characteristic earthquakes.* Another group of procedures, based on the elastic rebound theory and more recent variants such as time- and slip-predictable models, or Vere-Jones's stress-release model, try to use the time intervals between major events as the basis for predicting future occurrence times. The stress-release model treats historical data from a region large enough for interaction factors with neighbouring regions to be considered negligible. It suggests that major events tend to occur near the climax of a large-scale stochastic cycle (order of centuries, rather than decades) of stress build-up and release. The risk enhancement factors are low (order of three to five) because of the large regions and time-scales considered [26],[27]. It is of doubtful relevance to New Zealand because of the region's short historical record and complex tectonics, but attempts to modify the model to handle smaller-scale, interacting regions are in progress.

Characteristic earthquake models attempt to apply similar ideas to large events on particular faults or even segments of a fault. The data base for a particular fault is generally too small and incomplete for the model to be easily tested, or to give reliable indications of risk enhancement factors. However the ideas are important as one route by which paleoseismological information from the pre-historic period can be fed into risk assessment programmes. Versions of these models were also used in initial studies of earthquake probabilities for California [28],[29]. For a discussion of related ideas in a New Zealand context, see [30].

Group 2. Other catalogue based precursors

- *Precursory quiescence.* Examples of precursory quiescence have been noted in connection with earthquakes in many countries, including New Zealand. The reality of the phenomenon is difficult to question, but its use in predictive mode is still problematical. As

the theory of "seismic gaps" it was the subject of some of the first attempts to propose and verify a prediction model, but for various reasons the predictions proved to be greatly exaggerated [31] [32]. The great difficulty is in trying to distinguish a precursory quiescence from a random gap in the data. The most sophisticated methods currently available have been proposed by Y.Ogata and use his "ETAS" model to allow for the effects of varying background seismicity [33]. The methodology had a notable success in predicting a large aftershock following the Kobe earthquake [34]. An example of the use of Ogata's techniques with New Zealand data is given in [35], and further studies are currently in progress. Typically, the quiescent region for a magnitude 7 event may have a radius of the order of 100 km, and may last for a period of several years before the event occurs.

There is a potential conflict between the claims that quiescence and heightened activity can both precede a large event. More systematic studies of the regions and time-intervals involved are needed before this issue can be adequately addressed. An initial impression is that the time intervals and areas associated with quiescence are of a similar order of magnitude to but smaller than those associated with seismic excitation phenomena [36]. It is also possible for relative quiescence to develop inside a region of heightened activity, as in the aftershock studies referred to above.

- *Accelerated moment release.* This method has been developed only recently [37]. It relies on identifying a particular pattern of increasing activity prior to a major event, over regions of a similar size to those used in M8. Its applicability to New Zealand data has been studied by R. Robinson [2] with promising results. It is too soon to be able to quote risk factors, but insofar as it operates with greater precision over similar periods and regions as M8, risk enhancements of between one and two orders of magnitude seem probable.
- *Sensitivity to external excitation.* It appears that when a region is at near-critical stress, it may respond (by way of enhanced frequencies of small events or clusters of such events) with increased sensitivity to a range of external stimuli producing small perturbations in the stress field. Such stimuli may include the solid earth and ocean tide loadings [38], atmospheric loading [39], reverberations of the whole earth in response to major seismic disturbances [40], etc. Work in progress by Whiteside and Kozuch, in particular, suggest that regional and temporal variations in the response to such stimuli can help to identify regions of impending large earthquakes.

Group 3. Physical precursors.

- These include measurements electrical, magnetic and gravitational fields, measurements of water level and chemical compositions, geodetic measurements

including fluctuations in distance, level, and tilt. With the exception of the radon emission levels of one well, monitored for over 20 years by the solo efforts of Russell Robinson, no measurements of this kind are available for New Zealand, and we shall omit any detailed discussion. Where they are measured systematically, notably in China, and to a lesser extent (currently) in Japan, the results have tended to play a supplementary role, reinforcing impressions gained from catalogue based precursors. The situation in New Zealand (and elsewhere) may change radically when the results of the recently-installed GPS monitoring systems become available (see for example the discussion in [42]). These should provide regular, accurate measurements of the relative movements of the monitoring stations and hence of regions of accumulating strain. Even so, it is likely to be several years before sufficient information has accumulated to allow trends to be observed and interpreted, while the problems of linking such movements to estimates of risk may prove to be formidable.

In summary, a range of empirical studies are under way, in New Zealand as elsewhere, to determine the applicability of such empirical methods to the New Zealand context, and to assess quantitatively their contribution to forecasting the probabilities of major earthquakes. None of the methods outlined could yet be described as fully established. Taken together, however, the information they provide could already assist in the reduction of earthquake losses, and should not be ignored. Moreover, there is every indication that the quality of this information will improve with time, if only the resources are available to improve the quality and coverage of the monitoring systems. The most critical questions for the future may well relate to the ability of the community to make good use of this information.

4. FORM AND TIME-SCALE OF EARTHQUAKE FORECASTS

The precursory processes outlined in the previous section relate to very different time-scales. The character of the forecasts to which they could give rise, the requirements for producing those forecasts, and the uses to which they could be put, are likewise very dependent on the time scale. Thus, we are not talking about a single procedure for producing earthquake forecasts, but a family of interlocking procedures, which in principle vary from the estimates of background risk currently used in engineering, building code or microzoning calculations, to emergency response procedures in the wake of a major event. Some elements of forecasting intervene at all stages. Moreover the elements at one stage support and reinforce those at later or earlier stages. From this arises the need to integrate earthquake forecasting into a coordinated disaster reduction or hazard mitigation programme.

The following broad classification into time-scales is analogous to that proposed by earlier writers such as Rikitake [41]. The categories overlap, if only for the reason that lead time may depend on the size of the events targeted for

forecasting. Using a magnitude 7 event by way of example, the catalogue-based precursors considered in the previous section have been roughly slotted into the different time-scale categories.

- *Long term precursors of large events (lead times of 5 years or longer)* (stress release model, regional excitation models, precursory swarms)

The enhancement effect of the precursors has to be combined with but distinguished from the background level of seismicity. At such long lead times the effects are likely to be diffused over regions of the order of a hundred or more kilometres. Risk enhancement factors are not likely to exceed one or at most two orders of magnitude. Information could be displayed on a New Zealand-wide basis, by means of contour maps (levels of constant probability density or constant risk enhancement), or by highlighting gridpoints at the centres of regions where the probability or risk enhancement exceeds a nominated factor. At this diffuse level, a case could be made for publically releasing such information.

- *Intermediate term precursors (lead times of from 10 days to 5 years)* (precursory quiescence, accelerated moment release, precursory swarms)

Precursory effects on this time scale appear to be those for which the greatest uncertainty exists. They include both secondary precursory effects for large events, and virtually all precursory effects for smaller events (say in the magnitude 5.5-6.5 range). There are unresolved conflicts, as in the claims that both quiescence and enhanced activity can act as intermediate term precursors. Risk enhancement factors claimed for different precursors vary from one order of magnitude to two or three orders of magnitude. On an operational basis, the uncertainty surrounding the status of the proposed precursors is likely to reduce the weight that can be given to such information and hence the effective risk enhancements that they can provide. For the time being the most important role for intermediate term precursors may be in confirming and refining the indications obtained from precursors on a larger scale, for example from GPS information.

As the forecasts sharpen, and risk enhancement levels increase, so also does the sensitivity of the information. The more precise the forecasts, the more carefully the release of the information needs to be considered, to avoid panic reactions and other undesirable side-effects. As discussed further below, particular attention needs to be given to the timely communication of relevant information to particular user groups, and the form in which that information is presented.

- *Short-term precursors (lead times of a few minutes to a few days)* (foreshocks, possibly anomalous animal behaviour, some types of electrical signals)

Here too, and perhaps even more strongly, the significance of a particular observation depends very greatly on the complex of other information within which it occurs. For example, the predictive value of a small event, a putative foreshock, is limited if taken in isolation. This assessment could change radically if the event occurred in a region which was already the focus of interest from longer-term forecasts. The difficulties in objectively quantifying such interactions seem very great. Particular combinations of factors on different time scales are unlikely to repeat themselves, or at least not sufficiently often to obtain direct empirical estimates of their joint probabilities. There is some possibility of developing models within which these issues can be partially addressed, but for the foreseeable future this is likely to remain an area where, as in current Chinese practice, the interpretation of the accumulating information is best approached through discussion among a group experienced and skilled at such interpretations. Expert systems may be helpful in assembling and classifying experience for the assistance of future users.

- *Real-time and post-event warnings*

If a rough location of the epicentre can be anticipated, relays can be installed to register and electrically transmit signals from the initial shock waves to critical locations. Since the electrical signals travel faster than the seismic waves, they can be used to automatically switch off power to electric transport, cut off gas mains etc. At the same time, initial estimates of the size and magnitude of the event can be used to predict areas where damage or risk to human life is likely to be greatest, so that relief to those areas can be quickly organized. Real-time warning systems have already been introduced overseas for use during aftershock sequences [43], to halt the fast electric trains in Japan, and as part of seismic alert systems for major cities [44]. Tsunami warnings represent another area where real-time procedures are needed.

To try to make these generalities a little more specific, we sketch a hypothetical scenario for the evolution of a successful forecasting sequence (see Figure 1)

2005 Using a combination of strain build-up deduced from GPS measurements, and indicators of heightened seismic activity, heightened risks, of the order of one event per 10 years per 100 km square, are indicated for a region some 200 km long and 100 km wide, centred some 50 km off shore from Castlepoint. Starting from September, 2005, this region is highlighted on the regular 3-monthly risk forecast charts published by IGNS Inc, the official earthquake forecast authority. This fact is brought to the attention of local regional and municipal councils. Some temporary stations are set up

to supplement the national network and to provide more details about smaller events. Data from the region is intensively monitored for indications of quiescence, accelerating moment release, etc.

2007 (May) A quiescent region of about 60 km radius, towards the south of the region originally identified, is tentatively suggested from studies of the national catalogue, and supported by evidence from the temporary network. Surveillance is intensified, tsunami exercises are rehearsed, local civil defence are alerted. Strong-motion sensors are deployed at several points along the coast, and linked to automatic shut-down systems for gas supplies and hydro-turbines. However the only publically issued statements remain the three-monthly risk forecast charts, which continue to show heightened risks at the earlier gridpoints.

2007 (June) In the meanwhile, an additional region of heightened risk is identified in the Wanganui region and added to the risk forecast maps.

2007 (August) A cluster of small events occurs off Cape Palliser, just outside the southern tip of the quiescent region. After discussion, no action is taken. They seem too small, and to have the wrong characteristics, for either a precursory swarm or a group of foreshocks.

2007 (Early September) The temporary network picks up two events, magnitude 2.5, inside the quiescent region. These also are considered too small to be foreshocks of an event large enough to affect a region as large as that indicated in the earlier forecasts. They are reported to local civil defence as possible precursors of a moderate sized event.

2007 (Mid-September) Two magnitude 4.5 events occur in the northern part of the quiescent region, about 12 hours apart. They are thought likely to be foreshocks. Gas companies and dam operators in the region are warned to take especial precautions. Local civil defence circulates pamphlets to Castlepoint and Riversdale residents about the dangers of tsunami flooding. Emergency services are concentrated in Masterton and Napier.

2007 (two days later) A magnitude 6.6 event occurs offshore. Gas supplies are automatically shut off in towns in Hawkes Bay and the Wairarapa. An immediate tsunami warning is broadcast. A small tsunami is generated, and causes some minor damage to boats in Castlepoint Harbour. About \$2.5 million damage claims are lodged with EQC, together with claims for loss of production due to automatic shut-down of gas supplies. No major damage or loss of life is reported. Felt aftershocks continue for about 4 weeks, with some additional damage.

scenario of times of increased probability

Figure 1: Scenario of times of increased probability

2009 (April) A series of moderate size earthquakes (magnitudes 3.5-5) occurs in the Northern Wairarapa, causing some minor damage. When the next three-monthly review of long-term risk is carried out, these events plus the earlier off-coast event contribute to estimates of increased regional activity in a larger region with radius of the order of 300 km. Estimates from the accelerated moment release model suggest a magnitude 7 event or larger may be in preparation in Southern Hawkes Bay in approximately 2 years' time. There is evidence from the GPS programme of continuing land deformation across local faults.

Et Cetera.....

Perhaps this represents an optimistic scenario, with nature in a co-operative mood. Nevertheless there is nothing postulated in this scenario which is out of range of current observational and recording procedures. Nor, at any stage, was a fully-fledged earthquake warning generated. Had the scenario proceeded differently, with no large event occurring, only minor expenditure would have been incurred. Note that this flexibility depended heavily on effective communication, planned preparation, and an operational framework within which the accumulating information could be assessed and the results passed on for action by appropriate organizations. An informed and cooperative public, who respond to indicators of heightened risk without over-reacting, is also important, and needs time to establish.

Judging by Chinese experience, only a small minority of cases would be likely to proceed to the stage of a public announcement of a full-scale earthquake alert. Bearing in mind the relative scales of the countries, such an experience might not occur in New Zealand for a century or more. The Chinese approach is cautious, because of the heavy consequences of such an action, and the need for a clear consensus in the interpretation of the evidence. Such

unambiguous evidence is rare. In most cases the evidence is not clear-cut, and although there may be several indications of heightened risk, no clear interpretation of the time-scale and likely size of the event can be given. False alarms are rare, but many events pass unannounced.

5. TECHNICAL RESOURCES REQUIRED

The over-arching requirement, in our view, is for a planned programme incorporating both the further development of earthquake forecasting procedures and their integration with other aspects of hazard management. Individual components of a forecasting programme may not be very useful by themselves; their cumulative effect could have considerable national value. In particular, preliminary indications of areas of heightened risk could sharpen the effectiveness of real-time response procedures and the work of civil defence authorities.

Such a programme would need two streams operating in parallel, one relating to continuing scientific developments, the other to effective communication of the information. The technical stream would be mainly concerned with the continued investigation of precursors, the improvement and maintenance of monitoring procedures, and further development of quantitative methods of evaluating the precursory information. This would represent a continuation of the existing earthquake forecasting programme, and its integration with the work of other scientists working on related themes. It is a very active area at the moment, with new forms of both locally developed and international software becoming available almost on a monthly basis. The second stream would be mainly concerned with the problems of utilizing forecast information, integrating it with general hazard management programmes, and communicating it to users and to the public.

In this section we examine the requirements of the first of these streams, leaving the second to the sections following.

Some technical requirements for developing the programme for earthquake forecasting are itemized below.

- *Maintaining and upgrading the New Zealand seismic network.* The seismic network, and the catalogue of events produced from it, are likely to remain the central component of any earthquake forecasting procedures that may be introduced during the short- to medium-term future. The absolute imperative for a forecasting programme centred primarily around catalogue-based precursors is a high-quality, up-to-date catalogue. The present catalogue and procedures have major shortcomings from this point of view. For example, it is ridiculous to contemplate any form of current forecasting with a catalogue that is continually six-months behind real-time and contains crucial gaps. Full coverage of New Zealand to the level currently provided by the Wellington network should be a goal for the next 3-5 years. It is equally important to maintain the quality of existing stations and maintain and improve the processing procedures.
- *Facilities for preparation of homogeneous sub-catalogues.* The importance of homogeneous data-collection procedures for the assessment of trends and other fluctuations in seismicity is obvious enough to state, but rarely appreciated to the extent that is needed. Many of the existing catalogue-based precursors are substantially affected by catalogue inhomogeneities, particularly where improvements to the catalogue can be confounded with increases in background activity. The importance of such homogeneity for earthquake forecasting has been found to be critical in our experience of virtually all the catalogue-based precursors described in the preceding sections. Since evolution and upgrading of the network and processing procedures are inevitable and desirable, some way out of this dilemma is needed. The most promising solution at present appears to be the development of homogeneous subcatalogues, obtained by applying past procedures as exactly as possible to current events. This means that the software for such past procedures would need to be retained for such special purposes, even where the procedures for producing the main catalogue had moved on. Such special-purpose subcatalogues might utilise only data from selected stations, a superseded travel-time model and uniform processing procedures. Changes in occurrence patterns could then be checked on these sub-catalogues, with less likelihood of the results being artifacts of changes to the recording procedures.
- *Development of grid estimates for long-term and intermediate forecasts.* Trial efforts in this direction have been or are being carried out for several potential precursors. Most commonly, this involves surveying the data from a region around each grid point, on a variety of scales, the size of the region depending on the size of the events being investigated. Most effort has been

directed toward forecasting events in the high magnitude region ($M \geq 7$), but a goal of the programme might be to produce regular forecasts for events down to magnitude 6.

- *Integration of forecasts from different time scales.* So far little experience is available on trying to combine the results from different precursors. This is an aspect where, for the foreseeable future, expert judgement and common sense may have to take precedence over purely objective, quantitative procedures. However, the attempt to formulate quantitative methods should continue. A Bayesian approach, for example, might be used to combine forecasts. In any case further study on this aspect is needed, in the formulation and verification of procedures, and their incorporation into appropriate supporting software.
- *Incorporation of information from GPS programme.* This is just starting to become available for New Zealand, and will clearly be important for the future. The question of how to integrate information of this kind with information gained from catalogue precursors requires careful consideration.
- *Systematic monitoring of other physical variables.* The Chinese experience suggests that, if available on a systematic basis, these can play an important supplementary role in confirming or refining catalogue-based estimates. At present there is no such systematic programme in New Zealand, indeed hardly any experience of any kind. Pilot studies, at least, should be undertaken with some of the most promising methods, for example monitoring of water-levels and chemical content of wells, or of electric fields. Costs need not be substantial.
- *Development of real-time responses to initial strong motion signals.* As mentioned earlier, this includes not only electrical signals to shut down hazardous facilities, but also procedures for the rapid identification of areas of potential damage and injury immediately following a large event. There are precedents available from overseas, and there can be little excuse for delaying the incorporation of such procedures into hazard mitigation programmes in New Zealand.

6. IDENTIFICATION OF USERS AND THEIR NEEDS

A variety of different types of predictive information, at various time scales and of varying degrees of reliability, have been mentioned. How can this information best be used, and by whom?

Many of the issues which have to be addressed in relation to the use and communication of earthquake predictions were identified in early papers by Evison (e.g. [45]). Although the scenario has changed somewhat since that time, much of his discussion is still relevant. Further aspects and additional references are outlined in [8]. The main change of emphasis

is in the shift from attempts to predict a specific event to attempts to quantify local, time-varying probabilities.

The most pessimistic view of earthquake forecasting is that any predictive information that could be produced would have negative value to the community and would therefore be better not produced. The economic effects of down-turns in property values, exodus of population, uncontrolled increases in insurance premiums, would outweigh the benefits - likely to be relatively small in economic terms and in terms of loss of life - of improved but still uncertain earthquake forecasts.

This seems to us an unduly alarmist viewpoint. It is probably true that, for example, earthquake warnings for a city such as Tokyo could lead to a dramatic drop in land values and consequent economic disruption. At heart, however, such scenarios reflect the effects of releasing earthquake forecasts to unprepared and uneducated users. Many distortions are involved - for example the exaggerated land values in Tokyo, and the possible desire on the part of major property or factory owners to avoid taking necessary but expensive precautions. Such problems already appear in the implementation of building codes and zoning schemes, but this does not negate the value of those schemes to the community in general. Time-varying probability forecasts should be seen as enhancements and reinforcements of those schemes. Particular user groups, including insurance companies, civil defence, owners of critical facilities or major factories, should be involved in the development of procedures from an early stage. In this way, and through increasingly open public discussion of the issues involved, public awareness can be improved, and progressive measures for risk reduction and management can be introduced.

It is also not clear that problems would arise with the same severity in New Zealand as they might in Tokyo or California. In Wellington, property values are not grossly inflated, there is no massive investment in heavy industry, the population is relatively well-educated and responsive, and there is a tradition of mutual cooperation and welfare planning. Steps such as the publication of risk enhancement maps could, if Wellington itself was implicated, cause some migration from Wellington, including relocation of industry or business head offices, but in the long run this might not be undesirable. Insurance premiums might increase, but it is unlikely to be beyond the ingenuity of the insurance industry to find forms of contract which accept some element of time-varying risk.

Before any forms of forecast are made publically available, and indeed while the programme is still being researched and developed, it seems desirable to initiate a series of dialogues with potential user groups. These dialogues should traverse the social and economic aspects of introducing time-varying risk forecasts. At the same time they should identify the users' potential interests in such a programme, the types of information that would be of particular use to them, the most convenient ways of presenting that information, etc. Financial support from these user groups, perhaps in the form of joint projects, may be an essential component in

advancing both the scientific work and its uptake by the community.

So far we have addressed only the issue of forecasting the probabilities of earthquake occurrence, but (as in the discussion of site effects) there is a whole further forecasting stage relating to the probabilities of different levels of ground motion and potential damage at specified sites. These could be developed for time-varying risks much as estimates for these quantities have been developed for background risks.

There is also the question of the choice of format of presentation: probabilities, risk enhancement factors, grades of alert, maps or other pictorial aids, etc. In all such issues, dialogue with users will be important. At the same time, user needs can help to form appropriate guides for future research, while involvement of users in the decision-making process can reduce the likelihood of inappropriate decisions being taken, and at the same time increase users' awareness of the issues to be resolved and the status of current scientific capabilities.

A number of broad groups of users can be identified, and to conclude this section we indicate what seem to us to be the most important of these, and their interactions (see Figure 2 and the list below).

- Local authorities and civil defence
- The insurance industry and EQC
- Electricity, water and gas supply authorities
- Industrial companies and factories
- Local business
- The general public

With each group, particular issues are likely to arise which require special consideration. Such discussions should not be divorced from other aspects of hazard management, but should be introduced as part of the overall programme.

In all, there is a large programme of issues here which need further research, discussion and evaluation. One of our main points is that unless an early start is made on this programme, New Zealand will find itself unable to take proper advantage of new developments as they occur.

7. PROTOCOL AND PROCEDURES FOR ISSUING FORECASTS

It is our view that one agency should be designated the national earthquake forecast authority for New Zealand, so that only forecasts emanating from or sanctioned by that agency have official status. With that designation would go the responsibility not only for issuing forecasts as such, but for maintaining (without aiming at any form of monopoly) a basic research programme in earthquake forecasting in New Zealand, and for monitoring new developments overseas, so that new developments can be incorporated into the local programme as they occur. The authority should also have a responsibility for consulting with user groups, involving them in the decision-making process and ascertaining their

Figure 2

needs, so that information is communicated in the most appropriate way to particular user groups and to the general public, and user awareness is enhanced to the maximum possible degree. Procedures may need to be built in to ensure regular review of the authority's procedures by an independent committee, so that its monopoly position does not lead to a neglect of alternative methodologies. In setting up such arrangements, New Zealand should be able to benefit from experience gained in operating different types of arrangements in the United States, Japan, China and elsewhere.

One of the particular problems to be overcome with any procedures based largely on probability methods is the general lack of familiarity with, and even antipathy towards, the use of probability forecasts. This is already somewhat apparent in the reluctance of the New Zealand weather forecasters to make use of quantitative probability statements, even though this is routinely done, on the basis of very similar information, in countries such as the United States and Japan. Here again, patience, growing familiarity, and involvement of the users in the process of developing the forecasts, are the most likely routes to overcoming this prejudice.

As far as the general public is concerned, there is a particular need to consider how to communicate the different types of forecast information that we have identified in the earlier sections. Ranking these by lead time, these would include procedures for issuing long-range forecasts; procedures for upgrading these into intermediate term, localised forecasts;

development of command procedures for issuing earthquake alerts in the case of impending major events; collaborating with civil defence and other agencies in implementation of procedures for real-time and post-event predictions. Each one of these is a substantial issue in its own right. However, there is little point in investing effort into the scientific work unless a matching effort is put into ensuring that the information gained is communicated appropriately and effectively.

8. CONCLUSIONS

1. Although scientific opinion has turned against the likelihood of being able to produce reliable and accurate earthquake predictions, there is a rapid growth in the development of methods to extract both long-time and short-term information on likely areas of increased probabilities of occurrence.
2. Empirical work in progress or already carried out suggests that most of these methods have applicability to New Zealand data, and should be able to be developed to the stage of grid forecasts of regions of heightened probabilities. More work needs to be done on combining the results of analyses based on different types of precursors.
3. Benefits from an earthquake forecasting programme are most likely to come from using procedures at different time scales to reinforce each other within a coordinated overall programme.
4. Earthquake forecasting should be integrated into more general earthquake hazard mitigation and reduction programmes, and not developed in isolation.
5. Different user groups should be identified, and dialogues developed to ascertain their needs, their potential uses for forecast information of different levels, the most appropriate ways of communicating the forecast information to them, and possible joint projects.
6. One national agency should be designated the earthquake forecasting authority. It should have the responsibility not only for issuing different types of forecasts, but also for maintaining a basic New Zealand research programme, reviewing new research overseas, incorporating the results of such research into the forecasting programmes, and liaising with user groups and with other agencies responsible for hazard mitigation and reduction.

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