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Report on Early Warning Capabilities for Geological Hazards

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EARLY WARNING CAPABILITIES FOR GEOLOGICAL HAZARDS

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FOREWORD

In 1989, the member states of the United Nations declared the period from 1990 to the year 2000 to be the International Decade for Natural Disaster Reduction (IDNDR). Its objective is to "reduce the loss of life, property damage, and social and economic disruption caused by natural disasters, through concerted international action, especially in developing countries".

The fundamental importance of early warning for realizing this objective of disaster reduction was recognized in 1991. The IDNDR's Scientific and Technical Committee declared the subject a programme target, by which the success of the Decade would be judged by the year 2000. By drawing on global scientific knowledge and practical experience, the Decade's advisory committee encouraged all countries to ensure the ready access to global, regional, national and local warning systems as part of their national development plans. The IDNDR Secretariat has since coordinated an international multi-disciplinary framework to promote this issue. In doing so, it has been able to draw on the comprehensive views and abilities of the United Nations system, needs and concerns of individual countries, and related global expert knowledge.

The critical nature of early-warning for the protection of vital resources and for addressing national development objectives was highlighted by a technical committee session devoted to the subject at the United Nations' World Conference on Natural Disaster Reduction held in Yokohama, Japan in May 1994. Several of the expert presentations cited the importance of public policy commitment for successful early warning. The primary outcome of the Conference, The Yokohama Strategy for a Safer World: Guidelines for Natural Disaster Prevention, Preparedness and Mitigation further emphasized the importance of applied scientific knowledge and the public's awareness of hazard risks as essential components for more effective early warning practices.

The IDNDR Secretariat was requested by the United Nations General Assembly in 1995 to coordinate a review of the existing early warning programs and to suggest means by which global practices could become better coordinated and made more effective. Initial information was conveyed by the Secretary General's Report on Early Warning to the Fiftieth Session of the United Nations General Assembly in October 1995. (UN Document A/50/256, 9 October 1995). At that time, a further examination of new scientific and experimental concepts for accurate and timely short-term forecasting was requested of the IDNDR for the purpose of making recommendations on the applicability and development of more effective early warning in the context of international cooperation.

For the current work, six international expert working groups were convened to study different aspects of the early warning process: geological hazards, hydrometeorological hazards including drought, fire and other environmental hazards, technological hazards, the use and transfer of related modern technologies, and national and local capabilities pertinent to the effective use of early warning. Guiding Principles for Effective Early Warning were also compiled by the conveners.

This following report of the Working Group on Early Warning Capabilities for Geological Hazards summarizes global experience and reviews the current state of knowledge and practice on the subject. Recommendations are also made for improvements and areas that require additional international attention. The conclusions reflect the views of scientific and technical experts as well as those of the United Nations departments and agencies concerned. An effort was made to ensure that views of government authorities, non-governmental organizations and other elements of civil society were also represented, particularly as they relate to factors which determine the efficacy of early warnings.

This report is one of a series issued by the IDNDR Secretariat in October 1997 to review the current state of early warning systems. By the end of the Decade, these views will contribute to final recommendations for improved, and better coordinated, practices in fulfillment of the initial IDNDR programme target for the subject. They will first be considered by an International Conference on early warning systems for the reduction of natural disasters which has been held in Potsdam, Germany in September, 1998. This technical and scientific conference focusing on the application of successful warning practices was sponsored by the Government of Germany with the collaboration of United Nations' agencies and international scientific organizations. As a major topical event of the IDNDR closing process and the consolidation of global views, the conference has identified those accomplishments and local experiences which can best improve organizational relationships and practical effectiveness for early warning into the 21st century.

The following titles compose the series of information reports of the IDNDR Early Warning Programme:

Early Warning Capabilities for Geological Hazards
Early Warning for Hydrometeorological Hazards, Including Drought
Early Warning for Fire and Other Environmental Hazards
Early Warning for Technological Hazards
Earth Observation, Hazard Analysis and Communications Tech. for Early Warning
National and Local Capabilities for Early Warning
Guiding Principles for Effective Early Warning

The Secretary General's Report on Early-warning Capacities of the United Nations System with Regard to Natural Disasters presented to the Fiftieth Session of the United Nations General Assembly, October 1995. (UN doc. A/50/526).

The Secretary General's Report on Improved Effectiveness of Early-warning Systems With Regard to Natural and Similar Disasters presented to the Fifty-second Session of the United Nations General Assembly , October 1997. (UN doc. A/52/561).

These reports may be accessed on the IDNDR web site: http://www.idndr.org or on the EWC'98 web site at http://www.gfz-potsdam.de/ewc98/ They also may be obtained from the IDNDR Secretariat, Palais des Nations, CH-1211 Geneva 10 Switzerland
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EXECUTIVE SUMMARY

Geological processes like earthquakes, volcanic eruptions, and landslides have the potential to cause great harm and can constitute hazards. There are two major strategies for reducing these impacts: 1) avoiding the hazards, for example, by building structures and lifelines out of harm's way or by evacuating a threatened area, and 2) building structures to withstand the effects of the hazard. Implementing these strategies in a cost-effective and acceptable manner requires reliable information about where and when hazards are likely to occur, and what their consequences might be. The capabilities for providing such information vary among the hazards, with some common aspects.

In general, capabilities presently exist for identifying the areas where the occurrence of geological hazards is possible, but without indicating when they might occur. In some situations, a statement about the likelihood of occurrence may be made with specified reliability. The earthquake-prone regions of the Earth are well delineated in a general sense, and in some areas with high resolution, which provides an adequate basis for developing land-use plans and implementing seismic-resistant building practices at a national or regional level. Similarly, the locations of volcanoes are generally recognized, and much is known about the level of activity of, and danger posed by, many of them. Hazard assessments have been prepared for some volcanoes, but they are lacking for many other volcanoes that may threaten populated areas. Zones prone to landslides have been delineated in some regions based on topographic and geologic information, but landslide hazards in most areas generally are dealt with only in conjunction with construction or development projects on a local basis. Tsunamis, which can be triggered by earthquakes, volcanic eruptions, or landslides that displace water, threaten low-lying coastal areas, usually around the Pacific Ocean, Mediterranean Sea, and Caribbean Sea, and some of these areas have been mapped.

On some occasions, anomalous phenomena occur indicating that conditions for an earthquake, volcanic eruption, or landslide are building, but without indicating exactly, or even approximately, when an event might occur. Interpretation of these phenomena could lead to a conclusion that the event may occur sooner rather than later. The capabilities for making such judgments depends on the specific situation, including knowledge of past occurrences, monitoring data, and any other relevant information. Generally, recognizing symptoms for an earthquake are highly uncertain, whereas, signs of impending volcanic eruptions or landslides could be fairly reliable, in certain situations.

With respect to short-term predictions or forecasts, within hours or days of an event, capabilities vary substantially among the geological hazards. Although successful short-term predictions have been made for a few earthquakes, most predictions have been unsuccessful and there presently is no reliable capability that provides a useful basis for issuing short-term warnings before the occurrence of an earthquake. A capability is emerging, however, to predict and warn of effects within tens of seconds after an earthquake occurs, but before the seismic waves reach a specific place, using high-speed data acquisition, processing, and communications systems. In contrast, successful predictions of volcanic eruptions have been made in several situations that have resulted in saving many lives, although each impending eruption must be dealt with as almost a unique case. Landslides also can be predicted with some success, either in the general sense that they are likely in an area due, for example, to heavy rainfall, or in a specific sense based on recognition of incipient failure criteria. For earthquake-generated tsunamis there is an operational warning system for the Pacific Ocean. The occurrence of a large, shallow earthquake under water triggers a tsunami watch, pending confirmation by tide gauges. Arrival times of a tsunami can be estimated accurately and warnings can be given.

Further research on the geological hazards is essential to improve understanding of the processes that cause them and of their effects. Monitoring systems need substantial improvement as very few areas are monitored with sufficient numbers of modern, high-sensitivity instruments. Every country that is prone to geological hazards should complete a national hazards assessment, and, for the most active areas, regional and/or local assessments. These assessments should be incorporated into the on-going activities of the government agencies and communities responsible for economic and social development, particularly those involved with land-use planning and construction. Proper utilization

of mitigation measures and early warning systems can avoid enormous economic losses and protect lives. When phenomena are detected on monitoring systems or reported by observers indicating that a geological hazard may be developing, experts should be assigned to conduct appropriate investigations. Every hazard-prone nation should either develop the necessary expertise itself or establish access to it through some form of bilateral or multilateral assistance agreement.

I. INTRODUCTION

The Threat of Geological Hazards

The geological hazards addressed in this report include earthquakes, volcanic eruptions, and landslides. In addition, the report refers to tsunamis, which are water waves that can be induced by earthquakes, volcanic eruptions, and landslides that displace water.

Although the processes associated with geological hazards are distinct in many respects, there are many similarities as well, and their occurrences can, on occasion, be closely linked. Earthquakes and volcanic eruptions often trigger landslides and sometimes ice or water flows. A spectacular instance of this occurred in Peru in 1970 when a magnitude 7.8 earthquake caused a debris avalanche to bury the towns of Yungay and Ranrahirca killing about 18,000 people. Swelling of Kilauea volcano in Hawaii caused the magnitude 7.2 earthquake near Kalapana in 1975. All three hazards occurred in the 1980 eruption of Mount St. Helens in the northwestern United States of America, when an earthquake under the volcano started an enormous landslide from the volcano edifice, which in turn triggered the eruption, leading to further landslides and mud flows down valleys running off the volcano's flanks. Large volcanic eruptions may cause large floods by melting ice, as in the case of Iceland in 1996.

Geological hazards can cause enormous losses in property damage and human casualties. In 1995, Kobe, Japan, was devastated by a magnitude 7 shock that killed about 6,000 people. Almost 250,000 people died when a magnitude 7.8 earthquake flattened Tangshan, China, in 1976. In the northwest U.S., Mount St. Helens leveled surrounding forests and filled valleys with mud with an explosion in 1980. The 1991 eruption of Mt. Pinatubo in the Philippines buried Clark Air Base under several feet of ash, destroyed many villages with devastating mudflows, and continues to kill people even now with further mudflows. The ongoing eruption of the Soufriere Hills volcano on the Caribbean island of Montserrat has disrupted life there and forced the evacuation of Plymouth, the largest city. It is important to recall that tens of thousands of people in Pompeii and Herculanum were killed with virtually no warning by volcanic eruptions; such events today would be even more devastating with the greatly increased population in the region. In 1985, Nevado del Ruiz volcano in Colombia erupted, triggering gigantic debris flows that killed about 25,000 people. In 1987, landslides in Ecuador shredded the oil pipeline that brings that country's primary source of income from the Amazon Basin.

Although it is unrealistic to think that losses from geological hazards can be eliminated, there is no doubt that measures exist, and have been used, to reduce their impacts. The primary mitigation means are to site structures to avoid hazards and to build structures to resist their effects. Such actions require that we anticipate where the hazards are most likely to occur and to respond appropriately. In addition, under certain circumstances, it is possible to detect when a geological hazard is beginning to occur, which may make it possible to evacuate people from the threatened areas within days or hours of the event's onset and take steps to reduce destruction.

For a general summary and map of destructive earthquakes and volcanic eruptions see Tiedemann (1991), and for an overview of earthquake and volcanic eruption risk assessment see Tiedemann (1992). An overview about landslides is provided by United Nations Development Program (1997), and on mudflows by United Nations (1996). For a summary of approaches for coping with natural disasters, see UNDRO (1991).

Definitions and Terminology

In assessing early warning capabilities for geological hazards, it is important at the outset to state clearly what is meant by the words „early“ and „warning“.

Among experts on geological hazards, a „warning“ usually is a recommendation or an order to take an action, such as to evacuate an area. A „prediction“ or “forecast“, in contrast, is a statement that a geological hazard of a specified nature will occur with a given probability during a certain time frame in a prescribed geographic area. Usage of the words prediction and forecast vary among the hazards and some scientists hold strong opinions about this matter. Generally, prediction is used more commonly for earthquakes, whereas forecast is preferred for volcanic eruptions. This difference is reflected in sections of this report. In the following introductory discussion, the word „prediction“ can be taken to be equivalent to „forecast“. Thus, a prediction, which is usually made by a scientist, provides the basis for a warning, which is usually issued by a government official.

The meaning of „early“ depends on a person’s perspective and responsibilities. With respect to predicting geological hazards, it can have a variety of meanings, so some clarification will facilitate the ensuing discussion. Prediction capabilities with respect to geological hazards are often categorized with respect to the lead time as short term, intermediate term, or long term, or some equivalent terminology involving the word forecasting. The meaning of these terms can vary depending on the specific context of the discussion, and the distinctions can be blurred, but usually short term refers to a time span of up to hours or perhaps a few days, intermediate term of up to months or a few years, and long term on the order of decades or even an indeterminate time.

Nature of Predictions

From another point of view, issuance of a short-term prediction depends on observation of a physical change that provides a basis for estimating the culmination of the process, whereas an intermediate-term prediction reflects a situation of unrest without any indication of when the process might conclude, and a long-term prediction indicates the increased likelihood of occurrence of an event over an extended time frame.

Thus, a long-term prediction is more akin to expressing the potential for a hazard to occur and is usually expressed in probabilistic terms. A statement that a magnitude 7 earthquake or a large volcanic eruption has a 50% chance of occurring in a specified area within 30 years is an example of a long-term prediction. In this type of forecast, there is usually no reason to believe that the event will occur sooner rather than later during the time interval, which is similar to statements made by flood forecasters about the 100-year flood. A long-term prediction can contribute to a hazard assessment, which includes estimates of the effects of an earthquake in addition to information about its likelihood.

In contrast, an intermediate-term prediction might be based on recognition of some type of phenomena that is regarded to be precursory to the occurrence of a geological hazard, but which does not indicate that the actual occurrence is imminent. For example, land deformation (uplift, subsidence, cracking, etc.) or anomalous seismicity, which has been observed before some earthquakes, volcanic eruptions, and landslides, might be recognized as signs of an impending event.

A short-term prediction, though, would require recognition of a distinctive phenomenon that is believed to be part of the preparation process for the event and that indicates in some sense when and where the event might finally happen, and how large it might be. Thus, short-term predictions are more likely to be based on direct observations of phenomena related to a physical process.

Predicting Effects of Geological Hazards

Although predicting the occurrence of a geological hazard is of great importance, estimating the consequences of an event is of comparable importance. Predicting that an event will occur, but not predicting what the effects of it will be, leaves the official who must issue a warning without an adequate basis for doing so. Also, a prediction of effects is necessary for developing mitigation and response plans. It is usually very difficult to predict effects, however, with a high degree of certainty. Because of the uncertainties in predicting both an event and its effects, multiple scenarios can be helpful for planning purposes.

High-speed computation and communications systems have made possible another aspect of prediction that is rapidly developing, namely to predict effects after a specific geological hazard has taken place, or while the hazard is ongoing, but before the effect has occurred. For example, within minutes of the occurrence of a large earthquake under the ocean the possible height of tsunamis can be estimated by the Japanese Meteorological Agency or the U.S. National Oceanic and Atmospheric Agency's Tsunami Warning Center. In Japan, tsunami warnings are issued on television within about 5 minutes of a shock. Another example is the near-real-time mapping and the prediction of development of ash clouds due to volcanic eruptions in the Aleutian Islands and southern Alaska. Based on satellite images and prevailing wind patterns, the trajectories of ash clouds, which can disable airplane engines, are predicted and air traffic controllers warned of the danger. For well-instrumented volcanoes, it is possible within seconds following an eruption, to predict when a flow of water and mud down a valley might reach a city, with sufficient lead time to implement emergency measures before the flow arrives. Similarly, it is possible to detect the occurrence of an earthquake and send warnings before the seismic waves reach places more than several tens-of-kilometres away, in time to sound alarms or take other measures.

The seismic waves generated at the earthquake focus propagate outward at velocities of about 6-8 km/sec, and the more destructive waves travel at an even lower velocity. Therefore, it would take the first waves at least ten seconds to reach a distance of 100 km from the focus, for example, by which time the parameters of the event can be determined and disseminated automatically. This in fact has already been done in Mexico City following an earthquake, and the capability presently exists to do it in southern California. Such information can be used for a variety of actions, including activating valves, backing up computers, and redirecting electrical and communications circuits

II. EARTHQUAKES

General Comment

Earthquakes are caused by the sudden release of stresses that build up in rocks due to large-scale movements of the blocks or plates that comprise the outer shell of the Earth. They can also be caused by the movement of molten rock beneath volcanoes. The mechanism for releasing the stress is by slip on a fault surface; for a large earthquake this slip can reach tens of metres with a rupture a few hundred kilometres in length. The sudden slip sends seismic waves radiating in all directions, and these waves shake the land surface when they arrive. Rocks can vibrate violently, settle and slide. An earthquake therefore, can cause damage to structures in several ways: shearing a structure that happens to straddle a fault, shaking a structure, or weakening the ground upon which the structure is built. Human casualties usually result from collapse of structures or from secondary phenomena caused by the earthquake, such as fires, landslides, or tsunamis.

Earthquakes occur quite frequently: In an average year worldwide, there are several magnitude 8 earthquakes, on the order of ten magnitude 7 shocks, and about one hundred magnitude 6 events. It should be noted here that the magnitude of an earthquake is a measure of the energy released at the source or focus, whereas earthquake effects are measured by an intensity scale and generally decline in value outward from the earthquake source. There are various magnitude scales based on the amplitude of different types of seismic waves or estimates of the fault slip at the source, but these distinctions are not drawn in this report.

Occasionally, large earthquakes are preceded by phenomena such as small or even large earthquakes, deformation of the land surface, anomalies in the chemistry and flow of ground water, and variations in the magnetic and electrical fields. Whether such phenomena are indicative of the preparatory process for a large earthquake and can be used to predict it has been a subject of great research interest, particularly since the 1970's when there were numerous reports from China and the Soviet Union of earthquake precursors. The ability to predict earthquakes depends on the existence of such precursors, their regularity, and an understanding of their origin.

There is a voluminous body of publications in the scientific literature on earthquake prediction; only selected references will be given here. For additional references, see IASPEI Sub-commission on Earthquake Prediction (1991,1997), Sobolev (1993,1995), and Geller (1997).

Long-Term Prediction

Predicting where earthquakes are most likely to occur in the future, in a long-term sense, depends on a combination of determining where they occurred in the past and understanding why they occurred there.

Where earthquakes occurred in the past is documented in the historical seismicity record, which covers over a thousand years in some areas (China, Japan, the Middle East, for example), but is much less in other areas and may be short compared with the recurrence interval, that is, the time between events, for large shocks. In addition, the record of past earthquakes is also revealed to the discerning eye in the geological record. Offset stream beds, offset rock or soil strata, the form of fault scarps, and disrupted sediments have all been used to recognize prehistoric tremors, and radiometric methods have been used to determine when they occurred. This type of evidence can also be used to estimate how often such events occur and how big they were.

Why earthquakes occur in some areas and not in others is largely explained by the concept of plate tectonics. The outer shell of the Earth is broken into about a dozen large blocks that drift over the Earth's semi-molten interior. Earthquakes mostly occur where these plates collide, scrape past each other, or crack and spread apart. These plate movements give rise to the stresses that cause earthquakes. Earthquakes also can be caused by the rise of magma in association with volcanic eruptions, and, possibly for deep earthquakes, phase transitions in rocks.

It takes time for the stresses that cause earthquakes to build up, so a seismic quiescence that may last several decades or centuries, depending on the characteristics of the fault zone, may follow the occurrence of a large shock, resulting in a „seismic gap“ (See Nishenko and Sykes, 1993, and included references). This concept has been used to make a form of long-term prediction, namely, that an earthquake is unlikely in such an area soon after a large shock; also, a fault zone that is generally active, but that has not had a large earthquake for a long time period, could be considered to be „overdue“. The success of this approach, however, is debatable (Kagan and Jackson, 1995). Nevertheless, the approach has been applied in an analysis of the San Andreas fault system (Working Group on California Earthquake Probabilities, 1988). The approximate site of the Loma Prieta earthquake in 1989 south of San Francisco, California, was identified in this study, which is regarded as a successful long-term prediction by some scientists, but disputed by others.

Thus, a general understanding of the processes that cause earthquakes combined with a more specific understanding of the earthquake history of a fault zone, and hence its readiness to generate a future earthquake, provides a basis for long-term prediction, and, incorporating estimates of effects, hazard assessments. Earthquake hazard assessments have been prepared for many countries (McGuire, 1993). There is little doubt that most future strong earthquakes will occur in the seismic zones that have already been delineated, but strong earthquakes sometimes occur outside these zones.

The methodology for defining these zones is useful for identifying high-priority areas within which to employ mitigation methods and establish warning systems. Such knowledge should be used for planning purposes, particularly in establishing design standards for structures and in planning urban development.

Intermediate-Term Prediction

Indications that a strong earthquake may occur sooner rather than later takes us into the realm of intermediate-term earthquake prediction. Seismologists have long sought evidence that conditions may be ripe for an event.

One approach to this problem has been through the methodology of pattern recognition, which involves correlating among the numerous parameters that may have something to do with the occurrence of strong earthquakes. The characteristic parameters include various aspects of regional seismicity, geological structure, and geodetic variations. A sustained effort applying pattern recognition techniques has been carried out in Russia under the leadership of Keilis-Borok (Kossobokov and others, 1990, 1997). The approach is based on establishing criteria for anomalous variations in each of the parameters, in defining the significance of an anomaly, and in testing the model. For example, the occurrence of moderate earthquake activity or the absence of activity could be regarded as a harbinger of a larger shock in the same region within a certain time frame. Thus, recognizing the anomalous seismicity would „raise a flag" to warn of potential trouble. If flags based on several different types of phenomena were raised together, the case for potential activity would be reinforced. Tests of this model have yielded some positive correlations between anomalies and subsequent earthquakes, but the applicability and reliability of the method as a prediction tool remains in question. For example, Habermann and Creamer (1995) concluded that flag raising in the southwest Pacific is strongly dependent on the seismicity catalogue used and correlates with systematic errors in the seismicity catalogues.

In an alternative approach, investigators focus on detailed behaviour of a single parameter. For example, the magnitude 8.0 earthquake of 1986 in Alaska was predicted on the basis of precursory seismic quiescence (Kisslinger, 1988; Kisslinger and Kindel, 1994), although some aspects of the prediction were not correct. Also, the magnitude 7.9 earthquake of 1996 in the Aleutian Islands fell into the prediction window, proposed by several groups, based on accelerated energy release (Bufe and others, 1994).

Another area of study that may ultimately contribute toward intermediate-term earthquake prediction involves computer modelling of the physical changes caused in the Earth by an earthquake, particularly the redistribution of stress. To put this another way, when an earthquake occurs, stresses are released in the region of the causative fault, and the stresses on the rocks in the region are altered. In some areas the stresses may decrease, and in other areas the stresses may increase. Such changes in the stress field affect the earthquake potential of other faults in the region, and these can be calculated. Therefore, it is possible to evaluate whether the likelihood of earthquake activity on a specific fault has been changed by an event, and if so, in what sense. Stein and others have used this approach in modelling past sequences of shocks in southern California (1992, 1994) and Turkey (1997). Advances in measuring land deformation using the Global Positioning System (GPS) and other surveying techniques as well as radar imaging from satellites are contributing to this approach.

Thus, correlation of variations in earthquake-related phenomena and modelling could be useful methods for intermediate-term earthquake prediction in the future. It is clear, however, that this is very much a frontier area of seismological research, and does not amount, in any sense, to a proven capability for reliable intermediate-term prediction, Nevertheless, the present capabilities for intermediate-term prediction could be employed to help set priorities for the expenditure of limited resources for loss mitigation. For example, deciding which structures to strengthen or retrofit first could benefit from such information.

Short-Term Prediction

Short-term earthquake prediction depends on the existence, detection, and recognition of anomalous phenomena that are preparatory to the sudden onset of a hazardous event. There have been numerous reports of anomalies preceding strong shocks, but their significance with respect to a prediction capability has been hotly debated. See Sobolev (1993, 1995) for a review of the physical principles of earthquake prediction and Geller (1997) for a comprehensive bibliography on, and an evaluation of, short-term earthquake prediction.

The most comprehensive analysis of potential earthquake precursors has been carried out by the Sub-commission on Earthquake Prediction of the International Association for Seismology and Physics of the Earth's Interior (IASPEI) (1991, 1997). The types of phenomena proposed as precursors to the Sub-commission include anomalies in crustal deformation, seismicity patterns, electromagnetic field, seismic-wave propagation, geochemistry, and climate. In the 1991 report of the Sub-commission, of 28 proposed precursors, only 3 were placed on the preliminary list as being causally related to a subsequent shock. Two more precursors were added in the 1997 report. The total of 5 precursors listed are:

i) Foreshocks (seismicity hours to month before an event) near Haicheng, China, in 1975.

ii) Pre-shocks (seismicity months to years before an event) near Tenant Creek, Australia, in 1988.

iii) Seismic quiescence before strong aftershock in several instances in Japan.

iv) Radon gas concentration and temperature decrease in ground water near Izu-Oshima-kinkai, Japan in 1978.

v) Ground water rise in the Kettleman Hills, California, in 1985.

Whether these and other reported anomalies are truly related to a subsequent earthquake is the critical question, and the literature includes numerous articles on this matter. A further question concerns the regularity or utility of such anomalies. In other words, if we accept that at least some of the reported anomalies are in fact genuine precursors, are they sufficiently regular or common to provide a basis for a useful short-term earthquake prediction capability?

Laboratory experiments suggest that anomalies do in fact occur in rocks as they are squeezed before they break: cracks form and spaces between rock grains expand leading to reduced fluid pore pressure, among other phenomena. Also, rocks can creep or deform gradually before sudden failure occurs. This type of behaviour in rocks is also indicated in computer modelling studies. The question is whether such phenomena can be detected at or near the Earth's surface.

Regardless of the merits of the reports of short-term earthquake precursors, virtually all scientists who have studied earthquake prediction would agree that there is presently no reliable capability to provide short-term predictions of earthquakes. In its 1991 report, the IASPEI Sub-commission concludes: „Thus, at this time, we have not a single method on the List which could be said to be accepted universally and by which earthquakes can be predicted reliably“. And in its 1997 report, the Sub-commission states: „It is clear that we do not have an earthquake prediction capability, because the manner in which to use the few precursors on the List for predictions is not known.“

Moreover, it should also be noted that there is a range of opinions among seismologists about even the feasibility of short-term prediction. Several recent articles lay out the arguments surrounding this issue, but the controversy has existed throughout the history of seismology.

Geller and others (1997) take the negative view in an article entitled „Earthquakes Cannot Be Predicted“. They argue, „that the Earth is in a state of self-organized criticality where any small earthquake has some probability of cascading into a large event“. Kagan (1997) expresses similar views and concludes that, „an empirical search for earthquake precursors which forecast the size of an impending earthquake has been fruitless."

Wyss (1997), however, notes in a paper entitled, „Some Earthquakes Can Be Predicted" that fault slip is not always as sudden as Geller and others imply and that for „10-30% of large earthquakes, foreshocks occur during the days to months before the main shock." He also calls attention to laboratory and modelling results that show premonitory failure phenomena. Geller (1997) challenges these points.

In an article entitled, „Whatever Happened To Earthquake Prediction?", Scholz (1997) recalls the euphoric times of the 1970's with Chinese and Soviet reports of precursors and the development of a theory relating them to the preparation process leading up to earthquake initiation. He emphasizes that very few observations have been made near the point of earthquake initiation, the experiment near Parkfield in central California being the only one where extensive instrumentation has been deployed. Scholz notes that, „the Kobe [Japan] earthquake was found retrospectively to have been preceded by a host of precursors, ... There is no doubt in my mind that many earthquakes are preceded by real precursors, but their causative processes remain murky, mainly because we lack good observations."

Regardless of whether short-term earthquake prediction is inherently impossible or, more optimistically, unsolved due to lack of observations, few scientists would claim that it is a proven capability. And, most importantly for this report, at the present time there is no short-term earthquake prediction capability with any degree of reliability whatsoever.

Assessment of Early Warning Capabilities

The major seismic belts of the world are well defined and global seismicity information is readily available in the form of maps and catalogues. The concept of plate tectonics provides a framework for interpreting the significance of this information. Therefore, the regions that are threatened by earthquake losses are known, although destructive shocks outside these zones occasionally occur, and there is already an adequate basis for undertaking further studies and measures in those known regions to avert potential losses.

In earthquake-prone regions, the first step in addressing the threat is to conduct a hazard assessment, which is usually done on a country-wide basis. This is carried out by compiling and analysing data on historical seismicity, active faults, and seismic-wave propagation to estimate the likelihood of earthquake occurrence and the potential ground shaking. Estimates of fault activity can be made through geological mapping, geophysical surveying, and trenching to determine the characteristics of movement. The end result is a map that depicts the relative threat to the country or region, which can be used to establish building standards and land-use practices and to plan emergency response. This methodology is generally accepted and has been employed widely . The status of earthquake hazard assessments for many countries is summarized by McGuire (1993). Efforts are underway to increase application of the methodology under the Global Seismic Hazard Assessment Programme, which is a demonstration project of the International Decade for Natural Disaster Reduction.

When the regional hazard assessment is combined with information on local geologic conditions, such as areas of soft soils or unstable ground, maps can be produced that show in considerable detail the areas that will probably experience the greatest damage in the event of strong ground shaking. This method, referred to as seismic zonation, has been employed in many urban areas worldwide, and it has also been used to evaluate the threat to critical facilities.

Capabilities for identifying places where earthquakes might occur sooner rather than later, that is, intermediate-term prediction, are in a developmental phase. Laboratory experiments are identifying the basic constitutive relations that govern rock fracture, and numerical simulations can model complex conditions along a fault and in the surrounding region. This work could lead to a better understanding of the processes that cause earthquakes and aid in interpreting field observations. The results from these studies, even though they may be highly uncertain, could help guide the utilization of limited resources for mitigating potential earthquake damage. For example, in the absence of other criteria, the information could provide a basis for retrofitting bridges in one area before another one.

Short-term prediction of earthquakes, as discussed at length above, cannot presently be done with any useful reliability or consistency. The reasons for this are many: the challenge is very difficult due to the heterogeneous nature of the Earth and the uncertain state of stress within it, and few earthquakes have been monitored with sufficient instruments to provide a detailed view of the preparatory process leading up to failure. The processes that give rise to earthquake hazards are fundamentally complex in nature due to the heterogeneous nature of crustal rocks and the uncertain state of the forces that trigger the events. In other words, there are inherent difficulties that make reliable short-term earthquake prediction a very difficult research challenge. Prediction of effects after an earthquake occurs but before the seismic waves arrive, however, is a developing capability that promises to help reduce earthquake impacts.

III. VOLCANIC ERUPTIONS

General Comment

Volcanic eruptions are ejections of molten rock ("magma"), volcanic gas, and (or) pre-existing "country" rock onto the Earth's surface, driven by gas pressures in the magma or in ground water heated by magma. When gas pressure builds faster than it is relieved, an eruption will be explosive; when gas pressure is relieved almost as fast as it builds, an eruption will be effusive. In explosive eruptions, magma and overlying rock is fragmented into volcanic ash and larger blocks; in effusive eruptions little or no fragmentation occurs, and magma pours or fountains gently out of a vent.

Explosive eruptions pose three direct hazards:

i) Airborne ash and larger fragments are carried downwind and ultimately fall on land and towns. Accumulations of more than 10 cm, especially if wet, can cause many roofs to collapse.

ii) Ash, larger fragments, and hot gases rush down a volcano's slopes like a searing hot avalanche ("pyroclastic flow"). Pyroclastic flows kill almost every living thing and demolish structures in their paths.

iii) Volcanic mudflows ("lahars"), fast-moving slurries formed by mixing of ash and other fragments with water, bury towns at the foot of a volcano in metres or more of debris. The water can come from heavy rain, rapidly melted snowpack or glaciers, crater lakes, or, occasionally, from within large landslides of water-saturated debris. Effusive eruptions and their lava flows threaten property but few lives; people can outrun most lava flows but few structures can be moved from the path of a flow.

On average, between 50 and 60 terrestrial volcanoes are active every year (Simkin and Siebert, 1994). Of these, about half are newly active and the other half were active in the preceding year, in some cases through preceding decades and even centuries. Eruptions on oceanic islands like Hawaii are mostly of a fluid magma and gentle, effusive character. Eruptions from arc volcanoes like those of the circum-Pacific "Ring of Fire" (and the Caribbean and Mediterranean regions) are mostly of viscous magma and more explosive character. A Volcanic Explosivity Index (VEI), akin to earthquake magnitude, addresses the explosivity as well as the magnitude of an eruption. On that scale, about 20-30 mostly effusive, VEI 0-1 eruptions occur each year, as do ~30 slightly to moderately explosive, VEI 2-3 eruptions (e.g., frequent eruptions of Stromboli in Italy, up to the size of the 1989 Redoubt eruptions in Alaska). Only ~ 1 strongly explosive, VEI 4-5 eruption occurs per year (like the 1982 eruption of El Chichon, Mexico, or the 1980 eruption of Mount St. Helens, USA). Still larger eruptions like those of Pinatubo, Philippines (1991) and Tambora, Indonesia (1815) occur only once every few decades to few centuries.

Two recent volumes (McGuire and others, 1995; Scarpa and Tilling, 1996) contain excellent papers on major approaches to predicting volcanic eruptions. What follows is a much briefer treatment, with emphasis on general philosophy and capability rather than on specific techniques.

Long-Term Forecasts

One form of long-term forecast for volcanoes estimates whether an eruption is "overdue" and what type and magnitude of eruption is likely. A few volcanoes exhibit remarkably consistent repose periods and remarkably consistent, "characteristic" eruptions, thereby allowing a long-term anticipation of both repose interval and magnitude. Eruptions of most volcanoes, though, range through several orders of magnitude, separated by a wide range of reposes. If the magnitude of an eruption were proportional to the preceding repose, one could anticipate one by assuming the other. In practice, the relationship is more complex, with magnitude being influenced by variable rates of recharge by fresh magma and volatiles, the size of the magma reservoir, differences in magma composition, tectonic setting, magma-water interaction, and, importantly, the degree to which gas has escaped benignly from the magma.

Some workers have examined statistical patterns of previous repose periods of a volcano (e.g., Wickman, 1966), but only a few volcanoes behave systematically enough for forecasts to be made on the basis of such patterns. Any who use such forecasts should be aware that the behaviour even of those volcanoes can change at any time.

The other common form of long-term forecast is the volcanic hazards map. At a minimum, volcanic hazard maps indicate the areas that are subject to each volcanic hazard (e.g., to pyroclastic flows, lahars, lava flows, and falling ash and larger fragments) from an eruption of specified type and magnitude. Flowage hazard zones are typically based on the geologic and historical record of each type of flow. Ash fall hazards are based on past history and on wind rose diagrams. A planning basis eruption might be the largest in the history of that volcano, a much smaller, "most probable" eruption, or an intermediate case. Inferences from the volcano's eruptive history can be complemented by numerical modelling of each process and additional geologic, geophysical, or geochemical information about the current state of the volcano.

For a few volcanoes for which data are sufficient, probabilistic hazard maps are being prepared. Also, with rapid advances in Geographic Information Systems technology and the availability of digital topographic data, many if not most new volcanic hazards maps are being compiled digitally, which allows for numerical analyses of hazard processes (e.g., routing of flows down slope) and for overlays of population and other cultural data.

Because of the complexity of volcanic systems, many volcanologists simply document the volcano's past history and assume that its past is a guide to its future. But in both statistical reviews and hazard maps, the past is a only guide, not a guarantor, of the future. Increasingly, past history is being complemented with modern analyses.

Long-term forecasts of volcanic activity are useful for personal and community investment choices, such as in land, homes, and infrastructure. Neither land nor structures can be moved in the event of volcanic unrest or eruption, so wise investors will avoid areas of highest volcanic hazard.

Revised, Intermediate-Term Forecasts

Some volcanic eruptions are preceded by months, years, or even decades of seismic and other unrest. If the unrest is above background levels, yet not escalating in any systematic way, volcanologists can warn that the probability of an eruption has risen. At a few volcanoes, the statistics of unrest may be sufficient to estimate how much the probability of eruption has risen. But the actual date of an eruption can almost never be forecast more than a few weeks in advance.

Unrest raises the probability of eruptions significantly if "false alarms" are rare, i.e., if unrest almost always leads to an eruption; if false alarms are common, though, the increase in probability of eruption during unrest will be relatively small. Great caution is required within scientific circles, and especially in public statements, to not overestimate the hazard of low-level unrest. Closer surveillance is prudent, and awareness of the potential for false alarms is crucial.

The principal utility of revised, intermediate-term forecasts is to alert citizens and officials to an increased probability of eruption, to encourage fresh preparation and (or) testing of emergency plans, and to guide increases in surveillance of that volcano.

Short-Term Forecasts

Most if not all eruptions have detectable precursors, and systematic patterns in those precursors have allowed successful short-term forecasts, hours to days or, rarely, weeks before an eruption. Some precursory sequences permit specific "predictions" of the place, a short time window, and type and magnitude of an eruption (Swanson and others, 1983). Other potential precursors are ambiguous so several different outcomes remain possible, including the possibility that the unrest might not culminate in an eruption at all. For less specific, more probabilistic statements, we retain the term "forecast." Unlike for earthquakes, for which only a relatively small number of precursors have been observed, volcanology is blessed and burdened with ample eruption precursors. The largest problem for short-term volcanic eruption forecasting is not a shortage of precursors but, rather, insufficient frequency, spatial density, and parameters of observations to distinguish one interpretation from another.

The simplest short-term forecasts are based on recognition of recurring patterns. If immediate precursors of previous eruptions recur, another eruption is imminent. For example, exponential increases in long-period volcanic earthquakes are so common before eruptions that the recurrence of that pattern means an eruption is probably imminent. At some volcanoes, automated forecasting algorithms watch for runaway seismic energy release, tilt, or other change (e.g., Malone and others, 1983; Endo and others, 1996); inverse-rate methods (Voight, 1988) may offer higher resolution of final failure when rates of approach are rapid. A sudden, late seismic quiescence may be further evidence that an eruption is imminent.

Reliance on pattern recognition alone is risky, though, because precursors to successive eruptions often vary in relative prominence, in rates, or in details such as fluctuating rather than progressive change. Precursors of the last eruption cannot be assured before the next, and quite different manifestations of unrest may appear. Even greater variability is found from one volcano to the next.

To overcome limitations of pattern recognition, major efforts have been made to understand the underlying processes of volcanic earthquakes of various types, ground deformation of various patterns, and emission of gases in various amounts and ratios (Chouet, 1996; McNutt, 1996). One working model that has proven useful in the interpretation of volcanic unrest assumes a volatile-bearing magma near the shallowest concentration of volcanic earthquake hypocenters, at a depth also indicated by modelling of ground deformation (e.g., Decker and Kinoshita, 1972; Murray and others, 1995). This depth varies from volcano to volcano, and from eruption to eruption, but is typically a few kilometres and rarely more than 10 km. If that magma rises toward eruption, earthquake hypocenters and the "point source" of deformation will become shallower, the spectral frequency of earthquakes will decrease, and volcanic tremor may occur.

Volcanic gases are both a cause and result of magma ascent. Often, an increase in either the weight percent or volume percent of volatiles is the driving, buoyant force for magma ascent. As the magma rises, gases reach the upper limits of their solubility and are released. This degassing, in turn, induces crystals to form, and, because gas is preferentially concentrated in the decreasing volume fraction of melt, more and more gas exsolves from that melt. In especially volatile-rich magmas, discrete volatile droplets can separate even in the deep magma, and simply expand and escape as magma rises. In either case, gas will vent into ground water or the atmosphere and can be a useful precursor of eruptions.

As magma approaches the surface and an eruption nears, rates of ascent, brittle fracturing of country rock in front of the rising tip of magma, and gas emission all increase -- sometimes exponentially. Gas pressures rise in the tip of the magma because of decreased lithostatic pressure and concentration of that gas in a decreasing melt fraction. If that gas can escape into ground water or the atmosphere faster than its pressure grows, magma will probably stall and not erupt. If gas escape roughly balances the buildup of gas pressure, a relatively gentle, sustained eruption can result. If gas escape is limited (as in high-viscosity melts), gas pressure can build up and eventually overcome the strength of the overlying crust in explosive eruption (see Eichelberger, 1995; Hoblitt and others, 1996). Referring to the preceding model, volcanologists try to compare gas pressurization and degassing, inferring the former from seismic, geodetic, and gas emission data and the latter from the gas emissions alone.

Another type of short-term forecast that is required for volcanic eruptions, perhaps more than for any other natural hazard, is of the further course of the event. Unlike the relatively simple pattern of aftershocks after an earthquake, eruptions can escalate, fluctuate, or wane over the course of several months, years, or even decades. Forecasting and recognizing the end of an eruption is important if communities have been evacuated, because people will be anxious to return home.

Assessment of Early Warning Capabilities

Long-term forecasts of when a volcano will erupt are notoriously unreliable. Historically active volcanoes are well known and will probably but not necessarily be the next to erupt. Long-dormant volcanoes are less likely to erupt, but, when they do, often produce large, dangerous eruptions that can catch disbelieving citizens unprepared.

Long-term forecasts of the type and magnitude of future eruptions are simpler -- based on the range of past events. Mapping the extent of deposits from previous eruptions and modelling of how those deposits were emplaced form a good basis for hazard maps and related long-range hazards publications. These need to be adjusted for current topography and any major changes in the geology of the edifice, such as extreme alteration or emplacement of a plug-like dome.

Revised, intermediate-term forecasts of eruptions are also plagued by uncertainty. Unrest is easily detected and confirmed, but whether it will lead to an eruption is uncertain. At large calderas, roughly 1 in 10 episodes of unrest culminate in eruptions; at smaller volcanic centres, the odds of eruptive "success," given unrest, rise to perhaps 1 in 2 or 3. There is no reliable basis, at present, to distinguish unrest that will or won't culminate in eruption until just a few weeks and sometimes just a few days or hours before an eruption. This uncertainty reflects a delicate balance between magma ascent and magma stall during the deeper, early stages of an intrusion; later, if the magma reaches close to the surface, escalating ("runaway") processes usually become evident, though, even then, some intrusions can stop just before reaching the surface.

Short-term forecasts and even predictions can be relatively straightforward if a volcano is exhibiting a pattern seen before previous eruptions, and (or) unrest is escalating smoothly and quickly, with or without diagnostic near-final, sudden quiescence. Problems arise if the unrest is irregular (e.g., episodic, "stick-slip" unrest), or includes previously unseen trends. Intense seismic swarms, deformation associated with a shallow source of expansion, and increased gas emission collectively might be the last warning that a volcano gives before eruption, or they might be just another noisy step toward an eruption. Sometimes after a lengthy period of intense unrest, a volcano and those who are watching it rest, until the volcano erupts with little or no additional precursor because magma had already reached practically to the surface.

Forecasts of the further course of an eruption are still in their infancy. Interpretation of gas emission, seismicity, ground deformation, and comparisons of present eruption volume to volumes of previous eruptions and pre-eruption deformation give some basis for estimation. However, neither models nor the database of worldwide eruption experience allow confident forecasts.

Discussion of early warning capabilities for volcanic eruptions should not be left without mention of how short-term forecasts affect public response. Success at a few volcanoes has led some officials to expect the same for all volcanoes, and this, in turn, has led to considerable apprehension among some volcanologists. Each new success makes it more difficult to say, "Volcanoes are too complex to predict." Public expectations have been raised.

Yet, in truth, uncertainties in forecasts remain high for all but a few of the best-studied, best-behaved volcanoes. If the population at risk is small and cost of mitigation is not a serious concern, imprecise forecasts are easily translated into mitigation measures. But if a large population is to be evacuated or other socially and economically disruptive precautions are to be taken, officials will want predictions to the nearest day and with a fairly high degree of certainty -- more than is generally possible. The practical duration of evacuations is typically in the order of a few weeks; if the volcano fails to erupt (or climax) within that time, pressure to cancel the evacuation will be intense. If the first forecast is correct, future ones will be heeded; if not, future forecasts are likely to be ignored.

In effect, volcanic eruption forecasting progresses along a risky path. Forecasts (and predictions) are the *raison d'ètre* of much volcano research. Yet, uncertainties will almost surely produce some false alarms, at the same time that successes are raising official expectations and lowering official tolerance for false alarms.

IV. LANDSLIDES

General Comment

Landslides are a major threat to human settlements and infrastructure. The surface of the Earth is very dynamic and constantly adjusting to storms, earthquakes, and volcanic eruptions. Thousands of landslides occur annually, moving millions of tons of soil and rock and according to the International Federation of Red Cross and Red Crescent Societies (1996) accounted for 1,550 deaths per year in the period 1969-1993. Worldwide landslide deaths are increasing because of the increase in the world's population particularly in landslide-prone developing countries.

Landslides are a regional and site problem which presents challenges in the development of early warning systems and prediction. Disastrous regional landslide events can be caused by heavy regional storms or strong earthquakes, for example, landslides in the 1921 Kansu earthquake (China) may have killed in excess of 100,000 people. A single large, rapidly moving debris avalanche triggered by an earthquake in 1970 buried the towns of Yungay and Ranrahirca in Peru killing more than 18,000 people. A minor eruption of Nevado del Ruiz volcano in Colombia in 1985 triggered mud flows that destroyed the city of Armero, killing about 25,000 people. Landslides also affect artificial slopes, such as the rapid flow of mine waste dumps that was responsible for the 1966 Aberfan disaster in the United Kingdom causing 144 deaths. Many lateral spread landslides in the 1906 San Francisco and 1995 Kobe earthquakes were due to earthquake-induced liquefaction of artificially placed soil fills.

Of considerable importance is the hazard posed by the secondary effects of landslides, for example, landslide-generated waves and the failure of landslide dams. In 1963, a landslide-generated wave overtopped the thin-arch Vaiont dam (Italy) and resulted in a flood that was responsible for the loss of about 2,000 lives. Collapse of a landslide dam on the Min River in Sichuan, China sent a flood torrent down the Min River killing at least 2,500 people downstream. Although only a few large landslides have caused major disasters (e.g., Yungay and Armero), the aggregate damage from landslides worldwide is of disastrous proportions every year. In spite of improvements in recognition, mitigative measures, and prediction and warning systems, worldwide landslide damage is increasing (Schuster, 1996). This is due to due to:

i) increased urbanization and development in landslide-prone areas,

ii) development of new areas created by excavation, filling, and reclamation that are potentially unstable,

iii) deforestation of landslide-prone areas,

iv) large seasonal (or multi-seasonal) variations in regional precipitation compared with short-term historical averages, and

v) agricultural practices, especially irrigation, and regulations.

Landslides can be triggered by many different external stimuli, including intense rainfall, rapid melting of snow, earthquake shaking, volcanic eruption, storm waves, rapid stream erosion, and human activities, such as excavation, irrigation, fluctuations in reservoir levels or changes in agricultural practices (Wieczorek, 1996). These stimuli can cause a nearly-immediate response in the form of a landslide by altering the balance of stresses causing hillside instability. Storms that produce intense rainfall for periods as short as several hours can trigger abundant landslides. A locally intense storm during June of 1995 dropped up to 775 mm of rain within 16 hours triggering more than 1,000 landslides within a small part of Madison County, Virginia. The rapid infiltration of rainfall, causing soil saturation and a temporary rise in pore-water pressures, reduces the strength of slope materials and is the mechanism by which most shallow landslides are generated during storms. During earthquakes strong ground shaking modifies the stress balance within slope materials triggering landslides. The magnitude 7.5 Guatemala earthquake of 1976, generated at least 10,000 landslides primarily in Pleistocene pumice deposits which have relatively low strength under seismic shaking.

Landslides, which include many different types of slope movement, are difficult to predict because they range over many orders of magnitude in size, from small boulders to masses of earth/rock of several cubic kilometres, and in speed from creeping movements of mm/year to extremely rapid avalanches that travel at several hundred km/hr (Cruden and Varnes, 1996). Landslides also span the geologic-hydrologic interface from completely dry materials to flows resembling wet concrete making the characterization of material properties and analyses of their movements and behaviour very complex and difficult to predict.

Long-Term Prediction

In addition to the evidence of previous slope instability depicted in landslide inventory maps, conditions that influence susceptibility to future landsliding, such as geologic materials of low strength, steepness of slopes, or unfavourable dip of bedding planes, can be evaluated in terms of an assessment of slope stability and depicted on landslide hazard maps. Landslide inventory maps can be produced using interpretation of aerial photographs, topographic maps, geologic maps, and previous landsliding history of the region (UNDP, 1997). Landslide inventory maps show the locations of past slope instability, which are frequently the location of recurring slope movement in the form of reactivated landslides. In selected parts of Italy, for example, where in response to a storm several hundred landslides may occur, 30-50% of the landslides with depths greater than 3-5 m are located in areas of previous instability. However, landslide inventory maps are not useful for identifying areas subject to sliding for the first time. Another approach to landslide hazard mapping involves the determination of set backs that define the limits of hazardous zones along cliffs or riverbanks that may be affected by retrogressive landslide activity or the estimation of run-out distances for rock falls, debris flows, or rock avalanches using dynamic or empirical models (Cannon and Savage, 1988; Hungr and Evans, 1988; Nicoletti and Sorriso-Valvo, 1991).

Landslide hazard maps (Brabb, 1984; Guzzetti et al., 1997, Highland, 1997) generally indicate where landslides are most likely to occur, however the timing of landslides is generally unknown. A hazard assessment technique that incorporates the likelihood of strong shaking during earthquakes to determine potential landslide movement has been used to predict the areal limits of earthquake-induced landsliding (Wilson and Keefer, 1985). Most hazard maps are actually susceptibility maps because they do not directly incorporate time. Landslide susceptibility maps often depict the likelihood of landsliding in relative terms such as high, moderate, or low, based on analyses or weighting of factors contributing to slope instability. However, recent development of statistical analyses using GIS techniques have facilitated analyses of spatial data sets, resulting in graphical depictions of landslide potential in quantitative terms (Carrara and Guzzetti, 1995; Guzzetti et al., 1997). If climatological or seismological information on the recurrence of storms or earthquakes is incorporated, then a time-related element can be incorporated allowing determination of the time-dependent changes in the probability of landsliding (Campbell and Bernknopf, 1997). Although long-term prediction of landsliding based on such maps is not specific with respect to time, these maps can be useful for purposes of regional planning, transportation or other lifeline routing, where design lifetimes are relatively long term and the likelihood of landsliding is high. Continuing research into the factors affecting the distribution of landslides that occur during storms or earthquakes or of the mechanisms of landslides (Sassa, 1996) will probably result in future refinements in the criteria used to prepare landslide hazard maps.

Intermediate-Term Prediction

Landslide monitoring can provide information useful for intermediate-term prediction of landsliding. Monitoring of a single landslide can be very expensive, particularly if measurements at great depth are necessary, or if many observation wells have to be installed. Hence, monitoring of large landslides is restricted to only a few, economically important sites. The ability to monitor a landslide is not only technological, but has to do with the available funding. Many major landslide disasters, such as Vaiont, have been preceded by precursory evidence of landslide movement such as appearance of cracks, accelerating movement, or increased rock-fall activity, which is often useful for predicting the onset of more extensive or rapid slope failure. Monitoring can involve many different techniques (Mikkelsen, 1996) for collection of meteorological, hydrological, topographical and geophysical data. The recent development of automatic sampling, recording, and transmitting devices has made remote monitoring a more practical means of predicting landslide movement.

The acceleration of surface or subsurface movement provides the most direct indication of impending landsliding. Based on theories of material science and laboratory tests, techniques have been developed to predict the onset of rapid landsliding from increasing rates of movement (Saito, 1965; Fukuzono, 1985). These techniques were applied to predict the rock slide at the Chuquicamata mine, Chile five weeks before it occurred (Voight and Kennedy, 1979). On January 30, 1995, a large landslide of about 6 million cubic metres occurred along the Yellow River in Gansu Province of China. Although the landslide was large and moved very rapidly, more than 2,000 people had been evacuated and damage was minimal because the landslide had been predicted based on techniques of Saito (1965) within one day of its actual occurrence (Liao et al., 1996). Early warning criteria based on pre-failure movement have been successfully applied in coal mine waste dumps of British Columbia, Canada (Hungr and Kent, 1995). Most mines have developed criteria for the closure of the dumping operations based on the displacement velocity. As a result of continuous monitoring, large-scale failures can be predicted reliably and few accidents occur involving the personnel and equipment working on the dumps.

Fluctuations in moisture in soils can make predictions of landslide initiation or movement difficult. Predicting unusually wet seasons based on regional weather patterns, e.g., the usually wet winters associated with El Niño along the Pacific Coast of North and South America, may in the future become useful for intermediate-term forecasting of landslides. The interaction between climate and slope response is quite complex and the subject of current research. For example, it has been found that the critical amount of rainfall necessary to trigger debris flows or other shallow landslides varies regionally depending on climate (Wilson, 1997); consequently, development of rainfall thresholds for predicting landsliding requires detailed regional documentation.

Short-Term Prediction

Short-term landslide prediction can be applied to either the movement of an individual site or to the onset of regional landslide activity. With the development of transmitting systems capable of sending real-time information by telemetry or satellite, and the improved electronics of monitoring systems, individually instrumented landslides as well as regional instrument networks are increasingly being used for landslide warning systems. Immediate early-warning devices are used on transportation routes to warn of obstructions on a railway track or highway which may have resulted from rock falls, debris flows, or other types of landslides (Wyllie and Norrish, 1996).

Measurement of the intensity and duration of rainfall has been used as the basis for empirical regional thresholds for the triggering of debris flows and other types of landslides in many places, e.g. Hong Kong, Japan, Puerto Rico, Hawaii, and northern California. In Hong Kong, a rainfall-monitoring system is used for identifying periods of high landslide potential during which the government operates on an emergency basis to provide advice on remedial measures for landslides. Between 1985 and 1995, the U.S. Geological Survey, in cooperation with the U.S. National Weather Service (NWS), developed and operated a real-time warning system that was used to issue the first public regional landslide warning in the United States during storms during 1986 in the San Francisco Bay region, California (Keefer et al., 1987). Using real-time monitoring of rainfall in conjunction with precipitation forecasts, warnings were communicated to the public through local radio and television advisories issued by the NWS when rainfall thresholds were approached. With advances in radar estimates of precipitation, such as the NWS next-generation radar (NEXRAD), spatial prediction of landslides in near-real time is becoming more practical at a useful scale for hazard warning. However, currently such radar is not universally available, and furthermore, effectiveness of the radar can be problematic in mountainous terrain where the signals can be blocked by topography. Although demonstrated to be useful, for example along the coastal cliffs of England, the technology of real-time monitoring systems is of limited use as an early warning system, unless the monitoring coincides with a period of movement with sufficient time for response (Clark et al., 1996).

An inexpensive, durable, portable, and easily installed system has been developed to detect and continuously monitor the arrival and passage of debris flows (LaHusen, 1996). This automated system senses and analyses ground vibrations with a compact, solar-powered unit that is installed near specific drainage channels. An inexpensive geophone and an on-site microprocessor is used to continuously analyse vibration signals and detect debris flows and floods on the basis of frequency composition, amplitude, and duration of the vibration signal. The system can detect increased ground vibrations several minutes before a debris flow reaches the station, and continues to record vibrations above background level until the tail of a debris flow or flood has passed. The speed of approaching flows can be determined by detecting arrival times at sequential sensing sites along stream channels. In addition, continuous monitoring of the passage of debris flows allows estimation of the volume of debris that is passing the sensing unit. The system already has been installed and tested at Mount St. Helens and Mount Rainier, Washington; Redoubt Volcano, Alaska; Unzen Volcano, Japan; Cotopaxi Volcano, Ecuador; and Pinatubo Volcano, Philippines. An analytical method based on a routing model and corroborated by flume studies predicts the peak discharge and time of arrival of debris flows (Costa, 1997).

Assessment of Early Warning Capabilities

The geologic conditions responsible for landsliding are generally well understood and the stability of slopes can be analysed if site specific data are available. However, because site data are usually expensive and time consuming to acquire, and because the stability of a slope may change with time, for example due to infiltrating rainfall during a storm, early warning based on site specific analyses is not practical for large areas. Long-term predictions where landslides are most likely can be more effectively provided for large areas by landslide hazard assessment maps, although they do not give any indication of the time of landsliding. Landslide hazard maps serve effectively as long-term warning and give indication for avoidance or additional mitigation of landslide hazards through structural or non-structural means, such as zoning or land use planning (United Nations, 1996).

Landslide monitoring can provide information useful for intermediate-term prediction of landsliding. Precursory evidence of landslide movement such as appearance of cracks or accelerating movement is often useful for predicting the onset of more extensive or rapid slope failure. The recent development of automatic sampling, recording, and transmitting devices has made remote monitoring a more practical means of predicting landslide movement. The acceleration of surface or subsurface movement provides the most direct indication of impending landsliding. Based on theories of material science and laboratory tests, techniques have been developed to predict the onset of rapid landsliding from increasing rates of movement. The time and effort required for instrumentation, monitoring and interpretation of data limits the applicability of these techniques for intermediate-term prediction on a widespread scale.

Short-term prediction based on landslide monitoring has been greatly aided by the development of transmitting systems capable of sending real-time information by telemetry or satellite. With advances in radar, estimates of precipitation spatial prediction of landslides during near real time is becoming more practical at a useful scale for hazard warning. Inexpensive, durable, portable, and quick-to-install systems have been developed to detect and continuously monitor the arrival and passage of debris flows at a number of sites worldwide where debris flows are considered to be highly likely. Although short-term prediction of landslides will become more practical in the future with more inexpensive and quick-to-install monitoring systems, at present the technique is restricted to an extremely small number of sites in proportion to the area subject to landslide hazards worldwide.

V. RECOMMENDATIONS

General Recommendations

Using currently available methodology, the areas that are prone to earthquakes, volcanic eruptions, landslides, and tsunamis can be identified and the degree of the hazard can be assessed. Such hazard assessments provide an adequate basis for promulgating land-use practices to avoid these geological hazards and building practices to withstand their effects. All nations that are threatened by geological hazards should conduct national, regional, and, where appropriate, local hazard assessments. It should be noted that this is one of the three targets of the IDNDR.

Capabilities for recognizing the onset or initial phases of a geological hazard vary considerably among the hazards, but sufficient knowledge about the processes leading to the occurrence of a geological hazard exists to warrant focused studies of these phenomena. All nations subject to geological hazards should develop, or attain access to, scientific and technical capabilities for monitoring and analysing threatening situations.

Short-term predictions or forecasts for earthquakes, volcanic eruptions, and landslides are highly uncertain, although several successful volcano eruption and landslide forecasts have been achieved. Continued research in this area is needed. Techniques for detecting precursory phenomena are well advanced, but few areas are instrumented adequately on a continuing basis. Anomalous phenomena that could be related to the preparatory process for a geological hazard should be analysed by experts to determine requirements for increased monitoring.

Earthquake Recommendations

Organizational Responsibilities

Earthquake monitoring, research, and applications involve organizations from most levels of government, academia, and the private sector. These organizations generally have independent missions and resources, and they exist within larger organizations that have diverse missions and structures. Therefore, the assemblage of earthquake organizations is a disparate group that lacks any coherency other than a common interest in earthquakes. Hence, voluntary cooperation among them is essential. This cooperation is achieved through international organizations, professional societies, and joint projects of many types.

The large number of organizations within the United Nations system that have an interest in earthquakes is indicated by the membership of the Inter-Agency Working Group for the IDNDR, which includes about 20 organizations. The three organizations that have the largest responsibilities are:

i) United Nations Educational, Scientific and Cultural Organization (UNESCO) - promotes advances of science and information exchange.

ii) Department of Humanitarian Affairs (DHA) - promotes the reduction of earthquake losses through the advocacy of the IDNDR and by assisting specific countries in disaster mitigation projects.

iii) United Nations Development Program (UNDP) - assists economic development, which inherently influences land-use planning and construction practices.

In addition, the World Meteorological Organization (WMO) has provided essential support to seismology for decades by transmitting data over WMO data lines. The concept of WMO evolving into a World Geophysical Organization has been discussed, without any conclusion. An organization like WMO, with operational capabilities to conduct global and regional programs, does not exist for earthquakes. A larger role for WMO could help in this regard, particularly for multi-hazard projects.

Of great importance to global earthquake monitoring, a new international organization has been established in Vienna to implement the Comprehensive Test Ban Treaty (CTBT). The instrument systems under this organization include seismic arrays and other stations to detect underground and atmospheric nuclear explosions worldwide. Of course, the seismograph stations also detect earthquakes and will provide data for research on them. The Global Seismograph Network, about 130 digital stations operated by the U.S. Geological Survey and the U.S. National Science Foundation through the Incorporated Research Institutions for Seismology (IRIS), augments the CTBT network and is the primary source of data for global earthquake studies.

The International Council of Scientific Unions (ICSU), a non-governmental organization which promotes international activities among scientists, has an interest in earthquakes through the International Union for Geodesy and Geophysics (IUGG). Under IUGG, the International Association for Seismology and Physics of the Earth’s Interior (IASPEI) plays a major role in coordinating and promoting international earthquake studies. IASPEI has a commission on Earthquake Hazard Assessment and Prediction, split into two sub-commissions, one of which deals with earthquake prediction. Although this association is well organized and proactive, it has no funds for support of specific activities.

The exchange of seismic information is also facilitated by the International Seismological Center, located in the United Kingdom, which compiles earthquake data and issues a worldwide seismicity catalogue. Similar information is issued by the U.S. Geological Survey’s National Earthquake Information Center and the Federation of Digital Seismograph Networks.

Numerous professional societies have earthquake interests, including: European Seismological Commission, Seismological Society of Japan, American Geophysical Union, European Geophysical Society, Seismological Society of America, and the Earthquake Engineering Research Institute, to name but a few. The foregoing organizations largely provide coordination functions.

There are also highly regarded national seismological bureaus, agencies or institutions located in a number of countries that are particularly exposed to seismic risks. Monitoring, research and application projects are conducted overwhelmingly by these national or state/province level governmental entities or by universities, and to a lesser extent by the private sector. The government entities are of many types: science, emergency response, regulatory, etc. In universities, the work is usually done in earth science or engineering departments. The private-sector firms are usually in some aspect of the geotechnical or engineering business or in the insurance or financial sectors.

It should be evident from the foregoing discussion, that the conduct of earthquake programs is a far-flung enterprise. This effort could become even more effective and strengthened by taking the following steps:

i) The development of linked computer systems (Internet, World Wide Web, etc.) now offers a means for rapid exchange of data, which should be utilized to facilitate studies related to earthquake prediction and hazard assessment.

ii) IASPEI has surveyed „The Practice of Earthquake Hazard Assessment“ (1993) and has evaluated short-term earthquake precursors through its Sub-commission on Earthquake Prediction. These efforts are commendable and IASPEI should be encouraged and supported to carry its work further. For example, with financial support, IASPEI could formally identify the most earthquake-prone regions, evaluate progress in addressing the earthquake threat in these regions, and recommend steps to improve earthquake readiness.

iii) The IDNDR demonstration project Global Seismic Hazard Assessment Programme (GSHAP) was launched in 1992 to promote regionally coordinated approaches to seismic hazard evaluation, in coordination with IASPEI and other international endeavours.

iv) Assistance is needed, particularly by developing countries, in conducting programs to mitigate earthquake losses. Those United Nations agencies primarily concerned with the application of technical abilities, and others involved with operational programmes for the development of national capabilities are well placed to provide this assistance. They, along with similar programmes supported by international or bilateral technical assistance agencies, should be further developed and utilized. As an example of the types of activities that are useful, the IDNDR demonstration project, supported by Japan and conducted by the Secretariat, Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS) is aimed at applying mitigation methods to reduce losses in urban areas, especially in developing countries.

v) As the IDNDR concludes, after 1999 there will be a need for continuing coordination and promotion of natural disaster mitigation activities. It is essential that organizations within the UN system be assigned this responsibility, with particular attention being given to means that enable scientific knowledge and global experience to inform policy considerations appropriate for individual country requirements.

vi) Some earthquake experts, though not all, believe there should be an international capability in addition to coordination and promotion, to conduct geological hazard programmes, comparable to the capability currently provided by the World Meteorological Organization for hydrometeorological hazard programs. The concept of establishing a comprehensive international „geosciences“ hazards programme office should be evaluated.

Research Needs

Although substantial progress has been made in understanding the fundamental nature of earthquakes, assessing earthquake hazards, predicting their effects, and mitigating their impacts, much remains to be done. The study of earthquakes is a relatively youthful science; it began less than a century ago and has had an adequate global observational capability for less than 50 years. Much remains to be learned and research efforts should continue to receive high priority.

The highest priorities in the research area are:

i) Advance the basic understanding of earthquakes.

ii) Improve earthquake monitoring systems in areas of high seismicity that are not presently monitored adequately.

iii) Improve inventories of active faults and earthquake catalogues that are globally complete above a specified magnitude level.

iv) Advance methods for assessing earthquake hazards.

v) Advance studies for determining whether precursors exist that can provide a basis for predicting earthquakes.

vi) Advance methods for mitigating earthquake impacts.

Technology Transfer

Transferring the knowledge from scientists and engineers to practitioners who can apply it in mitigating earthquake losses is of equal importance to developing new information This is a difficult process and frustrations abound in bridging gaps among the various disciplines involved. As many mitigation methods involve building and land-use practices, the implementation of mitigation measures involves many competing interests, with few existing incentives and current mandates to move beyond singular viewpoints to a more comprehensive perspective within a number of the societies concerned. There is a particular challenge for public policy authorities to seek to integrate more scientific and technical viewpoints in the determination of national disaster prevention initiatives. Priorities in this area should include:

i) Increase studies to evaluate and demonstrate the efficacy of mitigation measures.

ii) Substantially expand resources for training programs on mitigation methods, particularly for experts from developing countries.

iii) Improve the availability of information resources on the science and technology of earthquakes for both public and public policy authorities.

iv) Improve infrastructure for exchanging information among countries.

Implementation

Although early warning capabilities for earthquake hazards exist only in a general way for long-term prediction, and, only to a limited extent, in special situations, for intermediate prediction, these limited capabilities can still help to reduce earthquake losses. Long-term predictions provide the basis for adopting building and land-use practices to withstand and avoid earthquake-induced effects. Therefore:

i) All countries should assess their vulnerability to earthquake hazards, with assistance from international and regional organizations, where necessary.

ii) Countries that are earthquake prone should evaluate the nature of the threat in sufficient detail to provide a basis for establishing an appropriate building code and adopting land-use plans which minimise risk.

iii) Where possible, the most earthquake-prone countries should consider strengthening or retrofitting vulnerable structures, particularly critical facilities such as hospitals, schools, primary infrastructure, and emergency facilities.

iv) All earthquake-prone countries should establish an institutionalized operational capability and plan for responding to an earthquake disaster.

v) When anomalous phenomena occur that are perceived to be associated with potential earthquake activity, earthquake experts should evaluate the situation on a case-by-case basis to determine the needs for increased monitoring and the threat to people and structures.

vi) Where possible, earthquake-prone areas should develop and employ capabilities for reporting the occurrence of a hazardous earthquake and for predicting its effects, for example, tsunamis and ground shaking, in near-real time to facilitate emergency response.

vii) International and regional organizations should provide assistance to developing countries in carrying out all of the foregoing recommendations.

Volcanic Eruption Recommendations

Organizational Responsibilities

The responsibility for volcano monitoring and warning is presently handled on a volcano-by-volcano basis, often involving a local office of a national volcanological agency and (or) a local university. These arrangements work well. In general, there is little need for warnings to be disseminated beyond the immediate environs of the volcano. An exception to this local rule is the need of the aviation community for global dissemination of eruption warnings. Jet aircraft that have encountered ash sustained serious damage and, in at least three cases to date, lost all power. Restarting ash-damaged engines is difficult and will not always be possible, so immediate global warnings of ash clouds are critical.

Global coordination and communication between observatories is facilitated by the World Organization of Volcano Observatories (WOVO), a commission of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). Excellent monthly and yearly reporting of volcanic activity is coordinated by the U.S. Smithsonian Institution's Global Volcanism Network and by the Volcanological Society of Japan, respectively. However, none of these organizations provides real-time, 24-hour-a-day volcano information that can serve the needs of the international aviation community.

In response to this evident requirement, a new structure for warning pilots is being organized by the International Civil Aviation Organization (ICAO), a body of the UN, with strong technical support from volcanologists and aviation meteorologists. Warning responsibility for regions of the Earth is now vested in nine Volcanic Ash Advisory Centres (VAAC's), typically located in major air traffic control and (or) aviation meteorology facilities around the world. Volcano observatories provide warnings of expected or actual eruptions to the nearest VAAC. The VAAC's, in turn, relay those warnings plus observations from pilots in the vicinity of the volcano to all aircraft and airlines of the region. Messages will also be forwarded electronically to all of the VAAC's, because airline dispatchers need to know even of eruptions a continent away, to provide extra fuel and instructions to intercontinental air crews.

Other organizations that assist in the general endeavour of volcanic early warnings include:

- UNESCO extends support for training courses, especially for scientists in developing regions;
- UN-DHA provides technical advice on volcanic emergency management through specific projects; and
- Bilateral partners, such as a volcano crisis assistance team of USAID's Office of Foreign Disaster assistance and the U.S. Geological Survey working with its partners in a number of developing countries.

Research Needs

Research that reduces uncertainties in eruption forecasts makes it easier for officials to act upon those forecasts. Specific research needs include:

i) Study of the behaviour of volatiles in and escaping from magma, through a wide range of physical and chemical conditions.

ii) Origin of subtle but important differences between various types of long-period earthquakes.

iii) Refinements of geodetic methods, such as radar interferometry and real-time GPS for measurement of ground deformation.

iv) Numerical modelling of the entire pre-eruptive, eruptive, post-eruptive process.

v) Initiation and (or) upgrading of monitoring at unmonitored and under-monitored volcanoes, taking advantage of new technologies such as global cellular telephone communications by which smart data loggers can be queried from afar.

Technology Transfer

A substantial gap exists between volcano observatories of industrialized and developing countries. Much progress has been made over the past two decades, and some types of measurements, e.g. by GPS, are now less expensive than they were just a few years ago. Despite their reduced cost, these technologies remain expensive for developing countries, as are the high costs of maintaining state-of-the-art equipment and staff. Recent high-tech advances threaten to widen the gap further.

Technology transfer is crucial for volcanology and for those people living around volcanoes in developing countries. Yet, some efforts of the past have foundered. New equipment is easy to transfer, but it won't be used well or for long if there isn't a deeply felt need from well-trained local researchers, careful training for technicians to operate the equipment, a generous inventory or ready access for spare parts, and sustained operational budgets beyond the initial capital expenditure for the provision of all these supporting capabilities.

Improved Electronic Communications and Public Education

Accurate forecasts will only be useful to the extent that officials and citizens receive, understand and employ them. Helpful tools to communicate warnings include:

i) Videos of volcanic hazards and crises responses, as in two public education videos recently prepared by IAVCEI.
ii) Exchanges between officials faced with volcanic crises and those who have recently faced such crises.
iii) Modern and reliable communications equipment. Many volcano observatories of the world have very limited communications capabilities that are neither adequate for the needs of the aviation community, nor to keep current with rapid advances throughout better-provided observatories. Wired or wireless telephone and Internet access for all observatories would significantly improve the communication of warnings.

Landslide Recommendations

Organizational responsibilities

Landslide investigation, monitoring, and hazard assessments involve organizations from many levels of government, academic institutions, as well as from private sector engineering and engineering-geology companies. Cooperation is achieved through international organizations, international meetings, professional societies, and joint projects of many types.

The International Symposiums on Landslides (ISL) were initiated in 1972 by the Japan Landslide Society. After the Third ISL in India in 1980, the operation of the ISL was undertaken by the International Society on Soil Mechanics and Foundation Engineering through its Technical Committee on Landslides. At the Seventh ISL held in Trondheim, Norway, 308 papers were presented along eleven themes. They included assessment and management of landslide risks and hazards, and early warning, monitoring and instrumentation (Senneset, 1996). Many disciplines are involved in landslide studies, including but not limited to geology, geotechnical engineering, hydrology, and forestry; consequently, the scientific meetings and publications covering landslide topics appear in many different technical journals and are sponsored by many different academic and professional organizations. For example, the International Association of Geomorphology holds conferences every four years with sessions, symposia on landslides and related topics. In 1997, the American Society of Civil Engineering sponsored an international conference on Debris-flow Hazards Mitigation.

The extent and economic significance of landslides in 136 countries and areas, including subsea landslides, were reported by Brabb and Harrod (1989). These reports have been a valuable contribution to the IDNDR. Landslide News, a yearly publication of the Japan Landslide Society, describes recent major landslide events worldwide and is distributed to a wide audience of practitioners. The U.S. Geological Survey operates a National Landslide Information Center (NLIC), a public repository of information on landslide hazards. The Directory of the World Landslide Inventory (Brown et al., 1992) is a worldwide guide to the people and institutions that deal with landslide hazards on a regular basis.

The International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory was initiated in 1988 at the Fifth ISL in Lausanne, Switzerland to assist the establishment of a detailed list of the world's landslides. This working group prepared a suggested method for the creation of the basic unit of the inventory, the „Landslide Report“, and suggested how these reports can be compiled in a landslide summary. In 1994, the Working Party became the International Union of Geological Sciences Working Group on Landslides which expanded its venue to include landslide terminology, information on unstable rocks and soils, development of a field manual for landslides, continuation of landslide inventory compilation, and a newly formed committee on Landslide Risk Assessments. The Working Group draws its membership from a wide variety of landslide researchers in 40 nations belonging to the International Association of Engineering Geology (IAEG), the International Society on Soil Mechanics and Foundation Engineering (ISSMFE), and the International Society of Rock Mechanics. The Working Party (WP/WPI) has assisted the United Nations in understanding the worldwide distribution of landslides by preparing reports suggesting a method for reporting landslides, how landslide reports can be summarized, a method of describing the activity of individual landslides, and a multilingual landslide glossary (WP/WPI 1990, 1991, 1993 a,b).

Research Needs

Although the methods of identifying areas subject to landslide hazards have dramatically improved, most parts of the world do not have adequate information on landslide hazards for regional or local planning, building, or regulation. The cost effectiveness of gathering information for hazard evaluation can be documented (Bernknopf et al., 1989), but legal, legislative, public authority, and insurance measures to minimize landslide hazards are well behind the technological aspects of landslide prediction. The highest priorities in landslide research include the following:

i) Advance the understanding of landslides.

ii) Advance methods for assessing landslide hazards.

iii) Increase the application of landslide hazard evaluation in rapidly developing areas.

iv) Improve real-time landslide monitoring systems for hazard evaluation and warning.

v) Advance mitigation techniques for reducing landslide losses.

vi) Develop, together with private insurers, improved methods for insuring against landslide hazards.

Technology Transfer

The application of new methodologies for landslide hazard assessment and warning must be successfully transferred from geologists and engineers to public officials, developers, and others, who for the sake of public safety must make decisions regarding regional planning, transportation and lifeline planning, and emergency services. Priorities in this area include:

i) Training geologists and engineers from developing countries.

ii) Demonstrate application of newly developed landslide hazard assessment techniques in pilot projects undertaken in consultation with local authorities.

iii) Improve national and regional landslide information centres for public distribution of landslide information.

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