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Anticipation of Geophysical Hazards

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Contents

Anticipation of Geophysical Hazards

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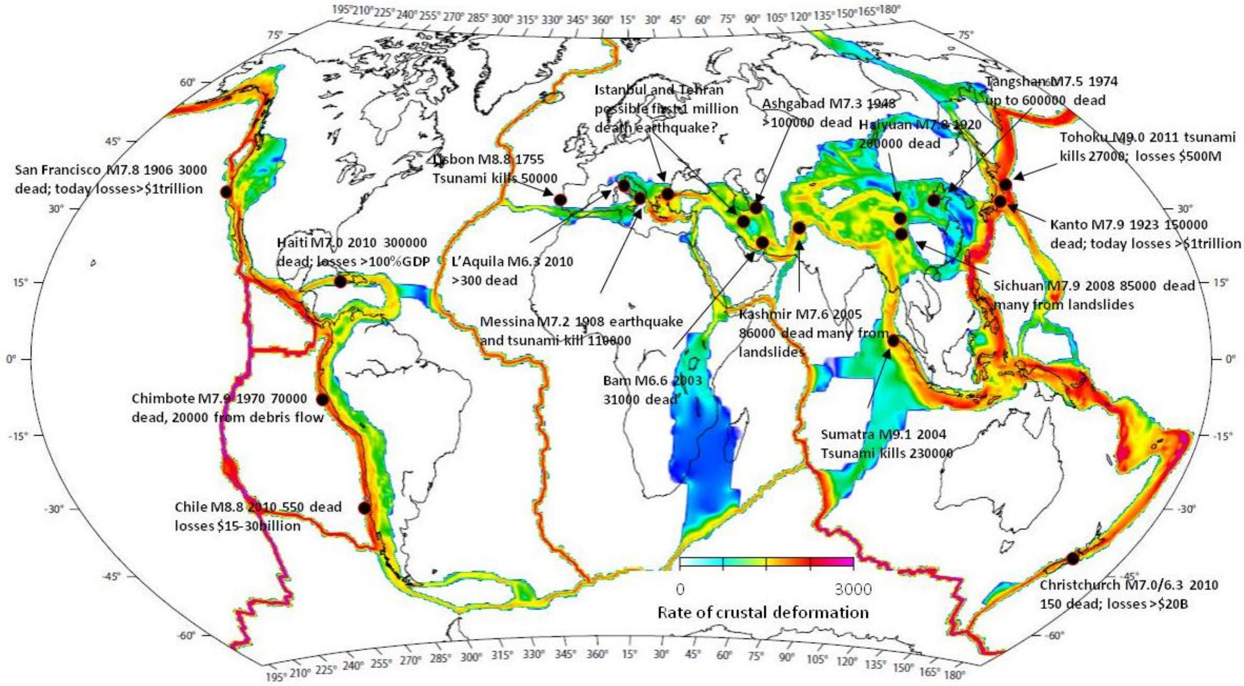
SUMMARY

The great majority of all natural hazard casualties in recent decades have been caused by geophysical hazards - earthquakes, volcanoes, tsunamis and landslides. Collectively these killed more than 2 million people in the 20th century and the death toll in the 21st century already approaches 0.75 million. The total economic loss in the 20th century adjusted for inflation exceeded $2 trillion, and in this century the loss already approaches $0.5 trillion[1]. Despite substantial increases in our understanding of these hazards, the rates of loss from them have increased progressively over time, largely because of increased societal exposure. The need for better geophysical science in disaster risk reduction is greater now than ever; even small advances have the potential to save millions of lives. We can see that past investment has brought notable benefits in recent decades; we have good examples to show that where we have focused research (e.g. on the geological hazards associated with Montserrat) our anticipatory skills have markedly increased. We now need to build further anticipatory geophysical programmes that will reduce the risk of disasters, saving both lives and livelihoods. These should focus on plate boundaries and the Alpine-Himalayan belt systems and capitalize on recent observational technologies. If we do so it is reasonable to expect that improvements in understanding of these systems, and innovation, will substantially improve operational anticipatory services by 2040. However, this will rely on a concerted, global, scientific effort, not only on anticipating geophysical hazards, but ensuring that enhanced skills are built into risk reduction. This paper reviews the nature of the hazards and the relevant current science, focusing upon anticipation of the location, severity and timing of the most destructive events. It attempts to identify the most potentially fruitful research directions in terms of impact reduction as well as their successful application.

[1] This estimate is obtained by summing the estimated cost of geophysical hazards from 2000 – 2012 on the NOAA hazards database. http://www.ngdc.noaa.gov/hazard/

Figure 1. Global distribution of major geophysical disasters, past and anticipated, against a global map of the rate of crustal deformation . The vast majority of deaths and economic losses associated with these disasters occur near mapped faults at high strain-rate active plate interfaces and within the lower strain-rate Alpine-Himalayan belt.



1. INTRODUCTION

Two thirds of deaths arising from natural hazards in recent decades have been caused by geophysical disasters[2]. Most resulted from earthquakes and their consequences but other primary and secondary geophysical hazards such as those from volcanoes, landslides and tsunamis, have also been significant contributors. Here we review present scientific capability in anticipating these hazards in terms of space, severity and time. We then provide an assessment of likely avenues of scientific development that may take place or are required, suggesting where effort should be focused in the next 20 years - both to maximize immediate benefits to society, and to strengthen our long-term capability to mitigate disasters. Hazards arising from geophysical processes are unevenly distributed around the globe, with the heaviest concentrations being at the boundaries between plates, and within the broad zone of continental deformation stretching from the Eastern Mediterranean through the Middle East, Central Asia, and China (Figure 1).

The term "anticipation" covers a spectrum of advance warnings of hazardous events whose common factor is that they can provide a basis for mitigating action by the community to which the warnings are issued. For such warnings to be useful, they must include the location, magnitude, and timing (or frequency, in some cases) of the anticipated events, with each of these parameters assigned an uncertainty that is small enough to make the statement useful to the recipient community. Short-term anticipation, for example, might reliably inform the evacuation of a vulnerable population - whereas long-term event frequency assessments can inform decisions about levels of permanent preparedness, such as seismic resistance of buildings, or on where new construction should be located. We assume that the anticipation will result from the application of a reproducible set of scientific procedures. Anticipation focuses on planning for future events, in contrast to responsive actions, which are activated once an event has started (for instance the issue of a tsunami warning or the automated shut-down of infrastructure).

This report focuses on anticipation, though it needs to be emphasized that this is simply one step in a chain of activities - all of which need to be successfully tackled if disaster risk is to be reduced. There have been plenty of examples recently - notably the Indian Ocean tsunami in 2004 and the 2010 Haiti earthquake - when events were anticipated in the sense that scientists

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[2] Over the last 20 years (ISDR 2012: http://www.unisdr.org/archive/27162).

knew of the imminent risks, but where little was done to reduce disaster risk; the reasons being that the risks were not communicated sufficiently effectively for those who needed to know and/or were not acted upon. Anticipation will *only* result in effective disaster risk reduction when communicated and acted upon appropriately.

1.1 Earthquakes

Over 2 million people died in earthquakes during the 20th century; approximately 75% of those deaths were caused by building collapse, with the secondary hazards of landslides and tsunamis accounting for most of the remainder (Daniell *et al*. 2011). The economic costs of earthquakes over the same interval amounted to about $2 trillion[3]. In the developing world such losses can (as, for example in the 2010, Haiti, earthquake) exceed the GDP of the affected country (Daniell *et al*. 2011). The first trillion dollar earthquake is being actively considered in Tokyo (Miyazaki 2010) and the western USA[4,5,6].

The global annual death toll from earthquakes increased steadily during the 20th century, and in the first 12 years of the present century 700,000 people died as a result of these (Daniell *et al*. 2011). Similarly, the rate of economic loss associated with earthquakes and their secondary impacts is increasing. Two of the five deadliest and five of the ten most costly earthquakes in history have occurred in the last 12 years (Daniell *et al*. 2011). These recent rapid increases do not reflect variability in the natural system; there has been no statistically significant change in the frequency of damaging earthquakes (Shearer & Stark 2012). Earthquake risk is increasing globally more or less in direct proportion to exposure in terms of the population and the built environment[7]; the increased risk results principally from the migration of the human race, in huge numbers, into cities that are exposed to earthquake hazard.

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[3] Adjusted for inflation at present values.
[4] Final Project Report USGS Hayward Fault Scenario; http://www.earthquake.usgs.gov/research/external/reports/08HQAG0016.pdf
[5] http://earthquake.usgs.gov/aboutus/sesac/docs/SESAC_summary0110_final.pdf
[6] HAZUS-MH Used to Support San Francisco Bay Area Earthquake Exercise http://www.fema.gov/library/file/dl_sfeqlosses.pdf
[7] United Nations International Strategy for Disaster Reduction Secretariat (UNISDR), 2009. *Global assessment report on disaster risk reduction*. ISBN/ISSN:9789211320282, 207 p. http://www.preventionweb.net/english/hyogo/gar/report/index.php?id=9413.

That hazard presents itself in two sharply contrasting settings. Most of the great earthquakes take place at the interface between tectonic plates (for example in many places round the Pacific rim, or in Indonesia and the Philippines). Here rapid accumulation of strain, and resulting short recurrence times of events on structures whose geometries are relatively well understood, have stimulated targeted observation of the hazards, resulting in some effective societal responses (Sieh 2006; McCloskey 2011). Many of the most *damaging* earthquakes, however, take place in the continental interiors, far from known plate interface structures, often striking unprepared populations (e.g. Bhuj, 2001; Bam, 2003; Kashmir, 2005; Wenchuan, 2008). Here, because the rates of strain accumulation are smaller and the hazards are more distributed, the magnitude – indeed, in many cases the existence – of the earthquake hazard is poorly characterized and different techniques are required to anticipate and reduce the impact of future destructive earthquakes.

The vulnerabilities of societies in these two different settings also differ starkly. Some developed countries exposed to earthquakes on known plate interface structures have an impressive ability to resist them. For example, fewer than 0.05% of the 7.5 million people exposed to Intensity VIII shaking in the 2010, Chile and 2011, Japan earthquakes died; and those that did, died from tsunami inundation[8] (England & Jackson 2011). The story is completely different in the continental interiors where earthquake mortality often exceeds 10% of the population, and (as for example in the 1976, Tangshan, or the 2003, Bam, Iran earthquakes) can be as high as 30% (England & Jackson 2011). About 150 million people in sixty megacities are exposed to earthquakes; these are the locations in which we should expect the greatest future death tolls (Tucker 2004; England & Jackson 2011). Many of those cities were destroyed by earthquakes in the past, at times when their populations were small fractions of their present sizes. A million-death earthquake during this century is expected, probably in one of the mega-cities that lie within the Alpine-Himalayan belt (Billham 2009; Hough & Bilham 2006).

1.2 Volcanoes

Volcanoes are the most spatially constrained of the geophysical hazards; magmatism is exclusively associated with the unusual subsurface conditions associated with plate boundaries (86%) and with intraplate hotspots (14%). High rates of volcanism typically coincide with the regions of high crustal strain identified in Figure 1. Despite their comparatively limited geographic distribution, volcanoes have the potential to produce direct global environmental and climatic impact via injection of fine ash and aerosols into the stratosphere. They are disproportionately located in countries classified as low and middle income by the World Bank.[9]

Worldwide there are more than 1500 potentially active volcanoes on land with around 20 physically erupting at any one time (Siebert & Simkin 2002). Volcanic eruptions are highly variable in style, magnitude, intensity and duration. A single eruption can, over a period of time, show significant variation with apparent ‘spikes’ in the level of activity. Eruptions can last for less than a day or for decades. Some volcanoes erupt frequently; others have gaps of hundreds to thousands of years between eruptions. For example Mt. Pinatubo had not erupted for over 500 years before its VEI[10] 6 catastrophic explosive eruption in June 1991 but Mt. Etna has had regular eruptions recorded since 1500 B.C. (Siebert *et al*. 2010). Eruptions are usually (but not always) preceded by periods of unrest, but many episodes of unrest do not lead to eruptions. The variable style and magnitude of eruptions means that the extent and degree of impact can vary from localised total destruction (e.g. 1997 destruction of the capital of Montserrat by pyroclastic flows and lahars) to global climatic and environmental impacts. On average, an eruption capable of causing significant local or regional damage/loss of life and global disruption to aviation has historically occurred every few years to every decade (Deligne *et al*. 2010); and one capable of causing a major global environmental and climatic impact[11] occurs every few hundred years (Deligne *et al*. 2010) (the last being the VEI7 eruption of Tambora in 1815; Oppenheimer 2003).

Volcanic eruptions can cause *direct* losses (e.g. fatalities, destruction and damage to buildings and infrastructure) and *indirect* losses (e.g. loss of livelihoods, contaminated drinking water supplies and crops, disruption to business and tourism via disrupted air travel, and long term environmental impacts (e.g. Lockwood and Hazlett 2010). Since 1600AD there have been

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[8] Data obtained from the NEIC Significant Earthquake data base http://earthquake.usgs.gov/earthquakes/eqinthenews

[9] World Bank. (Dilley, Maxx; Robert S. Chen, Uwe Deichmann, Arthur L. Lerner-Lam, and Margaret Arnold, with Jonathan Agwe, Piet Buys, Oddvar Kjekstad, Bradfield Lyon, and Gregory Yetman). 2005. Natural Disaster Hotspots: A Global Risk Analysis. Washington, D.C.: World Bank.

[10] Volcano Explosivity Index. The reported size, or "bigness," of historical eruptions depends very much on both the experience and vantage point of the observer. To meet the need for a meaningful magnitude measure that can be easily applied to eruption sizes, Newhall and Self (1982) integrated quantitative data with the subjective descriptions of observers, resulting in the Volcanic Explosivity Index (VEI). It is a simple 0-to-8 index of increasing explosivity, with each successive integer representing about an order of magnitude increase (Smithsonian Institution Global Volcanism Program)

11 Many eruptions, for instance those of El Chichon (1982) and Pinatubo (1991), and clusters of smaller eruptions, have resulted in notable global temperature falls.

278,880 fatalities as a result of 533 volcanic 'incidents'; where cause is known (274,501 cases) pyroclastic flows, 'indirect' causes, tsunami and primary lahars caused 90% of the fatalities (Auker and Sparks pers. comm.). Five individual incidents account for 58% of all fatalities. Preliminary statistical work that discounts these five incidents and considers the overall 'background' trend suggests that the application of modern science to anticipate volcanic hazards and disaster risk reduction has had an overall positive impact with more than 50,000 lives saved in the last 100 years (Auker and Sparks pers. comm.). However, science is not equally applied in all regions of the world and both actual and potential progress should ensure no more avoidable catastrophes like that following the small (VEI 3) eruption at Nevado del Ruiz, Columbia in 1985 (~28,000 deaths; Voight, 2003). The next large magnitude volcanic eruption need not be a disaster.

The widespread disruption of even small eruptions is well illustrated by the April to May 2010 VE14 Eyjafjallajokull event. This had a measured global impact on services and business with total losses estimated at $5 billion and the net aviation sector losses at $ 2.2 billion[12]. Partly as a result of improved hazard forecasting, the impacts of the much larger eruption of Grimsvötn volcano the following year were not so severe (Webster *et al*. 2011). Similar analyses of larger recent events are still sparse but estimates of costs from the *local* impact of the VEI 5 Mount St Helens eruption of 1980 stand at almost $1billion with forestry losses alone reaching almost $450 million[13]. Smart's Insurance Bulletin, May 18, 1981 reported that over 40,000 insurance claims were filed, 166 recovery loans were applied for and $215 million was spent on dredging rivers up until the autumn of 1981.

1.3 Landslides

In the last decade over 80,000 people have died in landslides; the vast majority of these in mountainous areas (Petley 2012a). Developing countries, especially in Asia, Central and South America, and the Caribbean are the most seriously affected areas (Kirschbaum *et al*. 2009). Coseismic landslides (triggered by earthquakes) account for about 60% of the fatalities, with landslides triggered by rainfall (especially monsoonal precipitation and that associated with the passage of tropical cyclones) representing the majority of the remainder. The economic costs of landslides are poorly quantified, but in many mountainous countries they represent a significant impediment to development (Kirschbaum *et al*. 2010).

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12 http://news.bbc.co.uk/1/hi/business/8634147.stm

At present it is difficult to estimate long term trends in terms of losses from landslides due to a lack of reliable data (Petley 2012a). Even in more developed countries that have invested heavily in landslide mitigation, such as Italy (Guzetti 2000), trends in landslide losses have not reduced (Petley 2012). There is strong evidence that losses in less developed mountainous countries, such as Nepal, are increasing (Petley *et al*. 2007). Given that landslide impacts are increased with higher population density (especially in urban areas), deforestation and precipitation intensities (Alexander 1992), it is reasonable to extrapolate that landslide losses will increase unless large-scale investment is made into mitigation and management programmes. Landslide activity is likely to increase as tropical cyclones continue to become wetter, as permafrost and ice thaw and melt more rapidly in mountainous terrains and heat waves become longer and more intense (Huggel *et al*. 2010).

Landslide hazards occur in all environments with slopes, though they are most intense in two particular settings. Primarily they occur within environments in which water actively erodes terrain, most particularly along coastlines and on riverbanks. Rates of coastal erosion through landslides can exceed 10 m per year, threatening communities located close to coastal cliffs (Pye and Blott 2006). Riverbank erosion is a significant hazard, especially for example in the Mekong Delta of Vietnam, where it is estimated that over a million people will need to be relocated in the next decade[14]. Second, landslides occur extensively in steep mountain areas, especially those with high rates of tectonic uplift (Larsen & Montgomery 2012) (i.e. those close to active plate boundaries in Figure 1). Rates of landslide activity are increased in areas where there are high rainfall intensities, such as is generated by the SW Monsoon in S. Asia and by tropical cyclones in E. Asia and the Caribbean. Thus, the most significant landslide hazards are located on the southern edge of the Himalayan Arc, in southern and central China, along the land masses bounding the Philippine Sea plate in East Asia, in Indonesia and in Central America, including the Caribbean islands (Petley 2012a).

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13 Washington State Department of Commerce and Economic development Research Division,http://volcano.oregonstate.edu/education/facts/CostVolc.html
14 http://english.vietnamnet.vn/en/society/22567/river-landslides-may-force-relocation-of-several-thousand-households.html

1.4 Tsunamis

Tsunamis have caused at least 300,000 deaths since 1900 (Daniell *et al*. 2011)[15] and have substantial economic impact. The greatest number of recent deaths resulted from the 2004 Indian Ocean tsunami which killed 230,000, though the economic impact of the 2011 Tohoku-oki earthquake and tsunami (estimated at $300-500 billion) was more costly (Daniell *et al*. 2011). The hazard from tsunami inundation is projected to increase as more people live nearer to the sea in coastal cities and densely-populated river deltas.

Tsunamis are generated when a large volume of the ocean is vertically displaced, such as by a submarine earthquake, a volcanic eruption, or a subaerial or submarine landslide. All of these sources, where close to the coast, have the potential to generate local, high-intensity inundation but, their impact at greater distance depends upon the mechanism of tsunami generation. Tsunamis generated from a spatially extended source, such as a large or great megathrust earthquake, can travel thousands of miles across the ocean without losing energy. The magnitude 9.5, 1960 Valdivia event generated off South America, for instance, produced a tsunami that travelled across the Pacific and struck the Japanese coast with waves up to 3 m high (Lida *et al*. 1967). Spatially restricted sources, such as submarine landslides and volcanic collapse, also have the potential to generate locally devastating tsunamis but, when the tsunami wave travels across the open ocean, it disperses more rapidly. Thus when the wave impacts on a coast distant from the source (except where this is large-volume, such as in the Storegga landslide off Norway in 8,200 BC, or the volcanic collapses in the Hawaiian Islands) its energy is reduced and the impact lessened.

Many recent tsunamis have been generated from earthquakes located at oceanic convergent plate boundaries. The high-impact tsunamis of 2004 and 2011 occurred in the Indian and Pacific oceans, but there is also significant tsunami hazard in the Mediterranean and the Caribbean. Although these devastating recent tsunamis have been associated with very large (magnitude > 9) megathrust earthquakes, where the key factor is the magnitude of sea floor displacement, some tsunamis are much larger than would be expected from the magnitude of their causative earthquake. These “tsunami earthquakes” (Kanamori, 1972) are particularly dangerous because there is little associated ground shaking and local populations may remain unaware of the scale of the hazard. In addition warning systems may not be triggered because these are only activated when the earthquake is above a certain magnitude. The recognition of tsunami earthquakes is leading to a re-evaluation of present understanding of earthquake mechanisms, where it is generally the case that rupture takes place at depth in well-cemented rock. Tsunami earthquake rupture takes place at shallow depth in unconsolidated sediments, previously believed to be impossible.

Tsunamis generated by submarine landslides have been recognised since 1929 when 28 people died on the Canadian coast, from an earthquake-triggered event, but it was not until in 1998, when the northern coast of Papua New Guinea was devastated by a localized, highly-focused, tsunami that killed 2,200 people, that the severity of the hazard was at last recognised (Tappin *et al*. 2008). It is now generally accepted that submarine landslides occur in many different environments, the so-called 'landslide territories' (Lee *et al*. 2007), along both convergent and passive plate margins. Where there is a tsunami earthquake along a convergent margin with significant sediment accumulation it may be difficult to identify the actual cause, earthquake or submarine landslide, because the failure mechanisms of both are influenced by the presence of the sediment. The locations of these sediment accumulations are known but their relationship to the generation of anomalously severe tsunamis is only established for the northern Japanese convergent margin; elsewhere the hazard is undefined.

Volcanic tsunami sources are as complex as those for earthquakes and submarine landslides, with major geographically influenced tectonic (Tappin 2009) and climatic linkages (Tappin 2010). Most deaths from volcanic tsunamis have occurred at convergent margins: the 1792 collapse on Mt Unzen, Japan, led to a tsunami which killed 10,000 people (Siebert *et al*. 1987); and the tsunami from the eruption of Krakatau, Indonesia in 1883 killed over 36,000 people on the coast of Java and Sumatra (Simkin *et al*. 1983). Most recently, in 2002, the eruption of Stromboli, in the Mediterranean caused a volcanic flank collapse that created a local tsunami 9-10 m high (Tinti *et al*. 2005). Volcanic tsunamis are also generated in other tectonic settings, such as on oceanic islands, such as Hawaii and the Canaries, where a major lateral collapse taking place today could cause severe human and economic losses from the resulting tsunami.

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[15] Figures are uncertain because most tsunamis are sourced from earthquakes, and differentiating who dies from what cause can be difficult.

2. SCIENCE-BASED ANTICIPATION

2.1 Earthquakes

2.1.1 Anticipation of location

The plate interfaces are narrow zones in which the locations of many seismogenic faults, and their associated seismic hazards, are well known. Here, accurate knowledge of the spatial distribution of hazards underpins a wide range of effective responses. Despite the highly publicized failures during the 2011 Tohoku earthquake, there were a large number of successes, based on solid science, which saved many lives and protected huge volumes of infrastructure. Some progress has been made in identifying the source regions of future earthquakes, although mistakes still outnumber successes. Stress interaction modelling, for example, led to the assessment that stress changes caused by the 2004 Sumatra earthquake increased the likelihood of nearby earthquakes (McCloskey *et al*. 2005). The M 8.7 Nias earthquake was consistent with this forecast, but other earthquakes forecast in that assessment have not occurred. Equally, the locations of “seismic gaps” can sometimes indicate areas of increased hazard, for instance that which was eventually ‘filled’ by the 2010, Maule, Chile earthquake (in this case, however, the magnitude of the slip was unexpected, and the general reliability of the seismic gap model has been questioned: Geller 2011; Stein *et al*. 2011).

In developing countries economic pressures fuel the desire for improved spatial anticipation of earthquakes. A decade of earthquake science on the Sumatran margin has indicated a large accumulation of strain which may result in a large earthquake in the near future (see, for example, Sieh 2006; McCloskey 2011). This has substantially raised awareness of the earthquake issue in western Sumatra, and has generated a focused preparedness campaign which is increasing the resilience of the inhabitants of this highly seismically active coastline. Nevertheless, much more research in the application of deterministic, physics-based earthquake forecasting will be required before advances such as those noted above may be converted into operational protocols. However, it is clear that significant probability gains can already be obtained by quantifying earthquake spatio-temporal clustering. These are currently being implemented for example by major programmes of the Italian Civil Protection and by the USGS (Jordan *et al*. 2011).

In contrast, the continental interiors hold zones of deformation that are hundreds or thousands of kilometres in width, and contain huge numbers of faults, whose locations are often unknown. Here, earthquakes with magnitudes in the range 6.5 to 8 cause death tolls of tens of thousands.

Almost all recent devastating earthquakes in continental interiors have been on faults whose hazard was poorly characterized, or even unrecognized, before the earthquake took place. Hindsight shows, however, that in most cases the fault and its associated hazards could have been recognized if current geological and geophysical knowledge had been applied to the affected area beforehand. Given the recent emphasis on the failures of the conventional probabilistic approach to seismic hazard in places where the distribution of faults is relatively well known, it would be unwise to export probabilistic seismic hazard assessment (PSHA) techniques uncritically to those parts of the continental interiors where the distribution of faults is poorly known. In such areas, we have yet to take the first step, which is to identify the distribution of hazard. Space-geodetic techniques, particularly GPS, allow us to measure strain at regional scales (Nocquet 2012), but these surveys are time-consuming and expensive. Recent advances in satellite radar interferometry offer the possibility of mapping strain accumulation over wide swathes of the continental interiors (Cavalie *et al*. 2008; Wright and Wang 2012).

2.1.2 Anticipation of severity

The energy likely to be released by future earthquakes is more difficult to anticipate than their location. At plate interfaces, the concept of characteristic earthquakes which held that earthquakes were characteristic of the fault segments on which they occurred, has been largely discredited by observations in Japan (Simons *et al*. 2011), Sumatra (Konca *et al*. 2007; 2008) and Chile (Lorito *et al*. 2011). Furthermore, the complexity of ruptures exposed by dense instrumentation of recent smaller events shows that many of these earthquakes crossed features that had previously been thought to represent barriers to rupture. On the other hand, the concept of interface coupling (Scholz & Campos 2012) provides a physical basis for fault segmentation and at least in some cases, e.g. under Simeulue Island (Meltzner *et al*. 2012) and the Batu Islands (Konca *et al*. 2007; 2008) off western Sumatra, this segmentation has controlled the termination of many ruptures over almost 1000 years. Observations of the variability of fault constitutive properties by, for example, the accurate location of aftershocks (McCloskey and Nalbant *et al*. 2009) and the modeling of these complex interactions using mathematical analysis of realistic physical models (Kaneko *et al*. 2010) will undoubtedly lead to better spatial and magnitude anticipation in the coming years.

In the continental interiors the anticipation of the energy released in future earthquakes is fundamentally different but again there are areas of clear progress and, perhaps more importantly, clear data collection strategies which have the potential to improve the situation dramatically in the next few years. Where strain rates are low and recurrence times are in consequence long, the problem of estimating the maximum expected event size using standard PSHA methods is difficult and some of its underpinning assumptions are unreliable (Geller 2011; Stein *et al*. 2011). These estimates are often based on earthquake catalogues whose duration is short (50 to 100 years) in comparison with the interval between the largest events in an area, which may be 1,000 to 10,000 years. This problem is at the heart of the issue that many devastating earthquakes in the continental interiors are unanticipated. Again though, understanding the deformation style and history provides important insight. Detailed geomorphological reconstructions informed by high resolution strain-rate maps have the potential to provide these data and to constrain the seismic hazard in these regions much more reliably than by using standard PSHA techniques.

2.1.3 Anticipation of timing

Short-term anticipation of earthquake shaking, such as might reliably inform the evacuation of a vulnerable population, seems to be as distant a prospect now as it has ever been. The picture is less bleak when we consider secondary hazards such as aftershocks (McCloskey and Nalbant 2009 – though the damage they inflict is relatively small compared to the main earthquake), landslides (see 2.3.3) and particularly tsunamis (see 2.4.3), where recent progress has made significant operational advances.

2.2 Volcanoes

2.2.1 Anticipation of location

The strong association of hazardous volcanism with plate margins and existing volcanic edifices means that the point location of future eruptive activity is relatively well constrained in any one region. Nonetheless with the current state-of-the-art an important distinction needs to be made between the few well-monitored volcanoes and the great majority that are not well-monitored or not monitored at all. For example in a study of 441 active volcanoes in 16 developing countries, 384 had rudimentary or no monitoring (Tilling 1989). Even in the USA, where the most frequently active volcanoes are the focus of intensive monitoring and associated scientific research, many volcanoes are under-monitored compared to the long-term hazards that they cause (Ewert *et al*. 2005). It is noteable that of the 20 biggest eruptions since 1800, half occurred at volcanoes that had not erupted during historical time. Globally our knowledge of the eruptive histories of each volcano is poor because of lack of data; for more than one third of volcanoes we know only about activity documented since the beginning of the twentieth century and much of this lacks sufficient detail (Siebert *et al*. 2010). To effectively anticipate volcanic hazards we need good global volcano monitoring, combined with the thorough understanding that comes from field study and geophysical modelling to interpret data. Global and local targeted initiatives will produce a step-change in our ability to anticipate volcanic activity.

2.2.2 Anticipation of severity

In the case of well-studied and monitored volcanoes where historical and geological data are available anticipation of severity (and eruptive duration) is possible within a probabilistic framework. Forecast uncertainty increases with the range of activity observed at any particular volcano. For example Vesuvius near Naples in Italy has produced a range of eruptions over the last 2000 years from the high intensity (VEI 5) activity that destroyed 'Pompeii' in A.D 79 to low impact lava flows in 1944. The modification of an intensity forecast in the light of the character of monitored unrest and sub-surface movement immediately prior to an eruption is not currently possible, but potentially on the horizon (see 3.2). Fundamentally the state-of-the-art in this domain remains empirically-based but draws on past activity, and generic modelling of hazardous phenomena which may be placed within a probabilistic framework (Marzocchi *et al*. 2010) or used to develop scenarios.

At poorly understood volcanoes it is not possible to anticipate eruption severity and duration, except by very general analogue studies.

2.2.3 Anticipation of timing

Forecasting of sufficient precision to provide enough warning to implement well-embedded effective emergency procedures already occurs at a few type-specific, well studied and monitored, volcanoes (such as at Soufriere Hills, Montserrat). The interpretation of monitoring data can enable the short-term (hours, days) anticipation of the onset of new eruptions or peaks in activity during long-lived eruptions. Fundamentally the state-of-the-art in this domain is still empirically-based but increasingly both deterministic and statistical frameworks are used to interpret these data (Eichelberger *et al*. 2012). There is also new scope for recording, understanding and interpreting sub-surface magmatic movement with new and improved detection methods (see 3.2 below). A critical focus for current research programs is improving our ability to anticipate the unrest that is most likely to lead to an eruption or change in eruptive style from one mode to another.

Anticipation of eruptive activity at poorly understood volcanoes is dominated by the unsatisfactory empirical application of models based on known analogues. For many volcanoes we only know about an eruption once it has commenced. Such volcanic eruptions are often detected first by satellite monitoring as part of the 'Volcanic Ash Advisory Centre' activities to divert air traffic. In many cases it is often not clear for several days which volcano was the source of the ash cloud (e.g. Nabro 2011).

2.3 Landslides

2.3.1 Anticipation of location

Anticipating the location of landslides is a widely-used approach to managing landslide hazards in high vulnerability areas (van Westen *et al*. 2008). Most commonly, planning regulations stipulate the levels of investigation and mitigation that are required for the development of sloping land. These planning regulations are informed by large area landslide susceptibility assessments that usually combine slope gradient and material type. Such measures have proven to be an effective first order approach to managing the potential impacts of landslides in areas in which planning regulations can be effectively enforced. Site-specific assessments of hazard areas are also well developed, generally using detailed site investigation techniques plus numerical modeling of likely stability.

However, there are three key limitations on current capabilities. First, there remains a dearth of effective techniques to generate local-scale landslide hazard and susceptibility analyses from regional scale assessments. Considerable effort has been expended in this area using correlation-based, factor-based and modeling-based approaches (van Westen *et al*. 2008), but the effectiveness of these techniques is far from clear (van Westen *et al*. 2006). Second, anticipation of the location of landslides triggered by co-seismic events remains very uncertain, primarily because the processes through which seismic excitation promotes instability are poorly understood (Wasowski *et al*. 2011). Finally, a significant proportion of very large landslide events appear to occur without a primary trigger, probably through the processes known as progressive failure (Petley *et al*. 2005). Almost all high mountain slopes undergo slow rates of deformation, but only a small proportion appears to collapse catastrophically. Presently, the anticipation of locations that are prone to catastrophic collapse through progressive failure remains problematic.

2.3.2 Anticipation of severity

In the context of landslides, severity might be defined as the potential to cause loss, which is defined by three key parameters: the area affected, the runout distance and the kinetic energy (i.e. the combination of the rate of movement and the mass of the material). On a site specific basis, after detailed ground investigation, it is possible to constrain reliably the likely volume of a landslide and the source area. Constraining landslide volumes from regional-scale hazard analyses is problematic, although standard scaling laws that convert surface areas identified as high hazard into volume are sometimes used (Stark & Guzzetti 2009). Run-out velocity is usually determined through numerical modeling, although until recently the codes used were based upon parameters that could not be measured, such that they were better suited for hindcasting than for forecasting. However, recently new codes have been developed that permit much better simulation of runout dynamics for most landslides (Schneider *et al*. 2010). These approaches require high resolution ground models and considerable computing power, such that for regional-scale analyses friction angle based approaches are usually used. Unfortunately, very large landslides demonstrate lower levels of internal friction than is usually observed, meaning that rates of movement (and thus kinetic energy) and movement distances are greater than models would indicate. At present there is considerable disagreement about the mechanisms that generate these values of internal friction (Schneider *et al*. 2011). The problems with the evaluation of the rate of movement remain sufficiently challenging that in most cases prevention remains the preferred mitigation option.

2.2.3 Anticipation of timing

Anticipating the time of failure has allowed the development of successful warning systems for landslides in a number of locations, such as in Hong Kong (Chan *et al*. 2003). These approaches primarily are based on understanding the triggering threshold of rainfall events in terms of precipitation intensity and duration. An experimental development of this has been the use of rainfall satellites, most notably Tropical Rainfall Measuring Mission (TRMM – NASA), to provide large-scale warnings (Hong & Adler 2007). Currently, these techniques are constrained by the low temporal resolutions of the satellites used, but the next generation of instruments will improve this capability markedly. Anticipation of the time of coseismic landslides of course relies on anticipating the seismic trigger, which is problematic.

For specific slopes, warning systems have also been developed that analyse movement rates, and in particular the identification of accelerating trends of movement (Petley *et al*. 2005). This is usually undertaken in conjunction with surface or subsurface monitoring of movement, although acoustic emissions may prove to be helpful in some circumstances. In high wall mines, the use of slope radar to monitor slope movements, and to provide warning of failures is developing (Petley 2012b). This has increased the safety of such operations markedly, although much work is needed on the observed patterns of movement and their proper interpretation.

2.4 Tsunamis

2.4.1 Anticipation of location

The most common, damaging tsunamis result from earthquakes along convergent margins, but, as discussed (see 1.4), forecasting the location of near-future tsunamigenic earthquakes is still extremely challenging. Recent events have challenged accepted theory on where great earthquakes are to be expected and in the context of new recording technology have advanced our understanding on this. Areas of particularly high earthquake hazard such as Chile, Japan and Sumatra have benefited from considerable research, however, there are still many convergent margins where little is known. More precise identification of areas most at risk from earthquake-generated tsunamis will depend on progress with the spatial anticipation of the source earthquakes discussed above. However, there are other ways in which we might improve our identification of the spatial distribution of tsunami hazard, with one important route through mapping sedimentary geological indicators of past tsunamis. Such evidence was available before both the 2004, Sumatra, and 2011, Tohoku-oki, earthquakes but was neglected by the relevant authorities until after the events. Extensive submarine areas of many convergent margins are poorly mapped thus their tsunami hazard potential is not known. A great deal more mapping of convergent margin seabed is required before we have any real appreciation of the geological structures present that represent a risk of rupture and tsunami generation. Some tsunamigenic earthquakes may involve slip on faults not located along the interplate boundary itself (Tsuji *et al*. 2011; McKenzie & Jackson 2012). Identification of these faults will contribute to improving the quantification of the hazard. In Europe there are several historical tsunamis for which there is no certain earthquake source (e.g. those in the Eastern Mediterranean in 365, 551, and 1303, off Lisbon in 1755, and near Messina in 1908). It seems probable that the convergent plate boundary in the Southern Aegean represents a significant hazard (Shaw *et al*. 2008), but identification of the key structures remains problematic.

The study of submarine landslides and volcanoes as tsunami sources is at a much less advanced stage than for earthquakes. Although models of tsunamis generated by volcano lateral collapse have been published (Ward & Day 2001; Pareschi *et al*. 2006; Lovholt *et al* 2008), there has been no systematic modelling of tsunamis generated from the different mechanisms of volcanic eruption. The locations of submarine landslides are still poorly defined in most parts of the world; only those in the North Atlantic have been mapped with any degree of accuracy. The application of new mapping technologies over the past 20 years has led to significant advances in locating submarine slides, but probably less than 50% of these data have been released. More importantly, we have a poor understanding of what triggers submarine slope failure. Along some convergent margins, where earthquake magnitudes are small, and tsunamis comparatively large, for example, Alaska, 1946 and Java 2006, it is now recognised that sources may have been either earthquakes or submarine landslides.

2.4.2 Anticipation of Severity

There is still significant uncertainty in anticipating: the earthquake slip distribution on which the tsunami energy largely depends (Geist 2002; McCloskey *et al*. 2008); tsunami height; and the extent of wave run-up. Coastal inundation is difficult to anticipate without high-resolution bathymetry because it depends on nonlinear interaction between the wave and the near-shore sea bed morphology, and during inundation, the land surface. Even with the recent Tohoku-oki tsunami, where there is a comprehensive data set, modelling of the earthquake as a single tsunami source does not explain all the recorded run-up measurements (Grilli *et al*. In Press), suggesting another additional source, possibly a submarine landslide. Progress is being made in modelling nonlinear effects (Schlurmann *et al*. 2010) and it is likely that increased coverage and availability of high-resolution bathymetry and land topography in threatened coastal areas will contribute to improve operational forecasts of inundation from a given source. With an accurate knowledge of the earthquake source, however, the progression of the deep-water wave may be reasonably well predicted.

Recent research on tsunami from both landslide and volcanic collapse reveals that, unlike earthquake-generated events, defining the upper physical bound on the initial tsunami wave is challenging. Runups of hundreds of metres are possible from the largest events, with a subaerial landslide in Lituya Bay, Alaska in 1958 creating a wave 500 m in elevation (Fritz, *et al*. 2001). Some of the largest pre-historic submarine landslides (e.g. Storegga at 2500 to 3500 km3) and intra-oceanic volcanic collapses, such as Hawaii, (e.g. Nu'uanu at 3,000 to 5000 km3) that created initial waves and local runups of hundreds of metres (McMurty *et al*. 2004) were not associated with convergent margins. However, historical catastrophic tsunamis from collapse (and eruption) have only been recorded from convergent margins.

2.4.3 Anticipation in terms of timing

Anticipation of both when a tsunami is generated and will strike the land is required. For earthquake-generated tsunamis the problem of anticipating the actual time of rupture is the same as that of anticipating the time of the associated earthquake - which is not achievable in the foreseeable future. In contrast much progress has been made in predicting the tsunami landfall once an earthquake has taken place and a tsunami generated. In essence, the scientific problem in the far-field is just the solution of the shallow water wave equation from the tsunami source to inundated shore. Where the wave travels hundreds of kilometres across the ocean there remain infrastructural problems with getting these forecasts to remote communities; the science needed to address this problem is available, and when applied, is in most instances successful (however, only earthquake thrust ruptures are modelled, and those from different mechanisms such as strike-slip ruptures are not - thus some tsunamigenic events will still be missed). Near-field anticipation is more difficult, but here also much progress has been made. It has been shown, for example, that, since the geometry of large-scale flexure of the accretionary prism in megathrust earthquakes is, to first order, independent of the slip distribution, the travel time to the local shore (but not the wave height) is constant for most earthquakes (McCloskey *et al*. 2008). Near-field warning systems based on rapid geodetic and seismic inversions are also being tested (Babeyko *et al*. 2010). We have a relatively poor understanding of the frequency of volcanic and submarine landslide tsunamis, although it is recognised that there is commonly a climatic control on their occurrence (Tappin 2010; Keating and McGuire 2004). There is a great deal of uncertainty over the likely impact of rapid global warming on these sources, especially submarine landslides along passive continental margins. There has been much speculation on the role of ocean warming on hydrate stability and thus on submarine slope stability.

3. KEY RESEARCH AREAS

3.1 Earthquakes

The grand challenge in earthquake science over the next decades is to understand a process in which strain builds up over length scales of 10-3-106m and time-scales of 10-4-1012s, but is collapsed into an earthquake through mechanisms that probably operate on scales from millimeters and milliseconds to kilometres and hundreds of seconds. The recently discovered phenomenon of “slow earthquakes” (Dragert *et al*. 2001), which take weeks rather than seconds to propagate, the demonstration that static and dynamic stress changes can bring faults closer to failure (King *et al*. 1994; McCloskey *et al*. 2005; Gomberg & Johnson 2005) and the ability to simulate complex aspects of seismic cycles with relatively simple mathematical models, suggest that this goal may be within reach.

New science should build upon the deployment of recent technologies such as those that measure deformation (including interferometry; Brenguier *et al*. 2008a) with Earth Observation (EO) satellites, and ground based Global Positioning Systems (GPS), and broad band seismology. However, it should also capitalize on recent science establishing the routine reconstruction of slip distributions in earthquakes, of stress interaction between earthquakes, of the constitutive properties of faults, rate and state friction, and distributions of interface coupling. Furthermore, it should seek to exploit the benefits afforded by routine processing of seismic data to produce open access, high level, products such as seismic catalogues. Achieving progress relies, however, on significant improvements in the following areas.

3.1.1 Data collection

Earthquake science is still severely limited by lack of data. Although a few areas, such as California and Japan, are heavily monitored, financial constraints result in heterogeneous data coverage; poor countries with highest exposure to earthquake risk are often most poorly monitored. The costs of existing technologies will reduce over time, but the greatest benefits are expected from the development of large-scale surveys with satellite observations, combined with targeted ground based data collection including progress in low-cost survey techniques and seafloor geodesy.

If the Sentinel satellites go ahead as planned, they will provide a step change in our ability to monitor earth deformation, and identify the location of seismic hazards. If those satellites do not fly, or are delayed, there is no other practicable way to make observations on the scale of 10s to 100s of kilometres with the 10-100m resolution that satellite data provide over the next decade.

The release of strain in earthquakes takes place on a time scale of seconds to minutes. Observations on that scale are essential if we are to learn about the physics of faulting. Sensor arrays are likely to transform observation of the natural world in many ways in the coming decades. The key requirement for sensor arrays in monitoring earth deformation is the ability to measure time with the precision of ~10-11s, which would allow continuous, and dense, monitoring of ground displacements near major faults.

Devastating earthquakes have a wide range of recurrence times from tens of years at rapidly straining plate boundaries to thousands or even tens of thousands of years in the continental interiors. Palaeoseismology and geomorphological analysis allows the reconstruction of many cycles of earthquake occurrence - which is necessary if we are to extrapolate insights gained from relatively short-term data collection to these long timescales. Currently paleoseismology is too labour-intensive to achieve its potential, but these limitations can be overcome by investment in new geochronological techniques, and building scientific and technical capacity both in scientifically developed countries and in the countries most exposed to earthquake risk.

3.1.2 Multi-scale experimental techniques

Theoretical developments concerning the constitutive properties of active faults need to be tested against observations, from the scale of microns to hundreds of kilometres. Laboratory experiments on the micro-mechanics of rock friction need to be integrated with intermediate-scale monitoring of induced seismicity, and high-resolution monitoring of small sections of active faults using borehole instrumentation. Large-scale regional and global monitoring of deformation and seismicity will test the up-scaling of theoretical models.

3.1.3 Statistical methods and testing procedures

Integrating large volumes of data (e.g. accessed via European-wide platforms16,17,18) with variable uncertainty and from multiple sources into testable models is a major challenge; there is a need for improved data assimilation routines. Development of Bayesian methods for exposing complexities in data-model relations and for handling the uncertainty in multiple data streams has already begun and needs to be accelerated. The development of falsifiable

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[16] The EU NERIES portal allows access to individual broadband seismograms recorded across Europe (http://www.seismicportal.eu/jetspeed/portal/),
[17] The VERCE project approaches continuous monitoring for use in seismic interferometry (http://www.verce.eu/),
[18] The EPOS project aims to combine different types of data for multiple hazards (http://www.epos-eu.org/).

forecast techniques and methods for testing them is crucial. Extending present work on the statistics of point process forecasting to extended 2D and 3D systems and the development of methods for the integration of data from many fault systems (trading convergence in space for convergence in time) into single forecasts, testable in tens of years for events with recurrence of hundreds of years, is vital. Further work aimed at understanding the behaviour of fault rocks at different stages of the seismic cycle is necessary and is at present being developed on a phenomenological basis codified in the laws a rate-and-state friction. Forecasts presently lack a rigorous micro-physical basis which must be further developed as well as a new generation of physical, numerical models and innovative ways to employ them.

3.2 Volcanoes

The strong contrast in the state-of-the-art in anticipating volcanic eruptions between well understood and less well known volcanoes (Section 2.2) draws attention to the need for large-scale programmes to detect and monitor poorly known volcanoes and their impacts. There is a similar imperative for research on modelling and interpreting sub-surface magma movement and anticipating its detectable signals and impacts at the surface. This should catalyse a step-change in our ability to anticipate better when unrest will lead to eruption and the scale and impacts of that eruption. These developments are necessary to be able to interpret and exploit new monitoring data. Finally, without a lasting improvement to the ways in which we collate, share and exploit existing and new data, it will be much harder to make full and effective use of these developments. Achieving this will require the following:

3.2.1 Advances in Volcano Monitoring

There is a need to develop synoptic scale and global satellite surveys (including interferometry; Brenguier *et al*. 2008b), particularly addressing monitoring insufficiencies around less well known volcanoes. This needs the development of rapid processing and global change detection systems. Change detection should include the observation of thermal anomalies, airborne aerosols and particles, ground deformation and morphological change. The improved spatial, temporal and vertical resolution of EO products will contribute directly to our ability to model and anticipate the impact of hazardous flows. Monitoring and analysis will also considerably benefit from developing the use of low cost or free satellite monitoring software.

The technical development of cheap rapid deployment sensors, combined with more effective collaboration with local monitoring agencies and use of 'citizen science' (exploiting smartphones, for instance) is likely to be important. For example low-cost sensors are already being planned using current Micro-electromechanical systems (MEMS).

Improved analysis of multi-parametric datasets at well-monitored volcanoes and developments in methods (e.g. muon tomography; Tanaka *et al*. 2010), designed to quantify sub-surface magma movement, should improve precision in forecasting the onset of volcanic eruptions and the assessment of mass eruption rate (an essential parameter for ash dispersion modelling).

3.2.2 Integration of field, laboratory and experimental research

A more robust generic ability to anticipate volcanic activity relies on interdisciplinary work focussed around a particular problem or volcano. Although there are some new initiatives that partially address this,19 a more concerted effort to integrate a 'source-to-sink' approach to understanding individual systems would yield high dividends.

Experimental work in this domain would address the lack of information about fundamental physical (and chemical) properties of sub-surface pressurised magma (e.g. rheology) and their surrounding rocks (e.g., fracture mechanics) and hazardous flows, including volcanic ash plumes. The collection of fundamental data relating to these properties combined with data from the new monitoring techniques described above should lead to new deterministic models that improve precision in understanding sub-surface properties; tracking magma movement and in forecasting impacts. New fundamental data relating to the properties of hazardous explosions and flows should support the development of models that anticipate the impact of these phenomena. A better understanding of plume chemistry and reactive chemical components in ash and aerosol will produce generic models of ash and volatile transport and dispersion that will increase precision in our anticipation of environmental and health impacts of volcanic ash and gas emissions; even for less well known volcanoes and high impact eruptive events. Such interdisciplinary research will provide a focus for the trialling and development of earth observation along with new technologies in the near field as well as provide the data to further develop real-time probabilistic forecasting and measurement and modelling of impacts.

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[19]In order to achieve effective early warning of an eruption onset, multiple different specialities and technologies should be coordinated to achieve real-time analysis, better understanding of precursory signals and forecasting of magma dynamics and volcanic hazards with alert systems in place for Civil Protection and decision -makers. Development of the 'Supersite' and 'Decade volcanoes' concepts to focus on specific sites. The majority of volcano observatories would greatly benefit from coordinated monitoring support from the international community but such working requires long-term relationships and the building of trust between partners and stakeholders. The NERC Natural Hazards call has made such collaboration possible (STREVA). The EU Supersite call made such a collaboration possible (EU FP7 FUTUREVOLC in negotiation) but further opportunities are not apparent. There are very few Supersites and not enough in the developing world.

3.2.3 Improvements to data assimilation and collection

There are ongoing initiatives20 to develop data assimilation techniques in support of modelling and recognition that there must be coordination of model development and transparency in terms of assumptions and uncertainties in hazard anticipation. In parallel, the need for coordinated collection and harmonisation of data relating to volcanic activity, together with open access and availability is recognised. These aims are set to improve the effective sharing and timely analysis of data, and stimulate model development and comparison. Improvements in data assimilation and the characterisation of uncertainty will improve the application of modelling, undoubtedly benefiting forecast precision and accuracy at both well known and poorly understood volcanoes. For example, global datasets on unrest and precursory activity are not yet available; precursory signals are not well understood and not always recognised. This type of coordination then offers the prospect of improved modelling and understanding of these phenomena to improve their interpretation during an episode of unrest. Despite this, existing initiatives, which have been driven by user-demand, are patchily resourced; still strongly reliant on community goodwill and have no immediate prospect for long-term funding.

3.3 Landslides

Landslides occur in response to a complex interaction between topography, materials and trigger events, especially in areas of steep topography and high process rates. The grand challenge in landslide science over the next few decades is to unravel the ways in which these interactions yield landslide events. Present levels of understanding are sufficient to permit the mitigation of individual slopes where resources allow, but understanding of landslide hazard in the worst affected areas is deficient. It is only through developing an understanding in those environments that a significant reduction in landslide impacts will be achieved.

In recent years landslide science has built upon improvements in: technological capabilities to measure slope deformation using ground-based GPS, Earth Observation satellites, radar and LIDAR, as well as more traditional geomorphological and engineering geological mapping: understanding the constitutive properties of shear planes and zones, including concepts of brittle deformation and of rate- and state-dependent friction, as well as power law concepts; and the detailed inventories of mass landslide events, especially those associated with seismic and tropical cyclone triggers. However, future advances will rely upon significant improvements in the following key areas:

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[20]These Include the NERC-funded Global Volcano Model project (http://www.globalvolcanomodel.org/index.php); the NSF-funded Infrastructure project (http://vhub.org/) and WOVOdat (http://www.wovodat.org/)

3.3.1 Data collection

Understanding landslides has been seriously limited by the lack of large-scale inventories of mass movements. In recent years, considerable effort has been invested in generating post-seismic landslide inventories (van Den Eeckhaut & Hervas 2012), and a small number have also been created for other triggers, such as typhoons. However, these remain very time-consuming and variable in quality given the use of visual interpretation by individual operators. In recent years considerable advances have been made in the combination of high resolution satellite imagery and new computational techniques for evaluating landslide signatures in terms of spectral response and morphology (Parker *et al*. 2011). Ongoing computational advances are likely to result in the development of automated inventories at low cost and high levels of reproducibility. However, this will rely upon the availability of suitable satellite sensors; the current diminution of non-radar based EO satellites is a major concern in this respect.

It is likely that most slopes undergo ongoing deformation; as such, a landslide is just an extreme (end-stage) of a continuum of behaviors. However, we have a very poor understanding of these background levels of behavior, or of the processes that cause a transition from creep to more rapid movement events. The development of INSAR based technologies is helping to address this shortfall, and the prospect offered by the planned Sentinel satellites of large area deformation maps at a high temporal resolution will greatly assist this effort.

Only in a small number of cases have field-scale landslide experiments been conducted to failure. Such experiments provide the potential to investigate under controlled conditions the processes that promote slope failure. Unfortunately, few experiments have been undertaken using the range of technologies that are now available. In particular, understanding triggering by extreme hydrological conditions and seismic forcing requires a new generation of field-scale experiments, backed up with laboratory testing that recreates representative stress states, to understand basic mechanisms.

3.3.2Computational analysis

A new generation of computer codes is under development that will provide much better representations of real world landslide systems (Schneider *et al*. 2010). In particular, the ability to model reliably both continuum mechanics and discrete elements, permitting a single model to handle the development of failure through complex rock fracture, and the runout processes through flow, will permit for the first time proper analyses of landslide mechanics. A new generation of codes will be required that simulate the behavior of seismic waves in mountain edifices, and the response of the slopes to that forcing, in three dimensions.

3.3.3 Locally-appropriate research programmes

As shown above, a reduction of loss of life in landslides more widely can only be achieved when the behavior of slopes in those environments is properly understood. Current mitigation programmes in high mountain areas often fail because they are based upon an understanding of European or North American slope systems, which are developed in different lithologies and subject to different environmental conditions. There is a real need for comprehensive monitoring programmes for slopes in the high mountains and coasts of the worse affected areas, such as India, Philippines, Nepal, Colombia, Pakistan, Haiti and Indonesia.

3.4 Tsunamis

The varied, and very different, source mechanisms of tsunamis, the recent recognition of landslides as a source of hazardous tsunamis, the development of new technologies to map the seabed and the increasing application of more sophisticated simulation of events stimulated by several recent catastrophic tsunamis, have resulted in new avenues of research that are still developing and which need to be pursued:

3.4.1 Tsunami source mechanisms

With regard to earthquake sourced earthquakes we need to improve our understanding of the different rupture mechanisms. We require more expansive thinking on where major tsunamis are likely to take place and from these develop warning strategies that can be utilised in mitigation. Even with great earthquakes, as demonstrated by the 2004 Indian Ocean event, we still do not understand why a rupture may propagate across major structural boundaries, thereby increasing both earthquake and tsunami magnitude. From a new understanding of earthquake rupture and distribution of submarine landslides we need to determine the relationship between tsunamigenic earthquakes, “tsunami earthquakes”, slow earthquakes, and submarine landslides – which fall within a continuum (Peng & Gomberg 2010). The recent recognition of rupture at shallow depth requires research on how strain can accumulate in soft sediment. We need to improve our understanding of the spatial distribution on a global scale of submarine landslides and their scale; from this to evaluate their likelihood of failure and thereby their hazard as a tsunami source (we thus need to carry out extensive seabed mapping along coastal margins to map earthquake ruptures and submarine landslides). The mechanisms of tsunami generation from volcanic eruptions need further work; the last major tsunami from this source was in 1883, Krakatau. There are numerous active volcanoes, many near centres of population, that on eruption have the potential to generate hazardous local tsunamis; these need to be better understood.

3.4.2 End to end modelling of tsunamis

To underpin our physical understanding of tsunami sources we need to improve the capacity to model them from source through propagation to runup. Prospects look good for simple earthquake sources but few models can simulate complex tsunami sources such as those that have both an earthquake and submarine landslide component. Numerical models of tsunami must continue to improve through a combination of testing with benchmark laboratory data, instrumental tide gauge recordings and field inundation measurements. Validation of mathematical models is essential in this.

3.4.3 Tsunami warning

To first order, tsunami warning in the far field is now generally very good, with pre-computed simulated earthquake events available for the Pacific, Atlantic and Indian oceans (Gica *et al*. 2008). New real time models (e.g. Real-time Inundation Forecasting of Tsunamis - RIFT), that can forecast tsunamis based on the actual source earthquake are also being developed and can at best produce a wave-height forecast in less than one minute (Wang *et al*. 2009). With this method the source mechanism can be selected, based on the epicentre's proximity to convergent, passive, or transform plate boundaries. These new developments should be used in association with SIFT type forecasting models in the far-field but have great potential for forecasting and warning from local tsunamis because of the rapidity and accuracy of the prediction. In Sumatra (and the Indian Ocean generally) since 2004 there has been a massive investment in warning systems, particularly with regard to locally-sourced earthquake tsunamis, that are recognised here as the main threat (Lauterjung *et al*. 2010). New software has been developed that within minutes can identify the location and magnitude of an earthquake and from this give a warning of a tsunami within five minutes. However, such warning systems are still restricted to a very few regions. It is essential that once issued the warning reaches those at risk, unlike the case of the Mentawi tsunami, Sumatra in October 2010. Here the warning was given in time to evacuate, but in this region many villages did not have access to televisions, phones or radios; so over 500 died (Lay *et al*. 2011). A key element is that we are too often focussed on past disasters, rather than building on these to develop a better understanding of the hazard in other threatened areas, with other and different tsunami source mechanisms (for example strike-slip faults as in Haiti and Turkey). We need to develop improved real time warning systems, based on new technologies, such as tsunami inversion from offshore GPS networks and nearshore seabed GPS pressure sensor buoys, which can be strategically placed, and are less likely to be damaged by a tsunami.

With regard to tsunami warning from submarine landslides, little work has been done because as yet their hazard is unknown. Some research has been carried out on warning systems for tsunami hazards associated with volcanic islands, using offshore wave gauges, and preliminary results are promising (Bellotti *et al*. 2009). The development and deployment of ocean bottom pressure sensors may be a way of identifying potentially unstable regions/locations.

4. IMPROVING GEOPHYSICAL ANTICIPATION FOR RISK MITIGATION

Sections 3.1-3.4 above all set out key hazard-specific research areas. However, several generic conclusions may also be identified. These are mostly cross-cutting and common to all of the hazards. They are perhaps the most important priorities for future research in relation to geophysical hazard anticipation.

Our increasing skills in anticipation arise from the development of physically-based models that are constructed upon, and can be tested against, observational data. If we are to continue to make progress in anticipating events we must not get sidetracked by probabilistic analyses based solely on the distribution of past events, even though this might appear cost effective in the short term. Instead we should persevere in the development of deterministic science that leads to a better understanding of physical systems, an approach which will undoubtedly have greater benefits in the longer-term.

To do this it is essential that we continue the acquisition and availability of appropriate, high quality data through the deployment of satellite technologies, ground (including marine) based observations and experimental programmes. These data should be made available to researchers through secure open data access. Open data integration will continue to need to combine skills from the Earth Science and Informatics (two areas where the UK already has a lead). We need to ensure that EO continues to develop in order to permit quantitative analysis of the spatial and temporal patterns of hazardous processes to improve the ways in which we detect events and changes. By these means, we may reasonably to expect to increase our anticipatory skills within a few years.

A similar increase in anticipatory abilities may also be expected through enhanced training of scientists, allied with increased collaboration between contrasting scientific disciplines from different geographical regions. Despite the fact that many scientists come from different hazard-specific disciplines, the various geophysical hazards are inextricably linked both by their source processes and their geography. Anticipatory science will benefit from a greater emphasis on systems analysis of particular problems through interdisciplinary research programmes focusing on regions around plate margins (Figure 1). These would include the development and exploitation of new monitoring technologies, working hand-in-hand with existing technologies and approaches to gather fundamental field and laboratory data. These should be components of long-term global initiatives that improve the ways in which we collate, assimilate and share data relevant to natural hazards worldwide, and ensure that mitigation strategies are based on holistic evaluations of all relevant data.

The main barriers to progress are those of resource. Recent advances have arisen from international coordination of data collection, processing and sharing stimulated by international projects and academic societies, notably the American Geophysical Union, but the principal gap remains the lack of data in the most vulnerable countries (see above). The fundamental route to increasing societal resilience to geophysical hazards is through improving basic knowledge about the hazardous phenomena, in particular advancing understanding of the processes that generate hazards. A key task, therefore, is to grow the skills base in those regions, and this is most efficaciously achieved by the training of young scientists at the doctoral and post-doctoral level.

The UK has a distinctive role to play in such capacity building. For historical reasons, the UK has always been strong in tectonics, volcanology and landslide science, and is now developing a strong base in modeling the stress on mapped active faults and in tsunami research. Because the UK has no major indigenous earthquake or volcanic hazards, comparatively low levels of landslide hazards, and an uncertain threat from tsunamis, the scientific approach has been to work in areas that offer the best understanding of the scientific fundamentals, rather to focus on a specific geographical region.

Finally, it is important that in reducing risk we make the best of what we already know about geophysical hazards and how to prepare for them, as well as bringing the results of the latest (possibly more uncertain) research more quickly to the end-user21. We should develop understanding of the way in which communities, organisations and governments interact with, absorb and alter science. We need to ensure the hazard science is integrated appropriately with other key socio-economic drivers of risk (e.g. those addressing poverty and lack of good governance) are factored into disaster risk reduction. Thus it is essential that physical scientists work closely with those from other sectors, particularly the social sciences, and particularly those impacted by geophysical risks, to ensure that the science undertaken is applied to improve mitigation.

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[21] United Nations International Strategy for Disaster Reduction Secretariat (UNISDR), 2009. Global assessment report on disaster risk reduction. ISBN/ISSN:9789211320282, 207 p. http://www.preventionweb.net/english/hyogo/gar/report/index.php?id=9413.

5. CONCLUSIONS

- The majority of deaths from natural hazards worldwide arise from geophysical hazards, thus it is clear that anticipation of these hazards must be an integral part of mitigation toolkits.
- It is clear that even limited advances in the anticipation of geophysical hazards have the potential to reap large rewards in minimizing the loss of life and socio-economic costs associated with these events.
- There have been significant improvements in our understanding of geophysical systems over the last decade. We should now capitalize upon these, exploiting proven technologies, to build improved anticipation based science for risk mitigation.
- There is a strong need to increase the collection and analysis of high quality datasets in order to improve our understanding of temporal and spatial distributions of geophysical hazards. Large, long term, multidisciplinary research programmes provide the optimum structure in which to do so.
- Development of the skill-base of the next generation of researchers and hazard managers must also be a key component of such programmes.
- We should undertake greater multi-hazard assessment, but frame this within broader risk perspectives to ensure that our science has most impact in mitigation schemes.

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