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Seismic and volcanic hazards in Peru: changing attitudes to disaster mitigation

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Over the last 15 years there have been dramatic shifts in the consensus over how best to cope with natural hazards in economically developing regions such as South America. One very positive outcome of the United Nations sponsored *International Decade for Natural Disaster Reduction* (IDNDR 1990–2000) has been that there is now greater interchange between the work of earth scientists examining the processes and mechanics of hazard occurrence and impact, and social scientists exploring the causes of human vulnerability to hazard – and thereby disaster. This paper traces the development of this new understanding with reference to earthquakes and volcanic eruptions in Peru, one of the most hazardous countries in South America. Particular focus is placed on the excellent progress currently being made by scientists in better understanding the physical dimensions of natural hazard exposure, and the ground-breaking work by social scientists in promoting new approaches to understanding and mitigating human vulnerability to disaster. The paper concludes by emphasizing the need to build on this research to produce more inclusive, incultured and unified strategies of disaster mitigation at the local, national and international levels.

KEY WORDS: Peru, Latin America, earthquake, volcano, tsunami, vulnerability, response

Introduction

Earthquakes, which together with droughts, floods and windstorms constitute the four principal categories of natural disaster in terms of losses, have claimed the lives of almost two million people since 1900. Over the same time period volcanic eruptions – usually but not always a spatially more limited hazard – have claimed nearly 100 000 victims (CRED 2002). Natural hazards are dynamic phenomena and there is now plenty of evidence that the world is becoming increasingly exposed to them, with each succeeding decade seeing more people affected adversely and monetary losses rising inexorably. Using constant 1990 costs in US dollars, Benson (1998) has estimated that the financial burden of all global disasters in the 1980s was *c.* $120 billion compared with *c.* $70 billion in the 1970s and *c.* $40 billion in the 1960s. Before 1987 there was only one case where the insured loss from a disaster exceeded $1 billion; in 1995 alone there were 14 such instances, with the Kobe earthquake in Japan costing over $100 billion (Thouret 1999; Chester 2002).

Understanding and mitigating this risk was the motivation behind the United Nations' *International Decade for Natural Disaster Reduction* (IDNDR) (Press 1984). The Decade (1990–2000) was aimed, in particular, at addressing the chronic escalation of vulnerability to loss in the economically less developed countries (ELDCs), many of which are more exposed to climatic and tectonic extremes than the countries of the rich temperate latitudes (Figure 1); for example, Degg (1992) estimated that 86% of the most populous cities in ELDCs are exposed to natural hazards of significant loss-inflicting potential compared with 65% of the largest cities of the North (see also Steedman 1995). Latin America epitomizes the issues of hazard exposure and vulnerability faced by many parts of

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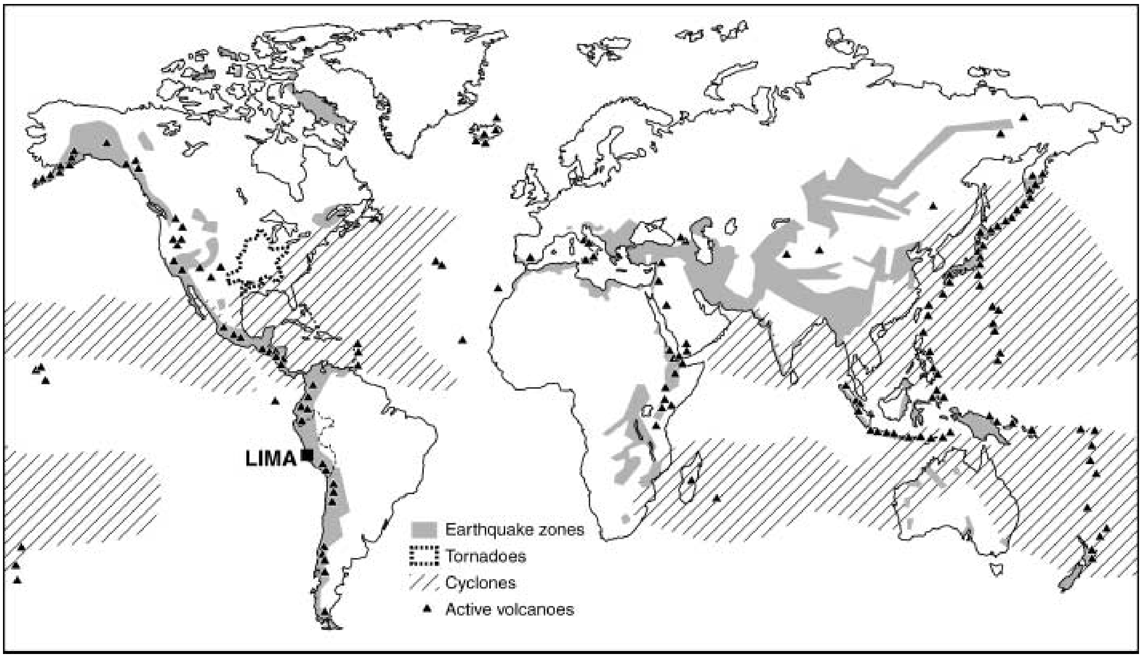

Figure 1 Some principal hazard zones of the world
Source: Based on Munich Re (1988) and other sources

the developing world. The region is exposed to a wide range of natural hazards, including earthquake and volcanic activity (Figure 1), windstorms, floods, droughts and landsliding, which regularly produce significant human and economic losses. Meteorological hazards have been the focus of much attention in recent decades, not least because of their link to intensified climatic activity including El Niño effects (Couper-Johnston 2000); but it is the earthquake hazard that (cumulatively) has proven most costly, decade upon decade, in terms of human fatalities and economic losses (OAS 1990; Degg *et al.* 1998). During the period 1900–1988, earthquakes and volcanoes accounted for 80% of the human fatalities and 50% of the total damage caused by natural hazards in Latin America (Stillwell 1992).

In this paper we explore the physical and social factors that combine to generate this susceptibility to earthquake and volcanic losses, with reference to one of the region's most highly exposed countries – Peru. We review some of the more significant developments in the understanding of these hazards and their impact in the country, the excellent progress that has been made on several fronts during the IDNDR, and the challenges that lie ahead in building on this work to produce a more inclusive and unified strategy of disaster mitigation.

Exposure to earthquakes and volcanoes in Peru

In terms of land area, Peru is South America's third largest country. Its current population of around 26.5 million is concentrated in the highlands and coastal region (Figure 2(a)), while the forested interior remains sparsely populated. The highland population has, until recently, been predominantly rural, whereas that of the coastal zone is primarily urban. The country forms part of the so-called 'Circum-Pacific Ring of Fire', which is characterized by high levels of seismic and volcanic activity accounting for approximately 76% of the global annual seismic energy release (Bolt 1993). The seismicity and volcanism of Peru are principally due to the collision between the Nazca oceanic plate and the South American continental plate (Dorbath *et al.* 1990; Tsapanos 2003). The initial zone of contact between the two is the Peru trench, located 150–200 km offshore (Figure 2(b)), where the Nazca plate thrusts beneath the much larger but less dense continental plate. Friction between the two plates generates the intense earthquake activity of western Peru (Figure 3), while heating and reworking of the subducted slab of crust is linked to Andean volcanic activity. Over millions of years compressional forces associated with the plate collision have generated the north–northwest/

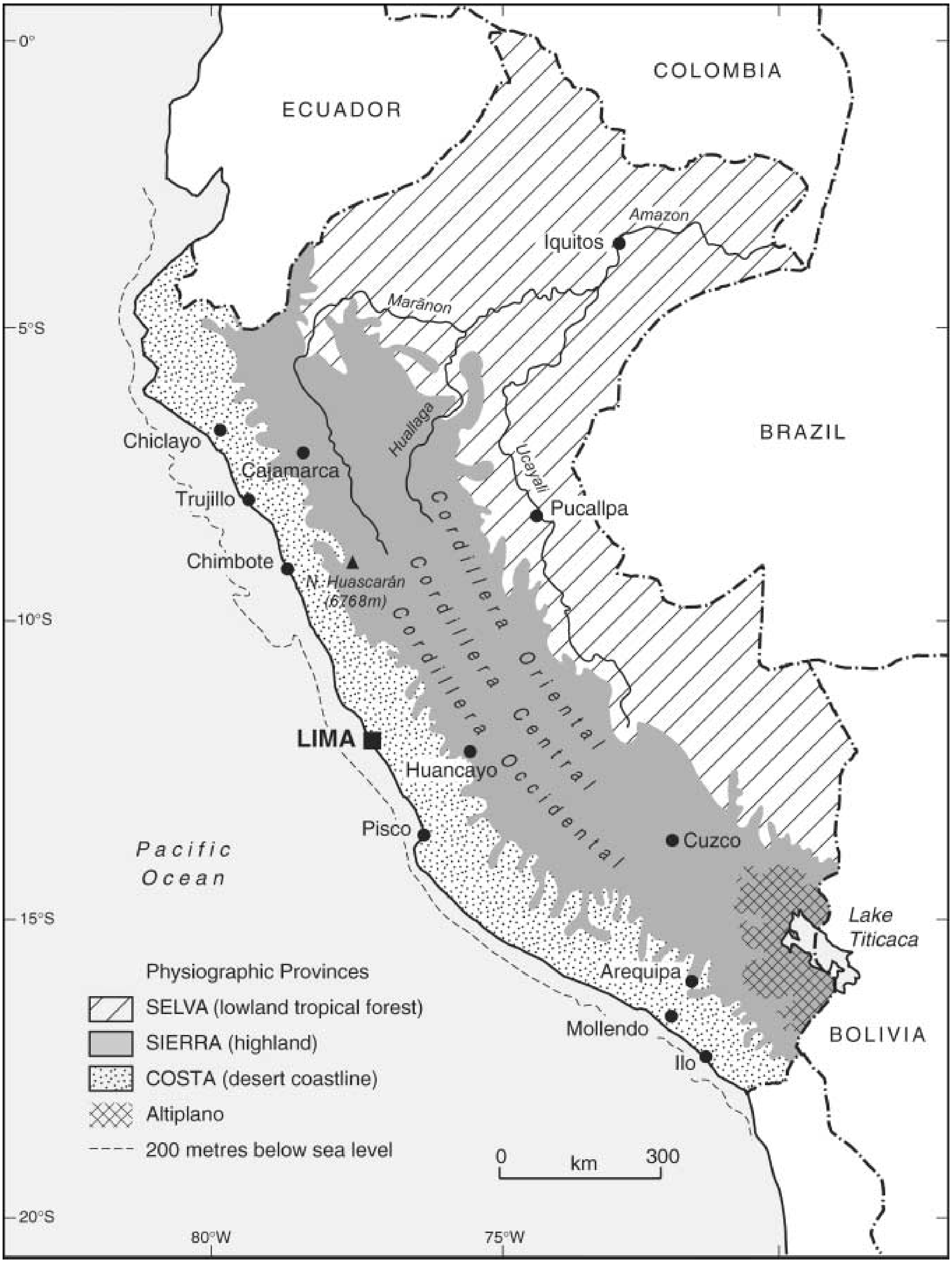

Figure 2 (a) The principal physiographic regions of Peru; (b) the tectonic setting of Peru
Source: (a) Based on various sources; (b) based upon Dorbath *et al*. (1990, 552)

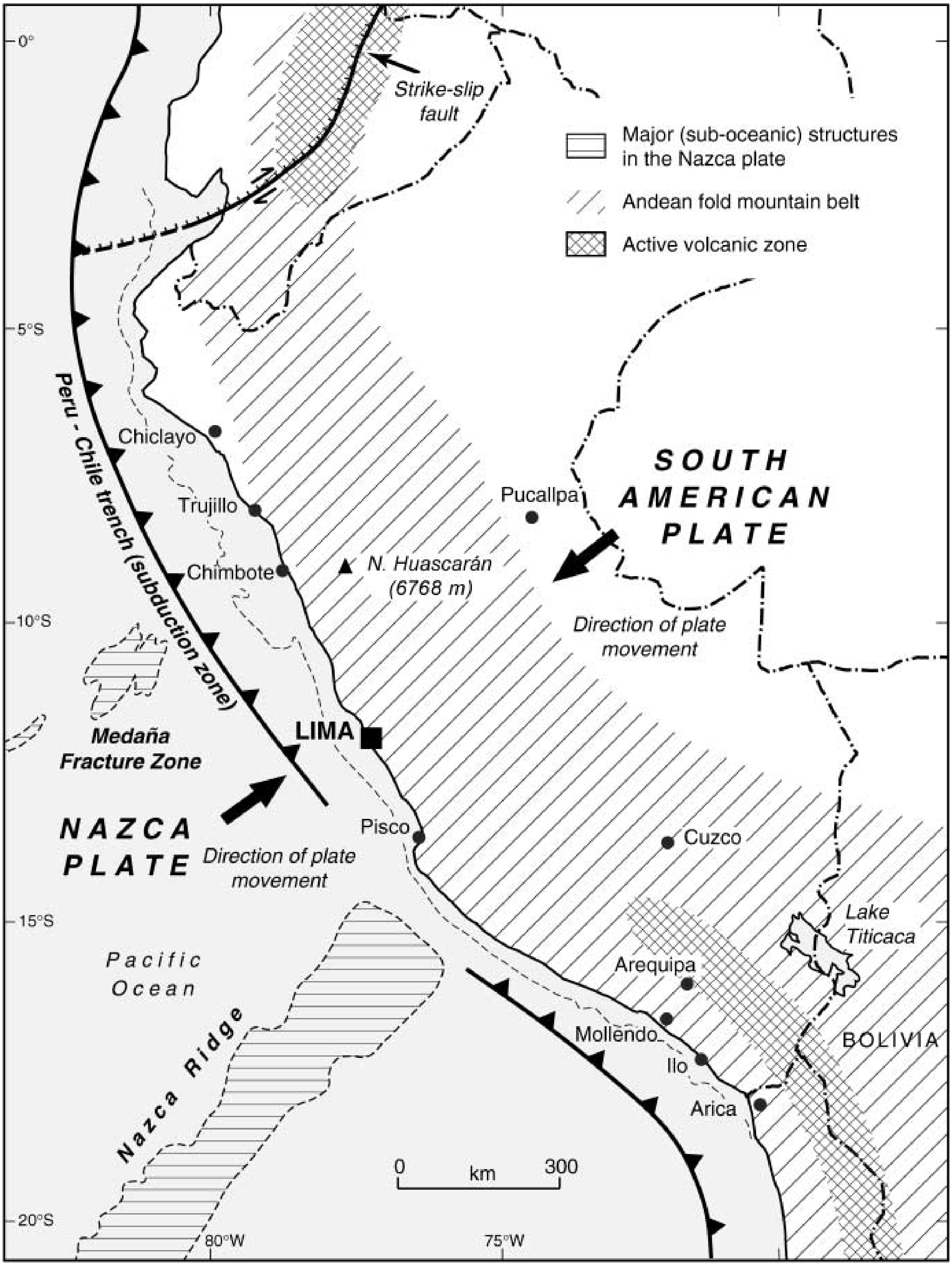

Figure 2 *Continued*

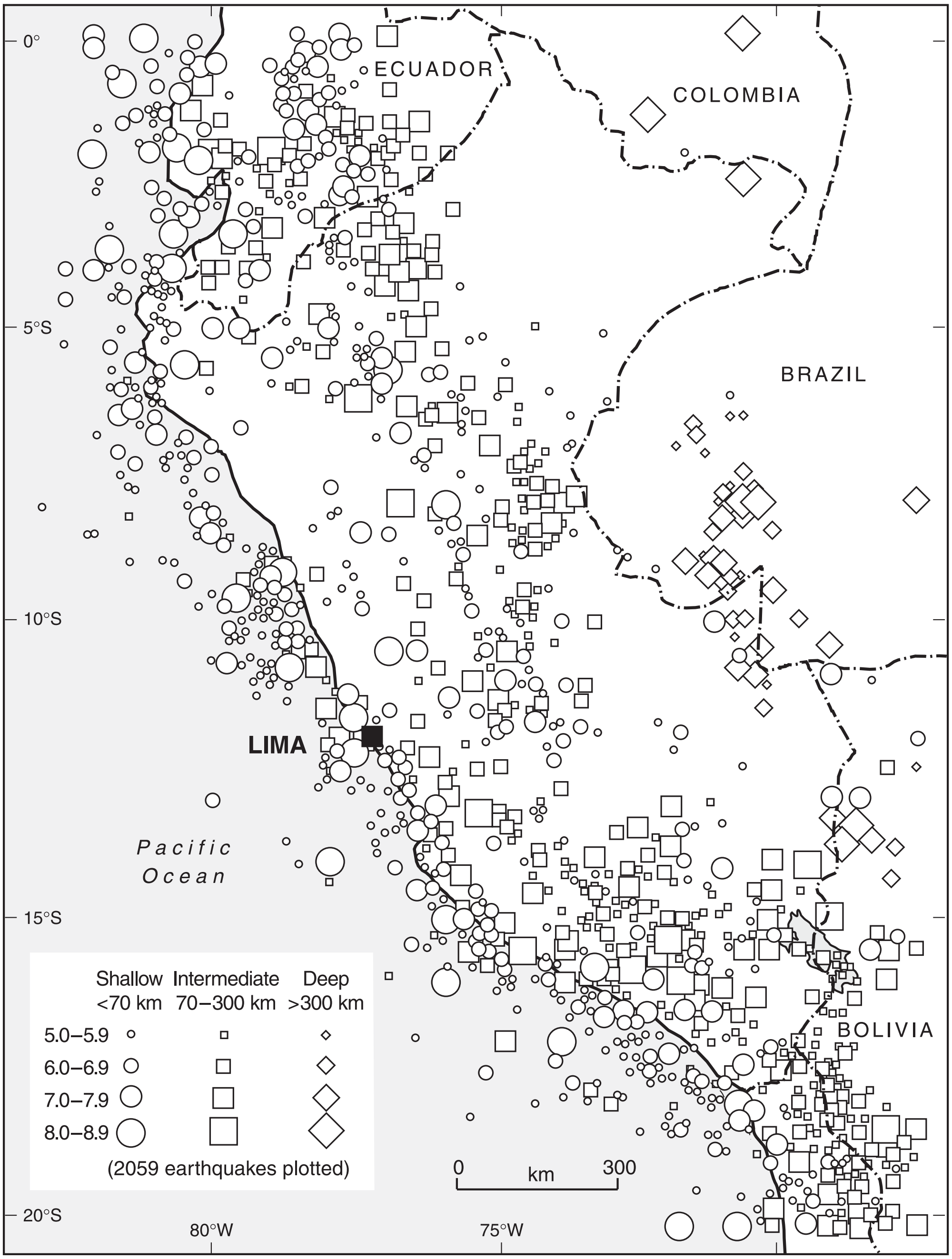

Figure 3 Peruvian seismicity ($M \geq 5.0$), 1900–1998
Source: Produced by NGDC, Boulder, CO

south–southeast trending Andean fold mountains (Figure 1), and other significant structural units at the leading edge of the continental plate, including major valleys bounded by active faults.

It is generally believed that the Nazca oceanic plate off Peru is divided into three major segments, separated by the northeast/southwest trending *Medana Fracture Zone* and *Nazca Ridge* (Figure 2(b)).

These segments move largely independently of one another, leading to considerable spatial and temporal variations in earthquake activity along the line of the trench (Stauder 1975; Nishenko 1985; Spence *et al.* 1999). In particular, the northern and central segments appear at present to be characterized by shallow (10–15°) angles of plate subduction, and this has been linked to the absence of active volcanism in northern and central Peru. In contrast, the southern segment, which comprises older, cooler and denser oceanic lithosphere, currently dips at angles of 25–30°, leading to more intense heating of the subducted slab to generate the magma that feeds both the active and dormant volcanic centres of southern Peru and northern Chile.

The central crustal segment (10° S–14° S) has been the most seismically active during the historical period, and appears to rupture in one of three ways: two thrust earthquakes rupturing approximately half the segment each (e.g. in 1678 and 1687); three thrust earthquakes (e.g. in 1940, 1966 and 1974); a single thrust event rupturing the entire segment (e.g. in 1746) (Dorbath *et al.* 1990). Many of these events have proved destructive to Lima and its environs, and have triggered damaging tsunamis. The northern segment, extending to approximately 10° S, has failed to produce a large ($M \geq 7.7$) thrust earthquake since an event in 1619 destroyed the coastal town of Trujillo. This could be because the plate boundary is strongly coupled with recurrence intervals greater than 500 years, or because it slips aseismically with little potential for generating high-magnitude earthquakes (Kelleher 1972; Beck and Ruff 1989). Seismic slip in the southern segment (from 15.5° S to the Chilean border) appears to occur mainly through large thrust earthquakes. Estimates of the recurrence interval for these vary from *c.* 250 years (Nishenko 1985) to the order of 100+ years (Dorbath *et al.* 1990). A notable large earthquake in this segment occurred on 9 May 1877 ($M \geq 8.3$). It had a rupture length of around 400 km and generated devastating, Pacific-wide tsunamis (Lockridge 1985). More recently, the 23 June 2001 ($M \geq 8.4$) Atico earthquake occurred along this section of coastline about 600 km southeast of Lima, and is among the largest events during the last 25 years to have occurred anywhere in the world (Tavera *et al.* 2002; Konagai *et al.* 2003).

Tsunamis have been triggered frequently by large earthquakes along the Peru trench, and have served to compound the damage caused by offshore earthquakes to low-lying coastal areas. This hazard is particularly acute along the coasts of central and southern Peru, where tsunamis have often attained run-up heights of several metres, and have occasionally reached more than 20 m above sea level and penetrated many hundreds of metres inland in low-lying areas (Lockridge 1985). The severity of tsunami impact in these areas has been exacerbated by the short time intervals (often less than 30 min) between earthquake occurrence and tsunami arrival, due to the proximity of the trench to the coast (Figures 2(b) and 3). The tsunami hazard appears to diminish in northern Peru (Kuroiwa *et al.* 1984), probably due to the combined influences of reduced offshore seismicity and increased width of the continental shelf. Shallow coastal water dissipates tsunami wave energy through sea bottom friction.

Figure 4 is a hazard zonation map that reflects these characteristics of earthquake and volcano hazard exposure in Peru. The zonation is based on a grid of 40 × 40 km exposure cells, and shows probable maximum earthquake intensities (on the 12-point Modified Mercalli scale) to be expected across the greater part of each exposure cell during a 50-year period, with a 10% probability of these being exceeded. The zonation has been produced using the earthquake ground motion estimates for Peru produced by Munich Re (1998) and others for 'medium' subsoil conditions, i.e. firm sediments. These estimates have been adjusted in the zonation to take account of the predominant surface geological and ground conditions of each exposure cell. This has been achieved using site response factors such as those identified by Espinosa *et al.* (1977), Algermissen *et al.* (1992) and Munich Re (1998), and topographical and geological mapping (e.g. Documental de Perú 1991; Karakouzian *et al.* 1997). The macrozonation highlights the following:

1. The coastal cities of Peru, particularly Lima, are severely exposed to earthquakes (and tsunamis). Indeed, Lima is closer to a major subduction zone than any other city of comparable size in the Americas.
2. The second city, Arequipa, is at risk from both earthquakes and volcanic eruptions.
3. Numerous smaller urban centres in western Peru are exposed to moderate levels of earthquake hazard.
4. Both volcanic and seismic hazards decline across the country in a broadly southwest/northeast direction. East of the Andes the land is part of the tectonically stable Brazilian shield, although population densities here are extremely low (Degg *et al.* 1999).

Hence, the most hazardous parts of Peru, in plate tectonic terms, are also the most densely populated areas and the locus of the majority of Peru's economic activity.

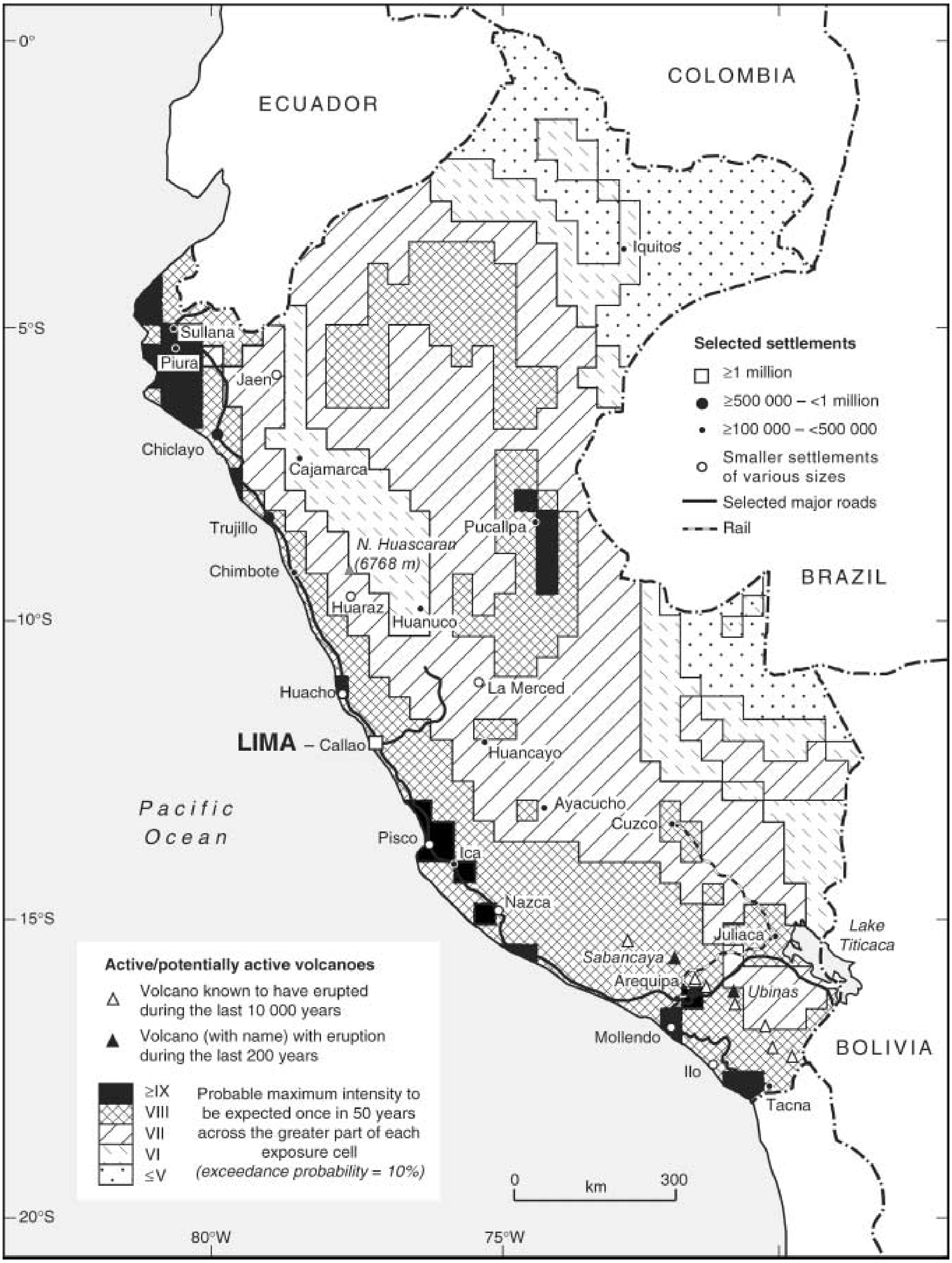

Figure 4 Earthquake hazard map of Peru
Source: Degg *et al.* (1999)

Earthquake and volcano hazard impact in Peru

Throughout its documented (i.e. colonial and post-colonial) history, Peruvian society has proved extremely vulnerable to earthquake hazards. The most dramatic manifestations of this have been the horrific humanitarian disasters caused by major offshore earthquakes during the historical and recent (i.e. post-1900) periods. For example, the 28 October 1746 earthquake ($M \approx 8.4$) devastated the coastline of central Peru, triggering a tsunami with wave run-up heights up to 24 m along the coastal plain of Lima. It destroyed the port of Callao, killing 95% of the town's 5000 inhabitants (Lockridge 1985); today Callao is Peru's largest port. More recently, the 31 May 1970 central Peruvian (Huaraz) earthquake ($M = 8.0$) was one of the worst earthquake disasters of the second half of the twentieth century. It killed more than 65 000 people, 18 000 of whom died through a single earthquake-triggered debris avalanche that fell from Mt Huascarán (Figure 2(a)) into the Rio Santa valley, burying the towns of Yungay and Ranrahirca in an instant (Plafker *et al.* 1971). The 23 June 2001 Atico earthquake ($M = 8.4$) destroyed more than 25 000 homes and badly damaged a further 41 000. In a single tragic event linked to the earthquake, more than 100 people were washed away by a series of violent tsunami waves (up to 6 m high) that struck the coastline 20–22 min after the shock. These people appear to have been tempted onto the ocean bed to collect fish stranded by the sudden withdrawal of water from the coast that preceded the tsunami (Kuroiwa 2002).

Peru's volcanoes have exacted a lower toll, largely because of the less extensive distribution of this hazard within the country (Figure 4) and the longer recurrence intervals for large Peruvian eruptions compared with earthquakes. The most recent major eruption in the country, that of Huaynaputina in February of AD 1600, nevertheless produced massive quantities of ash over a 16-day period obliterating villages for miles around, in what was, at the time, a sparsely populated region (Anon 1999a). At Arequipa, 80 km to the west–northwest of the volcano, many roofs collapsed under the weight of ash accumulation, while floods of hot water, charged with pumice, devastated the lower parts of valleys (e.g. those of the rivers Majes, Vito and Moquegua) draining from the volcano to the sea 120 km away (Bullard 1962). Recent research into the eruption, integrating historical sources with information gleaned from fieldwork, estimates that its magnitude was 6 on the 8-point *Volcanic Explosivity Index* (VEI) of Simkin *et al.* (1981); by way of comparison, the 1980 Mt St Helens eruption was VEI 5. The fall deposits covered an estimated 300 000 km^2 (de Silva *et al.* 2000; Thouret *et al.* 2002).

Much of the emphasis in studies of earthquake and volcano hazard impact in Peru has focused on cities, most particularly on its two largest cities: Lima and Arequipa. To some extent, this is justified by the high exposure of these urban centres to hazard (Figure 4), and by the arguably over-prominent role that they play in the social, political and economic fabric of the country and their respective regions. Both cities, but Lima in particular, grew at a phenomenal rate during the second half of the twentieth century (Figure 5). Lima is a classic example of 'urban primacy' and is currently home to an estimated 8 million people – some 40% of Peru's urban population – and generates around 70% of the country's economic output (Holligan de Díaz-Límaco 1998; Degg *et al.* 1999). Arequipa, the second city, has a population of 642 000, but greater Arequipa approaches one million inhabitants – some 5% of the national urban population (United Nations 2002). The human and national economic consequences of a major earthquake strike on Lima are only too clear. During the last 30 years, the economies of several Latin American countries have been devastated by the impact of single hazards that ravaged capital cities in which population and national infrastructure were over-concentrated. For example, the 1972 Managua (Nicaragua) earthquake produced an economic loss equivalent to 40% of the nation's GNP that year, while the 1986 San Salvador earthquake cost El Salvador 31% of its annual GNP (Coburn and Spence 2002).

As in other Latin American countries, so the phenomenal growth of Lima over the last 50 years (averaging 3.9% growth per annum) has not come about primarily through natural increase, since the average national population growth rate during this period has been 2.4% per annum, but through rural to urban migration. The proportion of the Peruvian population living in urban areas has increased dramatically, from 36% in 1950 to around 74% today (United Nations 2002). Migration to Lima has not been stimulated by rapid economic growth, as has been the case in some Asian ELDCs, but has taken place against a background of economic stagnation – even decline in recent decades – with the often inaccurately perceived economic advantages of the capital being viewed as more appealing than rural poverty. In both Lima and Arequipa, the result is an 'anarchy born out of poverty' (Holligan de Díaz-Límaco 1998, 10; Oliver-Smith 1999a), with the state and national economy unable to provide infrastructure, public services and employment to match the scale of inward migration. In

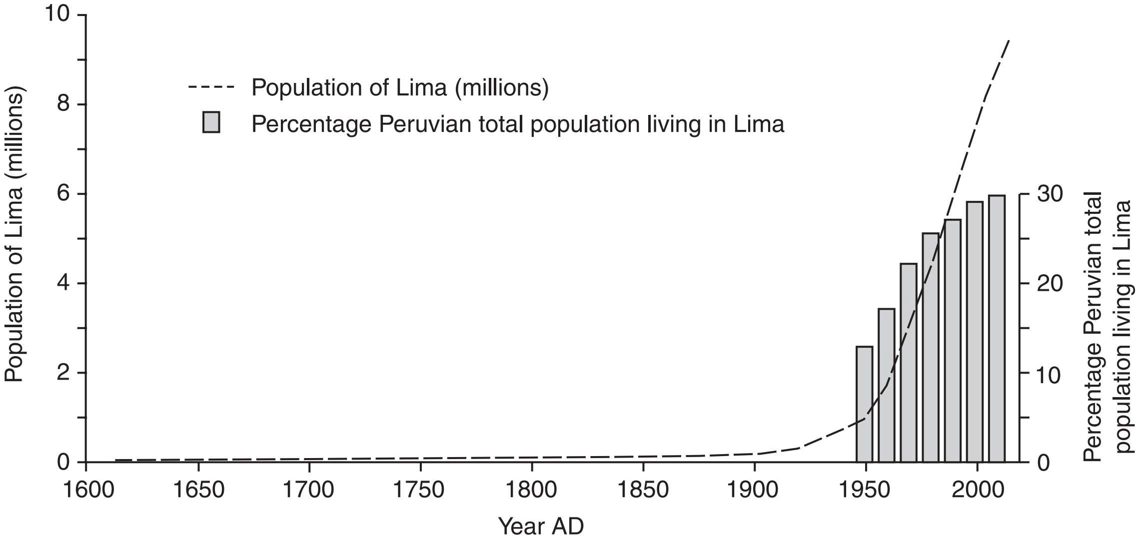

Figure 5 Graph to illustrate the growth of Lima, 1614–2015
Source: Oliver-Smith (1999a); United Nations (2002)

consequence, the poorest urban dwellers are often forced to construct their own housing using whatever materials are to hand, leading to poor quality and unplanned housing developments that are vulnerable to hazard. The vulnerability of poor migrants is compounded by the general upheaval (e.g. dramatically changed lifestyles, breaking of family and community ties, move to unfamiliar environments) resulting from migration from rural to urban surroundings (Chester *et al.* 2001). In this respect, rural communities often demonstrate a much stronger resilience to environmental extremes than urban ones, for a range of reasons, including greater closeness to nature and the inherent need for self-reliance in isolated rural areas. They are also more likely to be characterized by indigenous hazard mitigation practices and strategies that have evolved and been passed down over many generations; for example, based around shared knowledge about safe site selection and low risk building practices (e.g. see Aysan *et al.* 1995; Pelling 2003a).

Vulnerability in large cities such as Lima, however, is not just about poverty (Cannon 1994). Natural hazards typically have an uneven effect on individuals within communities, rich and poor, both in terms of immediate impact and post-disaster recovery (Morrow 1999). Susceptibility to disaster is not merely a question of income (e.g. that poor people are vulnerable people); but rather it involves the complex interplay of a range of political, physical, social, cultural and economic factors that generate different types of vulnerability in different social and environmental settings (Degg and Homan 2005). There have been various attempts to define which societal groups are the most vulnerable to hazards. For example, Morrow (1999) has classified vulnerability in a generic way on the basis of access to resources, in particular, household resources, economic and material resources, human and personal resources, family and social resources, and political resources, i.e. power and autonomy. On the basis of this, women, older members of a community and ethnic minorities, who may be socially and economically marginalized, appear particularly vulnerable to hazard impact.

Responding to earthquake and volcano hazard in Peru

Over the last 20 years a growing body of literature has been dedicated to bringing about a more effective response to natural hazards in Peru. The majority of this work has, in keeping with the ‘dominant’ (Hewitt 1983) international *hazard mitigation* agendas of the period, focused on the perceived need for a better definition of hazard zones, and a more effective hazard response. The latter has placed strong emphasis on ‘top-down’ hazard planning and regulation (e.g. through the design and implementation of building codes, and land-use planning) and improved hazard and disaster response (e.g. through hazard training and public awareness programmes).

From the late 1980s an 'alternative' hazard response agenda has gained credence (Chester 1993). This places greater emphasis on the need to understand the social, political and economic processes that create societal *vulnerability* to hazard (e.g. Hewitt 1983; Varley 1994; Twigg 1998, Pelling 2003b). It further argues that these are best tackled through 'bottom-up' (community based) initiatives to reduce vulnerability at the local level. Some key contributors to this agenda have worked mainly in Peru, but the ramifications of their work have proved influential at a global level.

The dominant (hazard) agenda

This has placed the emphasis on the need for a better understanding of the earthquake and volcanic hazards of Peru, as an essential prerequisite for improved response strategies. In keeping with the early thrust (and, indeed, the original spirit) of the IDNDR (Press 1984), the research has focused on trying to improve understanding of the hazardous processes themselves, and of the factors that influence their impact upon built environments. The need for work of this nature on the earthquake and volcanic hazards of Peru was unquestionable. For example, up until 1990 the Central Volcanic Zone of the Andes, which extends into southern Peru, was one of the 'largest but least well known areas of active volcanism in the world' (de Silva and Francis 1991, 3). Knowledge concerning exposure to earthquake hazard was at a more advanced stage, but little had been done to apply this knowledge in a systematic, nationwide strategy to reduce risk. Significant developments were made on both fronts in Peru in the run-up to, and during, the IDNDR.

In terms of volcanic hazard, two major research initiatives have been carried out in the last 15 years which have not only greatly improved knowledge of Peruvian volcanism in general, but which have also brought into focus the issue of hazardousness. The first project was undertaken in the late 1980s and early 1990s by the Lunar and Planetary Institute of Houston, Texas. Techniques of remote sensing were used to identify areas of active volcanism in Peru during the Holocene period (the last 10 000 years); i.e. the time span used by volcanologists to differentiate between active/dormant and extinct volcanoes (Simkin *et al.* 1981). The resultant reports showed that in addition to the Huaynaputina volcano, which was already known to have experienced a major eruption in AD 1600 (Hantke and Parodi 1966; de Silva *et al.* 2000; Thouret *et al.* 2002), eight volcanoes in southern Peru have been active during the Holocene, two of these within the last 200 years (de Silva and Francis 1990 1991) (Figure 6(a) and Table 1). From the perspective of hazard impact, the volcano of greatest concern was identified as El Misti because of its proximity to Arequipa, Peru's second city.

El Misti volcano and the threat that it poses to Arequipa has been the focus of a second major volcanic research initiative, conducted by a team of French, German and Peruvian scientists from a number of institutions. It has focused on questions of both pure research and hazard assessment, and is based on techniques of ground-based geological and hazard mapping, remote sensing (especially using SPOT satellite images), chronological studies using radiometric dating procedures and the interpretation of historical source materials (Chorowicz *et al.* 1992; Thouret *et al.* 1995 1999a 1999b 2001 2003; Juvigné *et al.* 1998; Anon 1999a; Lara *et al.* 2000). It concludes that even a moderate eruption of the volcano, such as that which occurred between AD 1440 and 1470 with an estimated recurrence interval of 500–1500 years, would cause considerable problems for the densely populated areas in and around Arequipa. Indeed, it is the opinion of Thouret *et al.* (2001) 'that the possible impact of Misti on Arequipa is as worrisome as that of Vesuvius near Napoli' (Le Beau 2001, 1).

From a top-down hazard management perspective it is also apparent from hazard mapping that land use in Arequipa is poorly adjusted to the volcanic threat (Figure 6(b)). Thick tephra-fall deposits would cover Arequipa and its airport; its northeastern suburbs – especially within river valleys – could be choked with pyroclastic flows/surges and further damage may result from lahars and rock-slide avalanches. In recent years, and because of population growth, the position has become potentially even more hazardous. Poor, densely populated suburbs have spread upstream beyond the northern boundary of the modern city towards the volcano and the old Inca town of Chiguata (Figure 6(b)), which was devastated by the eruption of 1440–1470. So rapid has been the recent population influx to Arequipa that today the number of people at risk from volcanic activity – *c.* 750 000 according to Thouret *et al.* (2001) – is over 100 000 greater than the total population of the city in the early 1990s. Research brings into focus the inability of local government to cope with such rapid population growth and the socioeconomic polarization between rich and poor areas that follows in its wake (Puente 1999). The dominant view has been that the hazard exposure is exacerbated by a lack of emergency-response planning and effective land-use zoning; future growth should be concentrated in the southeastern and western suburbs, ideally more than 25 km from El Misti (Thouret *et al.* 2001).

Table 1 The characteristics of the volcanoes of Peru, which have been active in the Holocene

Volcano	Characteristics
(Navado) Coropuna	At 6377 m Coropuna is the largest and highest volcano in Peru, is covered by ~130 km^2 of ice and has the potential to generate lahars. This is exacerbated by deep canyons (*quebrada*), which drain radially from the summit. On the southern flank small canyons drain into a major canyon (the Rio Majes), which intersects the coast at the town of Camaná (population *c.* 20 000; Figure 6(a)). A number of other valleys are also threatened, but these are sparely populated. Although there is no evidence of historical activity, Holocene activity is well attested.
(Nevado) Sabancaya	With a height of 5967 m, this is considered the youngest volcano in Peru and occurs on the northern flank of the older Ampato construct. Following quiescence after eruptions in 1752 and 1784, the most recent events occurred between 1990 and 1993 and were characterized by a 0.5–3 km high eruption column, tephra falling over a distance of 20 km to the east and the generation of small lahars. Under this and similar eruption scenarios, Sabancaya presents a similar – yet less severe – laharic hazard than Coropuna, because the upper part of the volcano is only covered by a small (3.5 km^2) ice cap. Thouret *et al.* (1995), however, estimate that agricultural settlements in the Colca and Sihuas valleys (Figure 6(a)) and an estimated 35 000 people are exposed to risk from a more extreme eruption, and that events similar to the 1600 Huaynaputina eruption could increase this figure by 70 000, to give a total of over 100 000. Hazard mapping has been carried out for each of these differing eruption scenarios.
(Nevado) Chachani	Summit elevation 6057 m (edifice height 2000 m), Chachani is not a single construct, but a series of related vents 24 km north of Arequipa. Although there is no evidence of historical activity and the volcano is often considered to be dormant, hot springs are suggestive of hydrothermal activity. Because the western suburbs of Arequipa only lie 24 km and 3000 m vertically from Chachani, a detailed hazard assessment is required.
El Misti	This is the most well studied and most accessible volcano in Peru and represents the greatest hazard. With a summit elevation of 5822 m and an edifice height of 2200 m, Arequipa lies only 18 km to the southwest and 2500 m vertically from the summit. As discussed in the text, various eruption scenarios have been constructed and hazard maps drawn.
Ubinas	Located ~70 km east of Arequipa, throughout the historical period Ubinas has been characterized by small lava and tephra producing eruptions which have destroyed crops and livestock in Ubinas village, 6 km to the southeast. A large deep canyon on the southeast flank drains into the Rio Tambo (Figure 6(a)), and a larger eruption could have similar effects to the 1600 Huaynaputina event. The area around the volcano is, however, sparsely populated and there is an absence of snow and ice at the summit, so moderating risk.
Huaynaputina	The largest major historic eruption in Peru began in February AD 1600 and lasted for 16 days. This eruption is often used to model the most extreme scenario that might be expected from any of the volcanoes of the region and, for this reason, the 1600 event has been well studied. The eruption was characterized by tephra deposition up to 1000 km from the vent; pyroclastic flows extending up to 10 km; water floods and lahars. The eruption caused widespread devastation. No activity has occurred since 1600.
Tutupaca	Maximum elevation 5815 m, Tutupaca, has not been intensively studied but consists of two edifices, showing glaciation and extensive dissection, suggestive of activity in the Pleistocene rather than the Holocene. There are, however, probable debris flow/debris avalanche deposits implying activity in the Holocene. A possible eruption may have occurred in 1802, which it is claimed showered ash on Arequipa. Tutapaca is probably not a major threat.
Yucamane	Maximum elevation 5550 m, Yucamane has been active in the Holocene. Indeed there is more evidence of Holocene activity than is the case at Tutupaca, with young lava flows distributed symmetrically around the cone. It is possible that the 1802 activity of Tutupaca actually originated from Yucamane. This volcano probably does not represent a major threat.
(Nevados) Casiri	Summit height 5650 m and has probably only produced Holocene lava flows. Little is known in detail, but does not seem to present a major threat.

Source: Based on information in de Silva and Francis (1990 1991); Chorowicz *et al.* (1992); Thouret *et al.* (1995 1999a 1999b 2001); Juvigné *et al.* (1998); Anon (1999a 1999b); Degg *et al.* (1999); Lara *et al.* (2000)

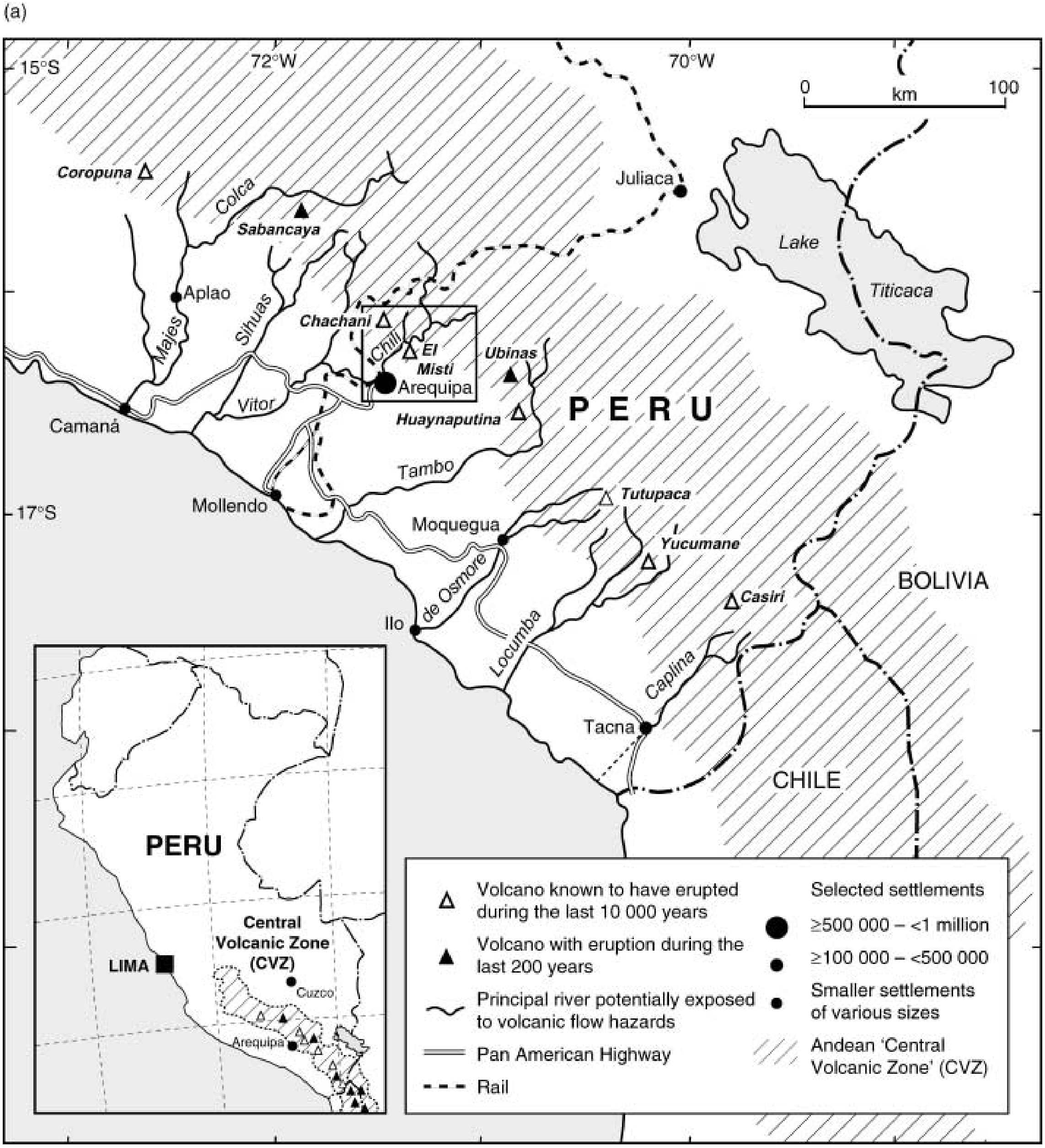

Figure 6 (a) Active volcanoes in Peru; (b) simplified hazard map of El Misti volcano
Source: (a) Based on data in de Silva and Francis (1990) and Documental de Perú (1991); (b) based on Thouret *et al.* (1999b, 106)

Land-use planning of this type has been a pivotal strategy in the dominant hazard mitigation agenda, and much of the initial national Peruvian research effort into earthquake hazard mitigation during the IDNDR was of this character. In this respect, the most influential research team in Peru has been that led by Professor Julio Kuroiwa of the Department of Civil Engineering at the National University of Engineering (UNI) in Lima. Since the late 1970s Kuroiwa has been preoccupied with the development and application of seismic hazard microzonation methods to urban planning

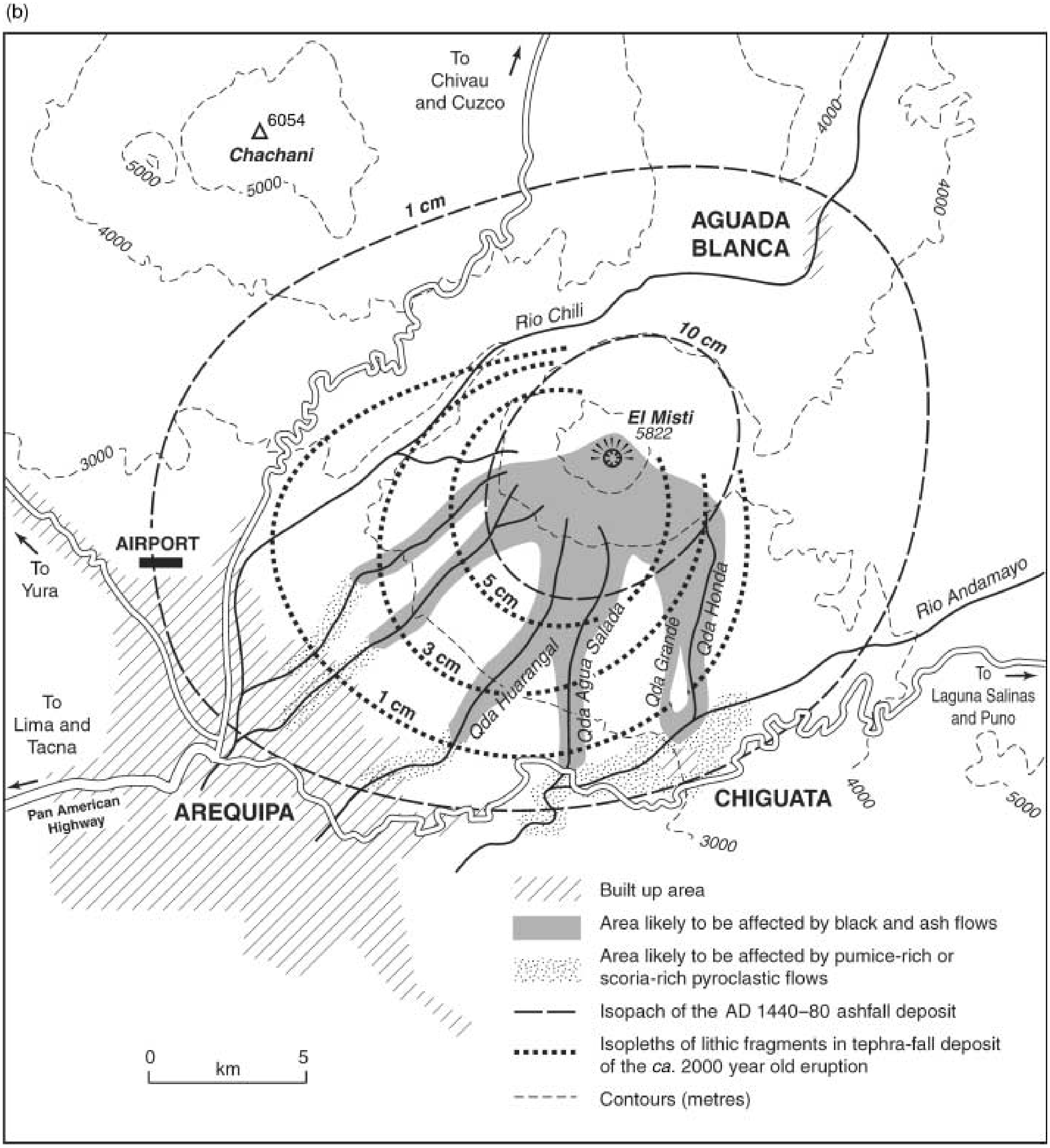

Figure 6 *Continued*

(Kuroiwa *et al.* 1978; Kuroiwa 1982) in an attempt to progress Peruvian hazard mitigation beyond a reliance on the seismic design of buildings according to a national code. Kuroiwa's work has focused not just on earthquake hazard but also on related natural hazards such as earthquake-triggered ground failure and tsunami inundation (Kuroiwa *et al.* 1984). A collaborative link with the Building Research Institute in Japan led to the creation of CISMID – the Peru–Japan Center for Earthquake Engineering Research and Disaster Mitigation. Funding from international agencies (e.g. UNDRO, OAS and USAID/OFDA) facilitated the application of microzonation methods to selected urban areas in Peru and the formulation and testing of emergency response plans. For example, in the late 1980s an evacuation plan for the low-lying areas of Callao (exposed to tsunami hazard; Figure 7) was prepared and tested with the participation of 17 000 university students; and land-use planning for disaster mitigation was completed for Punta Negra (a resort within the 100 km Metropolitan Lima coastal strip) as a model for land-use planning along this entire section of coastline (Kuroiwa *et al.* 1989; Toledo 1989).

In the mid to late 1980s the focus of the team's work shifted from urban planning to regional development planning. This move coincided with the amalgamation of Peru's 24 administrative departments into 12 regions, intended to give impetus to decentralization (from Lima) and more equitable economic development nationwide (Kuroiwa and Tanahashi 1988; Kuroiwa and Alva 1991). Kuroiwa and co-workers considered this to be the ideal opportunity to promote the value of hazard microzonation as a tool to inform regional development planning – and placed emphasis on the need for mircozonation of important regional urban centres with rapid population growth rates, as well as of existing/planned major civil works. They also considered hazard microzonation as an essential pre-requisite for educating the general public about hazards and how to protect self and property, as part of a more effective regional hazard response strategy (Kuroiwa and Alva 1991).

This thinking proved very influential in the formulation of Peru's early IDNDR strategy, *Peru's National Program for Disaster Mitigation* (PNPDM), which was published in draft form in 1988 (Kuroiwa and Tanahashi 1988). Within PNPDM, microzonation, and public education initiatives linked to this, was considered *the* key tool in disaster mitigation 'to achieve a safe and orderly expansion of urban conglomerates' (Kuroiwa 1996a, 7; see also Kuroiwa *et al.* 1992). The programme comprised an amalgam of the country's 12 regional disaster plans, with the objectives that by the end of the IDNDR, all construction in Peru should take disaster mitigation measures into consideration, and all Peruvians, including those living in the most remote areas, should know how to protect themselves and their properties from natural hazards (Kuroiwa and Alva 1991, 771).

In the early years of the IDNDR, multi-hazard microzonation projects were undertaken in several Peruvian regions under the auspices of PNPDM and INDECI (Peru's Civil Defense Institute). Peru's northern-most region, Grau, was targeted first (1989–92) in a project funded largely by the Japan International Cooperation Agency (JICA), followed by similar work (1992–95) supported mainly by the Canadian International Development Agency (CIDA) in the south-west around Arequipa (Sato *et al.* 1992; Kuroiwa 1996b). The microzonation studies focused on urban planning needs, with priority typically given to 'important cities' and the location of important civil works (Kuroiwa *et al.* 1992, 6204). New hazard microzonations were produced for central Lima at various stages during the decade (e.g. Alva-Hurtado *et al.* 1991; Degg *et al.* 1999; Figure 7), based on refined surface geological mapping and an improved characterization of the influence of site effects on earthquake ground motions (Kuroiwa *et al.* 1984; Martinez Vargas 1986; Karakouzian *et al.* 1997). The emphasis, throughout, was on hazard zonation to inform safe, ordered development, and on the education of civic leaders and the public to ensure appropriate hazard response in the face of environmental threats. In relation to the latter, the government declared 31 May, anniversary of the 1970 Huaraz earthquake disaster, the 'National Day of Education and Reflection on Natural Disasters' (Kuroiwa and Tanahashi 1988).

The alternative (vulnerability) agenda

An 'alternative' (i.e. alternative to the 'dominant' approach outlined above) hazard response strategy has gained prominence in Peru since the late 1980s. Its champions have largely, but not exclusively, been members of the non-governmental organization sector who see societal maladjustment to natural hazards as a development issue – rooted largely in the historical and recent social, economic and political processes that generate local vulnerability to loss.

A key proponent of this school of thought has been Andrew Maskrey, former director of Intermediate Technology in Peru. In 1989 he published a hugely influential volume on vulnerability to hazards, based on his work with disaster-afflicted communities in Peru and neighbouring countries. In *Disaster mitigation: a community based approach*, and subsequent works, he has challenged the dominant view that more and more people are living in vulnerable situations because of lack of knowledge or understanding about hazard exposure. He argues that the majority of people live in dangerous areas and unsafe buildings purely for pragmatic reasons. There is simply no other choice, or the choices that are available are perceived to present greater threats to survival than the threat posed by natural hazards. For example, living in an area prone to severe earthquake ground motion or tsunami inundation, in dilapidated housing, may well be perceived to pose less of an immediate threat to well-being than daily concerns such as

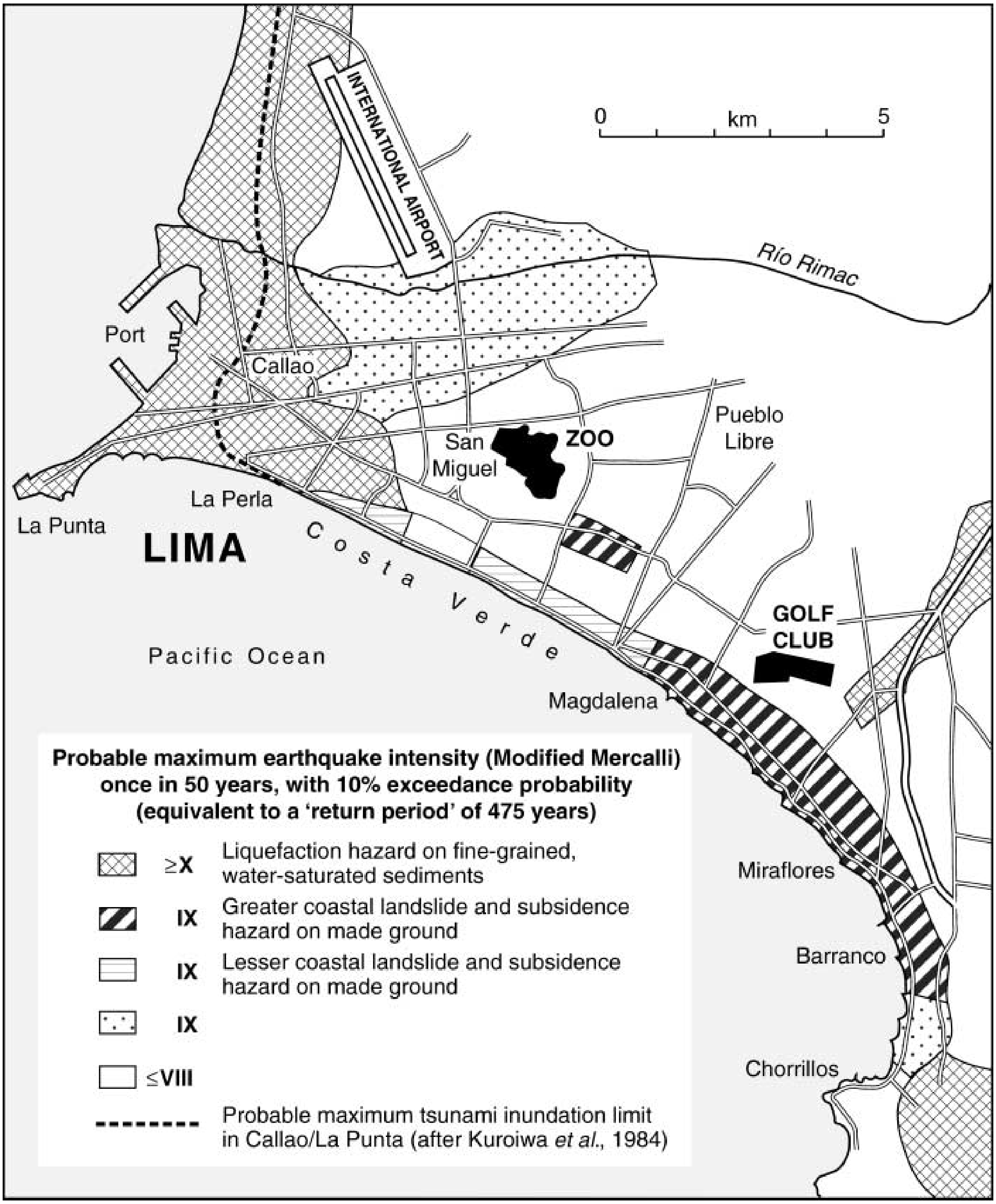

Figure 7 Earthquake hazard microzonation map for Callao and La Costa Verde, Lima
Source: Degg *et al.* (1999)

having no way of earning a living and having nothing to eat (Maskrey 1989). People are unlikely to change or adapt their living patterns to reduce vulnerability to natural hazard if it increases their vulnerability to other more pressing threats.

The alternative perspective also emphasizes institutional impotency in exercising change to reduce societal vulnerability to hazards. It questions the ability of most governments in ELDCs, including Peru, to control local development processes – such as the informal expansion of urban housing into hazardous areas and deficient building practices in an earthquake prone area (Anon 1997). It argues that government-backed mitigation programmes are often ineffective, not because of a lack of scientific technological knowledge (e.g. about earthquake hazard zones, or building susceptibility to damage), but because of their failure to engage with ordinary people (Maskrey 1992; Lavell 1994; Degg and Homan 2005). One important way to overcome this is by actively engaging the individual and community in disaster mitigation measures that have relevance to everyday life; i.e. they are part and parcel of a community-based development process aimed at improving the general quality of day-to-day living. The implementation of locally specific measures, Maskrey argues, helps to build up levels of consciousness and organization and to develop technologies, which in turn give people power to negotiate resources and policy changes with governments and agencies (Maskrey 1990). In other words, it empowers people to take control (with the support of agencies) of aspects of their own well-being, including disaster mitigation planning.

In this respect, there are possible lessons from Peruvian history that emphasize the role of the individual and community in effective hazard management. In another piece of innovative social science research, based on ethno-historical and archaeological records, Oliver-Smith (1994) demonstrated that the pre-Colombian (Inca) populations of Peru do not appear to have suffered massive mortality and destruction from sudden-onset disasters. This he attributes to a set of relatively effective community adaptations to natural hazards. These included safe site selection for settlements, and hazard resistant urban design, building technologies and building materials. It can be argued that the colonial and post-colonial history of Peru has engineered the gradual loss of this culturally ingrained capacity to adapt, initially, and perhaps most significantly, through the replacement of traditional Inca building practices by Spanish colonial techniques poorly adapted to the Peruvian environment (Oliver-Smith 1994 1999b). More recently, upheavals in society and the breakdown of traditional community ties and structures, caused by the mass migration of rural dwellers to urban environments, particularly Lima, have further reduced societal ability to cope with environmental limitations (Chester *et al.* 2001). Community-based disaster mitigation would appear to be a way forward in terms of trying to re-establish what has become known as a 'culture of seismic prevention' (European University Centre for Cultural Heritage 1993; Degg and Homan 2005).

Within Peru, proponents of the alternative agenda became increasingly vocal in their critique of the country's official IDNDR strategy, PNPDM, and in particular of its emphasis on hazard zonation and planning initiatives. Two years into the decade, Maskrey concluded 'the evidence so far shows that despite considerable scientific and technological advances in the field of disaster recovery in Latin America, the vulnerability of the majority of the region's populations to different hazards continues to broaden and grow' (1992, 10). LA RED (The Network for Social Studies of Disaster Prevention in Latin America) was established in Lima in the same year to act as a forum and pressure group for research focused on people's vulnerability to natural hazard, rather than on the hazards themselves. In an early report, LA RED were critical of another pillar of Peru's IDNDR strategy, namely its emphasis on large cities and complex emergencies. They supported this with a survey of small-scale disasters recorded in five Latin American countries (including Peru) between 1990 and 1994. A total of 5601 localized disasters were recorded, an average of three disasters per day that were largely being ignored by the national and international disaster-preparedness agendas (Maskrey 1996). In a report on an international IDNDR conference held at Huarez, Peru, at the mid-point of the decade, Franco concluded 'The IDNDR has undoubtedly arrived in Peru. We hope that some day Peru will get to IDNDR' (1996, 82).

The debate in Peru was duplicated at international level, and delegates at the 1994 IDNDR Yokahama Conference accepted the need for the IDNDR agenda to become more incultured with a greater focus on the causes of human vulnerability. This international acceptance of some key tenets of the alternative agenda led, in turn, to more inclusive approaches to dealing with the earthquake and volcanic hazards of Peru and its region.

Beyond the IDNDR: new response initiatives for a new century

As the IDNDR progressed beyond its mid-point, the research agenda at international and national levels changed quite noticeably. The early emphasis on applying science and technology in a 'technocratic' manner (Hewitt 1983) to tackle environmental hazards was gradually tempered by a growing acceptance that hazards are often merely the triggers of disasters, not their root cause (Cannon 1994; Blaikie *et al.* 1994 2004). The intrinsic value of research in the physical and social sciences aimed at reducing human vulnerability to these triggers was increasingly obvious (Chester 1993).

In Peru this trend was reflected in revisions to the PNPDM, which started to place more emphasis on the value of a 'bottom-up', incultured approach to mitigation, in contrast to the earlier emphasis on 'top-down' regulatory/planning frameworks. The need for this change was only too apparent, as the early work on hazard zonation and associated land-use regulation had proved far less effective in engaging local authorities and the general public than had been envisaged (Kuroiwa *et al.* 1992; Kuroiwa 2000). A series of educational initiatives was started from 1993, beginning with the publication by the Minister of Education of a special training publication for schoolteachers, entitled *The need for knowledge on disaster prevention to be part of the basic culture of Peruvians* (Kuroiwa 1993). In 1996 this was revised and an additional 5000 copies circulated. Towards the close of the IDNDR, the Ministry of Education agreed to formalize teaching on disaster prevention and mitigation at elementary education level nationwide, this level having been chosen because many of Peru's poorest children do not progress beyond elementary schooling (Kuroiwa 2000).

Many researchers in the 'pure' physical (hazard) sciences started to show greater awareness of the social dimensions to their work. For example, the ground-breaking investigations by Jean-Claude Thouret and his team in the south Peruvian volcanic zone show an increasing awareness of social context through the 1990s. Pure geological research in the early part of the decade, focused on monitoring, mapping and predicting volcanic processes (e.g. Chorowicz *et al.* 1992; Thouret *et al.* 1995), assumes a far more socially attuned slant by the close (e.g. Thouret *et al.* 1999a 1999b 2001). Similarly, social scientists of the vulnerability school, who became increasingly concerned with the concept of building local capacity to cope with disasters as the decade progressed (Anon 1997), were aware of the need for 'appropriate' technological and hazards research (e.g. see Aysan *et al.* 1995; ODA 1995; Degg 1998; Coburn and Spence 2002) to inform community-based initiatives such as self-help hazard-resistant building technology. A good example of this work is provided by the San Martin project undertaken by Intermediate Technology and partner agencies in the Alto Mayo region of northern Peru. In the mid 1980s, the Alto Mayo had one of the fastest rates of urbanization in the country, much of this unplanned and of poor standard – generating vulnerability to hazard (Anon 1997). The area has a long seismic history, which was augmented in May 1990 and April 1991 by two significant events that destroyed large amounts of infrastructure and thousands of houses in the area. As part of the reconstruction process, the San Martin district was one of two regions chosen to pilot a four-year information and training programme aimed at building local capacity to reduce vulnerability. Training modules were produced for key community personnel, including local government officials, civil defence committee members, teachers, journalists and master builders. The latter, in particular, have played a key role in influencing the activities of thousands of self-builders by promoting design and structural adaptations to traditional quincha (basket weave cane) house construction to increase seismic resistance and modern-day acceptability (Maskrey 1995). The overall aim has been to shift the local civil defence system 'away from defending people from external factors, towards defending people against their own vulnerability. We want to build internal capacity to cope with natural hazards ' (Anon 1997, 2).

This changing focus in disaster mitigation looks set to achieve even greater prominence over the next 10 years. At the global level the RADIUS initiative, launched in 1998 under the auspices of the IDNDR Secretariat and GeoHazards International, produced a *Comparative Study on Understanding Urban Seismic Risk Around the World* based on an Earthquake Disaster Risk Index (EDRI), compiled using five factors, including hazard and vulnerability (Davidson *et al.* 2000). At the regional level, the INDNR-RADIUS project in Latin America made strenuous efforts to engage representatives of all key sectors of the risk management community, and to ensure 'active involvement and participation of the local people, the ones who know most about the local social, economic, political and cultural conditions' (Villacis and Cardona 2000, 1). Similarly, the *San Jose Declaration* (1999) from the IDNDR Hemispheric Meeting in Costa Rica 1999 (aimed at natural disaster reduction in the Americas in the twenty-first century) gives equal weight to the needs to modernize hazard monitoring and measurement networks to enhance forecast and warning capabilities; to strengthen national institutions in charge of disaster mitigation; to develop a regional culture of prevention and mitigation; to involve local communities and their organizations in the processes of planning and policy formulation; and to analyse vulnerability within the framework of sustainable development (Anon 1999b).

In Peru, where so much influential work on vulnerability has originated, the reframing of disasters continues. The National Education and Training Directorate of Peru's Civil Defense Institute (INDECI) now considers 'Building a culture of prevention – an essential part of the development of any society' (Anon 2003a, 46). On 8 October 2003 the country celebrated 'International Day for Disaster Reduction' with a number of activities aimed at raising awareness among the population about the 'need to *consolidate* a culture of disaster prevention' (Anon 2003b, 6; our emphasis). Perhaps most significantly the complex and politically sensitive issue of how to empower people generally, and poor people in particular, to engage in the risk reduction process is starting to receive serious attention. A recent bulletin of the *International Strategy for Disaster Reduction* in the region comments, with reference to Bolivia and Peru, on the need for 'institutional change' to enable localized risk management capacity building. It concludes that positive change is gradually being implemented in both countries through the decentralizing of State actions (duties and associated resources) to municipalities, and the strengthening of incentives to promote civil participation (Ferradas 2003).

The consensus view of how best to respond to hazards such as earthquakes and volcanoes has moved, therefore, a long way in the last 15 years as greater emphasis has been placed on tackling the causes of human vulnerability to hazard. To some commentators, however, there remains an over-emphasis, in international and national disaster mitigation agendas and research at least, on urban areas and on mega-cities in particular (e.g. ODA 1995; Mitchell 1999; Davidson *et al.* 2000; Chester *et al.* 2001; Munich Re 2001; Kuroiwa 2002; Pelling 2003a). This emphasis is understandable given the concerns highlighted in this paper about the over-concentration of people and economic activity in cities such as Lima. As research from Latin America has shown, however, it is important not to lose sight of the small, localized hazard impacts that affect countries (particularly ELDCs) and regions on a far more regular basis. Although the cumulative effect of these impacts has received little attention to date, in many parts of the world they affect the livelihoods of local communities on a regular basis – causing injury, death, disruption, loss of family income/property and damage to local infrastructure and community facilities. As such, these events are far more representative of the ingrained, pervasive nature of human vulnerability to natural hazards in countries such as Peru than the catastrophic hazard impact with a return period of 100+ years. The enduring message that comes from work such as that at Alto Mayo in the Peruvian Andes is the need for physical and social scientists to work together with (small) urban and rural communities to reduce vulnerability to the 'ordinary'. Individual and collective resistance to the 'extra-ordinary' will follow.

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