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EXECUTIVE SUMMARY

We present a report of our reconnaissance trip to the area of the magnitude 8.3 June 23 2001 southern Peru earthquake and tsunami. The earthquake is the best example in nearly 40 years of the maximum-size earthquake that might occur on the Hikurangi subduction zone. Despite the great magnitude of this subduction interface earthquake, it produced only "moderately strong" levels of earthquake shaking (peak ground acceleration of 0.3g on alluvium from the one strong motion accelerograph in the earthquake area, and Modified Mercalli Intensity 8 in the epicentral area), and relatively minor ground damage (liquefaction and landsliding). It did however produce a large and devastating tsunami. Our comparison of the Moquegua accelerograph record and attenuation curves for subduction interface earthquakes shows that the strength of shaking was typical for subduction interface earthquakes. If we apply our observations to New Zealand, they imply that a Hikurangi subduction interface earthquake may be less damaging to built-up areas in the southeastern part of the North Island (e.g. Wellington and Napier/Hastings) than earthquakes on major active faults in the shallow crust. However, the extent of the strongest shaking in a subduction earthquake (300km for the southern Peru event) and the associated tsunami generation will make the earthquake very significant in the regional context.

1.0 INTRODUCTION

1.1 General

In this report we present the main observations made during a two week reconnaissance trip to the area of the M8.3 June 23 southern Peru earthquake and associated tsunami. The reconnaissance trip took place some five weeks after the earthquake and was funded by the Earthquake Commission Research Foundation (EQC) and the Institute of Geological and Nuclear Sciences (GNS). Unlike previous reconnaissance trips this trip was run by GNS rather than by the NZ Society of Earthquake Engineering's (NZSEE) "Understanding Earthquakes" programme. This is because the trip was largely for the purpose of understanding the physical features and natural hazards of the earthquake and the associated tsunami, rather than the more multidisciplinary scope of NZSEE trips.

This report is based on the public seminar "Tsunami", which was given at the Te Papa Museum of New Zealand in September 2001. It is focused on describing our important observations and the implications for understanding subduction interface earthquake and tsunami hazards in New Zealand.

1.2 The Earthquake

On June 23, 2001, a large area of southern Peru and northern Chile was shaken for over a minute by a strong earthquake. The earthquake was centred approximately 175km west of Arequipa (Fig. 1a), and was given a Moment Magnitude (M_w) of 8.3 by the US Geological Survey. The magnitude of the earthquake was such that it was classed as a great earthquake ($M \geq 8$). The earthquake was produced by slip on the subduction interface between the Nazca and South American plates (Fig. 1), in which the Nazca plate thrusts beneath the South American plate at a long-term rate of about 70 mm/yr. Great earthquakes such as the June 23 event are typical of so-called "Chilean-type" subduction zones (Uyeda, 1982), in which the subduction interface is strongly coupled (locked) due to the shallow angle and high friction between the two plates, and also because of the rapid convergence rate between the plates. The earthquake produced damaging shaking, ground deformation, liquefaction and tsunami inundation in a 300km long zone in the Arequipa area (Fig. 1).

At magnitude 8.3, the southern Peru earthquake is the largest to occur in the world in the last 25 years. The maximum strength of shaking during the earthquake was Modified Mercalli Intensity 8 (L. Ocola pers comm.; Fig 2a), which was a moderately strong level of shaking. This level of shaking typically topples statues, chimneys, columns, damages poorly constructed buildings, and lightly damages the more well constructed buildings. The duration of shaking was over a minute and the strongest (damaging) shaking lasted about 30 seconds. A considerable number of aftershocks also occurred, some larger than magnitude 7 (Fig. 2b).

A significant feature of the earthquake is that it produced a 7 m high tsunami that hit the Camana coast (Fig. 3) about 15 minutes after the earthquake. The 130 fatalities from the earthquake were mainly due to the tsunami. Another 21,000 people were displaced or otherwise effected significantly by the earthquake. Nearly 15,000 dwellings were destroyed and the Peruvian Government have allocated the equivalent of US $300M to earthquake-related relief.

1.3 Motivation of Reconnaissance Trip

The motivation of this reconnaissance trip was to make first-hand observations of this natural hazard event, an event similar to one that could happen in New Zealand. We saw the great southern Peru earthquake as highly relevant to seismic and tsunami hazard assessment in New Zealand. It is the best example to occur in the world since the Alaska earthquake of 1964 of the maximum-size earthquake expected on the Hikurangi subduction zone. The Hikurangi subduction zone in contrast has not produced any such earthquakes in the 160 year historical record. The South American and Hikurangi subduction zones both appear to be strongly coupled or locked (south of Napier for Hikurangi), and involve the rapid subduction of oceanic crust beneath continental crust (Fig. 1). As such the Hikurangi subduction zone is somewhat similar to a "Chilean Type" of subduction zone (Uyeda, 1982). The occurrence of the great southern Peru earthquake and previous earthquakes in the long historical record of Peru (Becks and Ruff, 1989) shows that these subduction zones accommodate at least part of the plate boundary slip by the occurrence of large-to-great earthquakes. In contrast, our 160 year historical record in New Zealand has been too short to capture any of these large-to-great earthquakes and associated tsunamis from the Hikurangi subduction zone. The southern Peru event therefore presented us with a rare opportunity to see the onland effects of the maximum-size event that we might expect on the Hikurangi subduction zone, where the Pacific Plate thrusts underneath the Australian Plate at a long-term rate of 40 to 50 mm/yr.

The main difference between the two subduction zones is that a larger portion of the locked part of the Hikurangi subduction zone is under land and at slightly shallower depths in the eastern North Island than is the case in southern Peru. It is therefore possible that the Hikurangi subduction zone could produce stronger shaking over a larger area of New Zealand than the southern Peru earthquake did in 2001, and this is a consideration that is addressed later in the report.

1.4 Objectives

Like some of the reconnaissance trips of recent years to come from New Zealand, this trip was focused on understanding the natural hazards associated with an earthquake of special relevance to New Zealand. Since the built environment and procedures of emergency management response in Peru are generally different to those of New Zealand, we realised that our observations of damage and response would have to be 'calibrated' for New Zealand conditions. For example, we would have to assess what the damage to a poorly constructed building would equate to for a strongly constructed building in New Zealand. Similarly, we had to assess what the likely emergency management response would be to the earthquake and tsunami if a southern Peru-type event took place in New Zealand. Our objectives of our four person reconnaissance team (Fig. 4) were as follows:

To observe and document the distribution, strength and duration of earthquake shaking associated with this great subduction interface earthquake.
To observe and document the distribution and severity of ground deformation (i.e. liquefaction and lateral spreading) associated with this great subduction interface earthquake.
To observe and document the tectonic effects (primarily coastal uplift and subsidence) associated with this great subduction interface earthquake.
To observe and document the distribution and severity of tsunami inundation associated with this great subduction interface earthquake.
To examine tsunami deposits produced by the tsunami to aid identification of paleotsunami deposits in New Zealand.

The details of our reconnaissance programme and the team members involved are given in the Appendix.

2.0 OBSERVATIONS

The areas visited along the 300km-long earthquake area in chronological order were Arequipa (the second largest city in Peru), Camana, Chala, Ocona, Mollendo, Punta de Bombon, and Moquegua (Fig. 3). In the following sections we describe our observations according to the three categories of; (1) ground shaking and associated damage, (2) ground damage (i.e. landslides and liquefaction), and (3) tsunami and other effects.

2.1 Ground Shaking and Associated Damage

The city of Arequipa is located almost 100km away from the rupture zone. From our collection of first-hand accounts and our survey of the city we conclude that the shaking damage was relatively minor and confined mainly to areas of soft ground conditions, where amplification of ground motions occurred. During the earthquake the cathedral in the main centre of Arequipa lost one tower (Fig. 5). Similar damage occurred to the other tower during an earthquake of estimated magnitude 9 in 1868. Other than the cathedral, the buildings damaged were mainly those with reinforced concrete frameworks and unreinforced brick infill situated on very soft and poorly drained ground. Some modern buildings also sustained significant damage in Arequipa, probably due to poor site conditions. The top floor of the 1971-vintage military mess hall at the Arequipa military base (Fig. 7) was severely damaged by the earthquake. The building is not unlike some buildings of similar age in New Zealand. At the time of our visit to the military base all of the personnel had to eat their meals outside the condemned building, though the cooking was still being done inside.

Hillslope subsidence and slope failure damaged the Pan American highway and other main highways within the 300 km long earthquake zone. In Figure 8 we show typical damage to the highways and the use of white painted boulders to divert the traffic away from damage.

The only strong motion accelerograph record of the southern Peru earthquake came from the city of Moquegua (Fig. 3). This city sustained the most significant earthquake shaking-related damage of all the cities we saw because of the widespread "soft soil" site conditions (gravel alluvium) beneath the city. The accelerograph showed that a peak ground acceleration of 0.3g had occurred in the city (Fig. 2), which we consider to be compatible with the level of damage observed in the city. The measured PGA of 0.3g is therefore likely to represent the maximum PGA produced by the earthquake, based on the fact that we did not see any other damage as extensive along the whole 300 km extent of the earthquake zone. This includes the epicentral area, where the strongest MM Intensity (8) was felt according to the Instituto Geofisico del Peru (Fig. 2a). The soft ground conditions will have amplified the shaking accelerations and the damage. Since a large proportion of the buildings were of adobe construction, the damage to the city was extensive (Fig. 9). Earthquake shaking and toppling of buildings against others down the steep hillslopes would have further exacerbated the considerable damage. Damage to younger and more well constructed buildings was also significant, such as the school building shown in Figure 10. Again, this building appeared to be constructed at a similar standard to some buildings in New Zealand.

In total contrast to Moquegua was the city of Mollendo, which showed a virtual absence of earthquake-related damage, despite being closer to the ruptured subduction interface than Moquegua. This city is located on granite, or "hard rock" in engineering terms. These site conditions were such that damage was light from the earthquake. Most buildings including those of adobe construction were undamaged (Fig. 11).

There were several places in the earthquake zone where seemingly well-constructed bridges were significantly damaged. We show the one bridge we visited in Figure 12, which shows the bridge broken in several places where the foundations have failed significantly. The bridge appeared to be of similar construction to many bridges in New Zealand.

Many buildings were lightly damaged but still being used along the entire earthquake zone. We stayed in a number of hotels and ate in a number of restaurants with cracked walls and ceiling. We also observed considerable relief efforts going on in the earthquake area, despite the fact that we were there some 5 weeks after the earthquake. Various relief organisations from around the world (e.g. Red Cross) had stations set up along the earthquake zone.

2.2 Ground Damage: Landslides and Liquefaction

We saw very little evidence of earthquake-induced landsliding from the southern Peru earthquake. The one feature observed (Fig. 13) was a 100 m high rock slide near the epicentre of the earthquake (Ocona area). This was also where we saw one of only two areas of liquefaction. The other area of liquefaction was near the south end of the earthquake zone, in a farm paddock near Punta de Bombon. Surprisingly these were the only areas of liquefaction we saw, despite the great size of the earthquake and abundance of suitable conditions for liquefaction (coastal plains with a high water table and sandy sediments). It is possible that tsunami inundation in the Camana area could have destroyed liquefaction features, but our overall impression based on our survey of the 300 km long earthquake zone is that liquefaction was minor during the earthquake.

2.3 Summary of Earthquake Shaking Effects

We only saw evidence of moderately strong levels of shaking along the entire length of the earthquake zone. The strongest shaking appears to have occurred in Moquegua, where the alluvial ground conditions almost certainly amplified the ground shaking to cause the worst damage we saw in the entire reconnaissance. The only recorded PGA from the earthquake of 0.3g (i.e., a moderately strong level of shaking) came from the Moquegua accelerograph, and this PGA appears compatible with the level of damage seen in the city. Cities located on hard rock sites within the earthquake zone (e.g. Mollendo) had virtually no damage, so the strength of ground shaking (e.g. PGA or MM Intensity) was considerably less than in Moquegua. Only minor liquefaction was observed within the earthquake zone, and significant damage from mass movement was observed along the Pan American highway and other major highways. In general, no shaking intensities stronger than about MM 8 were observed in the entire earthquake zone.

2.4 Impact of Tsunami and Inland Shift of Coastline

A large tsunami accompanied the southern Peru earthquake, and struck the coast at the central part of the earthquake zone (e.g. Camana area; Fig. 3) about 14 minutes after the earthquake. Numerous eye witness accounts described it as a 7 m high wall of black (sand-laden) water.

The tsunami was the cause of nearly all of the deaths in the earthquake, and will have had a large impact on the economy of southern Peru. It inundated large areas of cropland in the Pucchun-south Camana area, and also devastated the coastal tourist town of Las Cuevas and northern Camana.

2.5 Las Cuevas-South Camana

On first arriving at Las Cuevas, we found it hard to imagine that the near total devastation of the coastal town was due to tsunami (Fig. 14). Instead, our impressions of the damage was that it was due to earthquake shaking. However, it was clear from the line of water-transported debris at the edge of the cliff at Las Cuevas (Fig. 15) and the distribution of debris throughout the ruins that the tsunami had violently impacted the area. The tsunami came several hundred metres in from the sea to the base of the cliff, smashing buildings and walls above high tide level, and depositing a layer of sand (up to 10cm thick) and debris across the entire area.

In the Las Cuevas-south Camana area, the eye-witness accounts of the tsunami impact were insightful in allowing us to differentiate between earthquake versus tsunami damage. People felt the earthquake shaking but did not report any damage associated with the earthquake. It was the impact of the black wall of water that produced the near total damage to the coastal part of the town. For example, the tsunami wave was observed to have come over the top of a two-storey discotheque, smashing through the roof and blowing out the windows (Fig. 16).

In our reconnaissance of the Las Cuevas-south Camana area we were initially surprised at how close the holiday settlements were to the coastline. However, after talking with the local we found out that the settlements were initially built well back from the coastline and that the earthquake had caused the coastline to shift by 100 to 200 m inland (Fig. 17a). The severely damaged coastal promenade shown in Figure 17b was well above the high water mark prior to the tsunami. According to the local residents the shift of the coastline inland by 100 to 200 m allowed the sea to progressively damage and breach the promenade over the following 5 weeks and also led to the development of lagoons and the deposition of sands and gravels inland. We interpret the inland movement of the coastline position to be due to the effect of coseismic subsidence and/or from removal of sand by the retreating tsunami. In a subduction earthquake the overlying plate slips up the subduction interface and the surface can change elevation relative to sea level (Fig. 18). Furthermore, we consider the tsunami to have great capacity for removal of sand from the beachfront when the water went back out to sea. Another key observation was that the damage to buildings from the tsunami was worst on the northwest side of buildings (Fig. 17a). This obliquity presumably occurred because the tsunami came in from the northwest. It would do so if the area of maximum seabed deformation was to the north, perhaps near the epicentre.

All around the Las Cuevas-south Camana area we saw severe damage to man-made structures that were in the path of the tsunami. Concrete and cement block structures were smashed up and tossed about as if they presented no barrier to the waves, and sand was deposited in the standing seawater. The standing seawater lasted for days after the tsunami on the streets of the ruined settlements (Fig 14).

One of our more sobering thoughts is that the Peruvians were lucky that this earthquake happened in winter time. In the summer time Camana is a summer resort town, much like the summer beach resort towns in New Zealand. Thousands of people from Arequipa spend part of their summer on the coast. If the earthquake had happened in the summer time in Camana then the actual casualties sustained from the tsunami would have been much greater. Nevertheless, the impacts of the earthquake and tsunami in the seaside holiday resort of Las Cuevas and south Camana were considerable. Such effects as a sense of homelessness, loss of family members, having to deal with the tainted water supply, and the threat of disease from bad water and decaying material were observed at the time of our visit, some five weeks after the tsunami.

2.6 Pucchun

Considerable damage to farmland occurred in the Pucchun area just north of Camana. Pucchun is a 2km wide irrigated coastal strip of flat land. The up-to-1km inland extent of the tsunami can be clearly seen as a colour contrast in Figure 19. The light grey fields are covered in sand from the tsunami inundation, whereas the darker fields escaped tsunami inundation. Localised earthquake shaking-related ground deformation was also observed at a pumping station in the middle of the farmland. A high gravel bar was breached in several places along the coast, causing coarse gravels to be deposited in a large tongue inland from the breach (Fig. 20). Eye witnesses described the tsunami as a big black wave ("una ola negra") overtopping and breaching the gravel bar. The eye witnesses were lucky enough to escape the tsunami alive on foot, whereas many others perished. The occasional body was still being recovered from the farmland at the time of our visit.

In summary, the main effects of the tsunami wave in Pucchun were that standing seawater was left behind after the tsunami, salination of the soil occurred over the zone of inundation, and a layer of sand 10 to 20 cm thick was deposited over the rich topsoil (Figs. 21 and 22). Tsunami deposits were also laid down inside many buildings in the Las Cuevas-Camana area, with the added problem of being highly erosive before deposition. In a church in Las Cuevas (Fig. 21) the sand-laiden waters eroded the cement-veneered walls of the church enough to expose the underlying bricks.

2.7 Summary of Tsunami and Coastline Modification

The most significant coastal effects of the earthquake occurred in the Camana area, where a number of coastal resort towns were devastated by the tsunami that accompanied the earthquake. The effects were shift of the coastline and damage and inundation by a 7 m high black (sand laden) tsunami wave that arrived about 15 minutes after the earthquake. The run-up, or inundation, was about 5-7 m above sea level. The tsunami wave was devastating and erosive, smashing buildings and structures as it advanced across the near coastal area. The tsunami was the cause of nearly all of the deaths in the earthquake. Sheets of sand were deposited over thousands of hectares of crop land in the Pucchun area, and salt water was left standing among the destroyed buildings and devastated crops. Salination of the inundated farmlands will impact crop production for some time into the future, and the tsunami will generally have had a large impact on the economy of southern Peru. The death toll would have been considerably greater if the tsunami had impacted the area in summer, when the coastal resort towns are full of holidaymakers.

3.0 IMPLICATIONS FOR NEW ZEALAND

The southern Peru earthquake has provided us with the best opportunity in the last three decades to see the effects of the type of earthquake that might occur on the Hikurangi subduction zone in New Zealand. Our most important observations that are of relevance to New Zealand are given in the following paragraphs.

The earthquake shaking was "moderately strong" in areas of "soft ground" (0.3g on alluvium in Moquegua, the only recorded PGA for the earthquake) and considerably less in areas of hard rock (e.g. Mollendo). We therefore consider it possible that shaking during a Hikurangi subduction zone earthquake will be of similar levels, and the influence of site conditions will be significant. The most serious damage would occur in areas of "soft ground" (e.g. Napier/Hastings, Gisborne, Wairoa and numerous parts of greater Wellington), whereas places underlain by basement rock would experience less damage. It is likely that the earthquake would not be as hazardous to these cities than earthquakes on the nearby crustal active faults (e.g. a M~7.5 event on the Wellington Fault), which would rupture the ground surface instead of rupturing some 22km beneath the city as in the case of a great Hikurangi subduction zone earthquake. The shaking from the subduction zone earthquake would therefore be more attenuated at the ground surface than the shaking from an earthquake on a crustal fault. A crustal active fault event may also produce considerably stronger shaking at the short spectral periods most damaging to one to two-storey buildings than the subduction zone earthquake (i.e. a PGA of about 1g for the former versus the 0.3g measured in Moquegua and maximum MM Intensity of 8 in the epicentral area for the latter). Great subduction zone earthquake tend to be much richer in long-period energy than short-period energy, which could explain the relatively low levels of earthquake damage from the southern Peru event.

The southern Peru earthquake rupture zone was 300 km long, which in the eastern North Island would stretch from southern Wairarapa to southern Hawkes Bay. A Hikurangi subduction earthquake would therefore affect all of the southern North Island (or more), so it is possible that the impact of this earthquake would be more significant in the regional context than an earthquake on a crustal fault. The regional extent could be further enhanced by the locked part of the Hikurangi subduction zone being largely under land in the Eastern North Island, which brings the source of earthquake shaking closer to the ground surface than the case of southern Peru.

The southern Peru earthquake produced a major tsunami in the central part of the earthquake zone. We expect a similar tsunami to accompany a Hikurangi subduction zone earthquake, and thus consider tsunami hazards to be very serious for centres such as Gisborne, Napier, Wairoa and greater Wellington. Loss of life, near-total destruction of nearshore buildings, subsidence, salinisation and tainted water supplies will result from a tsunami when it impacts one or more of these areas.

We have drawn many parallels between the southern Peru earthquake and those expected on the Hikurangi subduction zone, and should express some caution in this regard. We therefore acknowledge the fact that the two subduction zones are not identical, in that the locked area of subduction zone is mostly beneath the seabed in southern Peru, whereas it is mostly under land and therefore slightly shallower overall beneath the eastern North Island. We therefore think it is plausible that the strength of shaking might be slightly stronger in the eastern North Island as compared to southern Peru during great subduction interface earthquakes. However this difference might not be great, since the Youngs et al (1997) subduction interface attenuation relationship (Fig. 23) shows that the ground motions from these earthquakes increase only slightly if the depth to the interface is decreased significantly (e.g Fig. 23 shows a less than 0.05g increase in PGA for a source distance decrease of 30 km) There is also the question of how typical an example the earthquake is of great subduction interface events in general. With this question in mind we have plotted the 0.3g acceleration recorded for the earthquake at Moquegua with the Youngs et al subduction interface attenuation curves (Fig. 23). The 70km distance used to plot the Moquegua record is the estimate of the closest distance to the subduction interface from Moquegua. On the basis of the Moquegua record it appears that the accelerations from the southern Peru earthquake were typical of subduction interface earthquakes. The Moquegua peak ground accelerations appear to lie slightly above the soil curve, which amounts to an insignificant difference.

4.0 FUTURE WORK

During the course of our reconnaissance we identified future research that will improve the understanding of earthquake and tsunami hazards in New Zealand. These are:

- To establish the extent to which the ground motions of the southern Peru earthquake are typical of other subduction interface earthquakes on the Chile-Peru subduction zone and elsewhere in the world. The earthquake produced only "moderately strong" levels of shaking (PGA 0.3g on alluvium and considerably less on rock) which appear to be typical of the shaking levels measured in other subduction zone interface earthquakes. However, we recommend that this comparison should be the focus of further critical examination before the earthquake is formally used as a basis for hazard assessment in New Zealand. Examination of the felt reports from other subduction zone earthquakes in similar settings to the southern Peru earthquake would be of considerable value in understanding the range of effects that could be produced in a future great Hikurangi subduction zone earthquake.

- To model the tsunami wave heights and runup along the East Coast that might be produced by a great Hikurangi subduction zone earthquake. Observations of tsunami effects from the southern Peru earthquake and from other great subduction earthquakes could be used as a reality check for the output of the models.

5.0 ACKNOWLEDGEMENTS

We wish to thank Her Excellency Carmen Silva, the former Peruvian Ambassador to New Zealand for her assistance in getting our reconnaissance trip organised at short notice. We thank the staff of the Instituto Geofisico del Peru, in particular Dr Ocola for invaluable discussions and logistical support during the reconnaissance trip, along with the numerous residents of Camana, Pucchun, Moquegua and elsewhere who shared their knowledge and first-hand accounts of earthquake effects with us. The EQC is sincerely thanked for funding the reconnaissance trip in a timely manner. Russ Van Dissen and Russell Robinson (GNS) are thanked for their very helpful in-house reviews of the report. Finally, we thank Gaye Downes and Peter Wood (both GNS), Debbie Cunningham (Wellington Regional Council), David Middleton (EQC), the Ministry of Civil Defence and Emergency Management and the New Zealand Society for Earthquake Engineering for their inputs to the "Tsunami" seminar at the TePapa museum, which was transcribed to form the base for this report.

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APPENDIX

1. Personnel

The following scientists comprised the reconnaissance team:

Mark Stirling (Hazards scientist and trip leader): Mark is a scientist at GNS who specialises in multidisciplinary probabilistic analysis of earthquake, tsunami, landslide and volcanic hazards. His primary tasks were in addressing Objectives 1, 2 and 4 above.
Robert Langridge (Earthquake geologist): Robert is also a scientist with GNS who specialises in earthquake geology. He a key member of the team involved in understanding the tectonic deformation across the Hikurangi margin of the North Island. He has experience on previous reconnaissance trips (Izmit, Turkey) and his tasks on this trip were in addressing Objectives 3 and 5.
Rafael Benites (Seismologist): Rafael is a GNS scientist and Peruvian native. He joined the team while on vacation in Peru. His knowledge of Peruvian seismicity, well-established links with Peruvian colleagues who had just returned from the earthquake area, and command of the Spanish language were essential for the success of the trip. He contributed considerably to Objectives 1-3.
Hector (Coco) Aleman (Seismologist): Hector is a senior seismologist based at the Geophysical Institute in Lima. He had already visited the earthquake area prior to our visit so was able to take us to many of the key areas of interest. He therefore contributed to all of our stated objectives.

The reconnaissance team members are shown in Figure 4.

2. Programme

Our 14 day reconnaissance programme was as follows:

Days 1 to 3: Mark Stirling and Robert Langridge travelled from Wellington to Lima to meet with Rafael Benites and Peruvian colleagues, the latter having just returned from the earthquake area.
Day 4: The reconnaissance team flew to Arequipa, the main city in the earthquake area. The rest of the day was spent examining damage in the city.
Days 5 to 9: Ground travel around the earthquake area to examine damage associated with the earthquake and tsunami, and deposits associated with the tsunami.
Day 10: Travel back to Lima.
Day 11: Post reconnaissance discussions with Peruvian scientists.
Day 12-14: Travel from Lima back to New Zealand.

Figure Captions

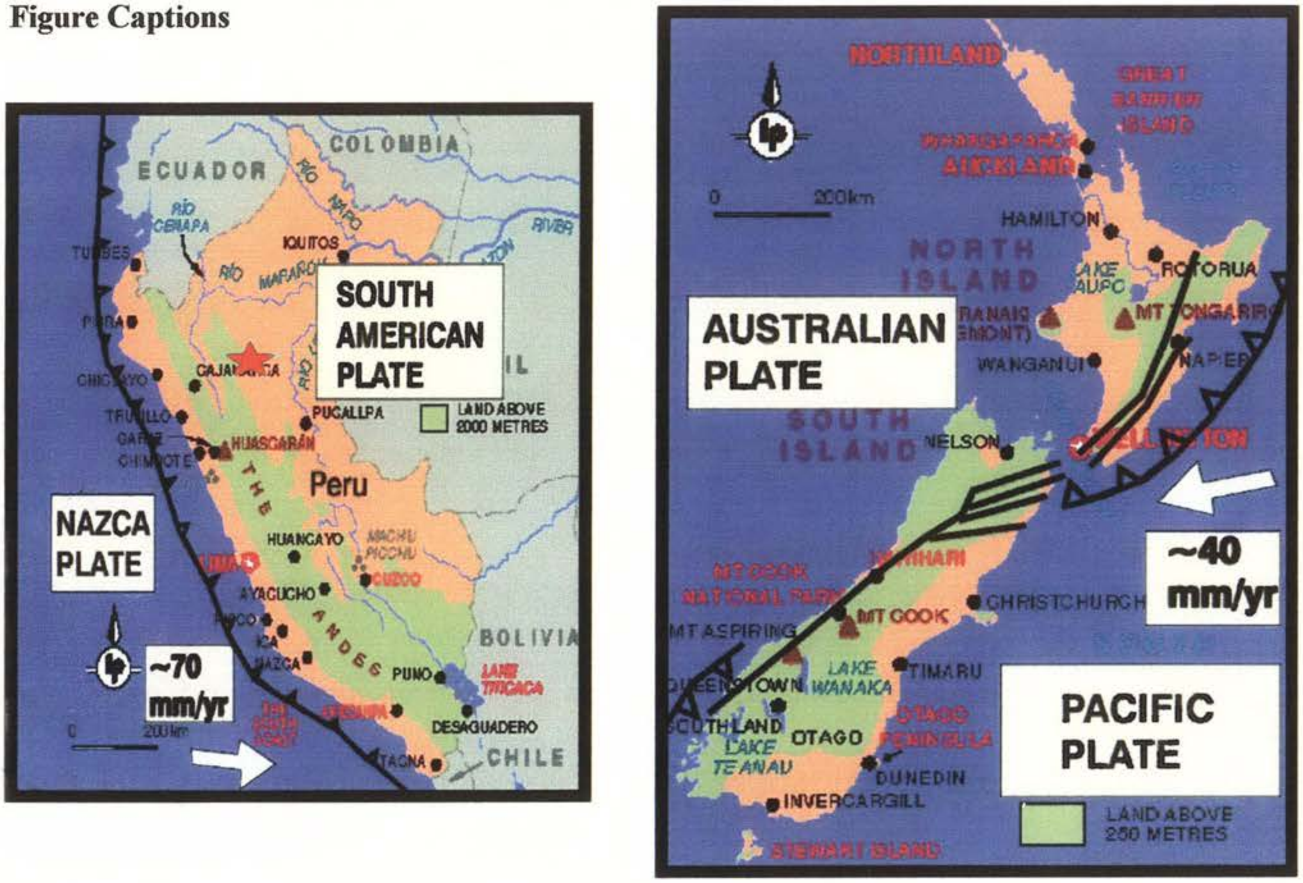


Figure 1 (a)

Plate tectonic setting of Peru and New Zealand, comparing the subduction zone setting of the eastern North Island to that of Peru (a); and a cartoon cross section of a subduction zone (b). In Peru the overriding plate is the South American continental plate and the subducting plate is the oceanic Nazca Plate. In the eastern North Island, the continental Australian Plate overrides the oceanic Pacific Plate. The southern Peru earthquake was centred just north of Arequipa on the Peruvian map. The subduction interface is the locked zone of contact between the two plates (marked "rupture area" on the figure) and great earthquakes are produced when then two plates let go and release many years of accumulated strain.

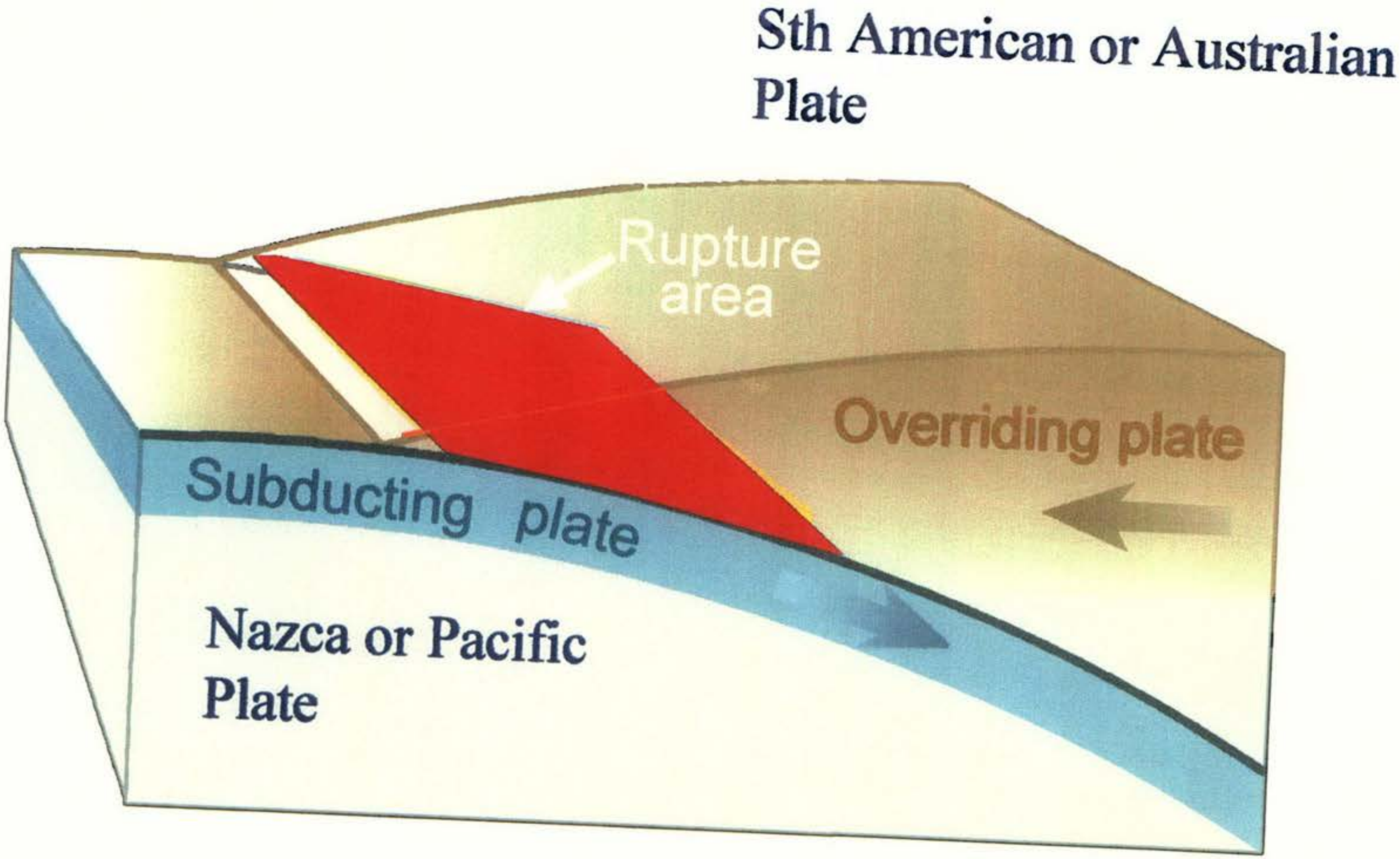
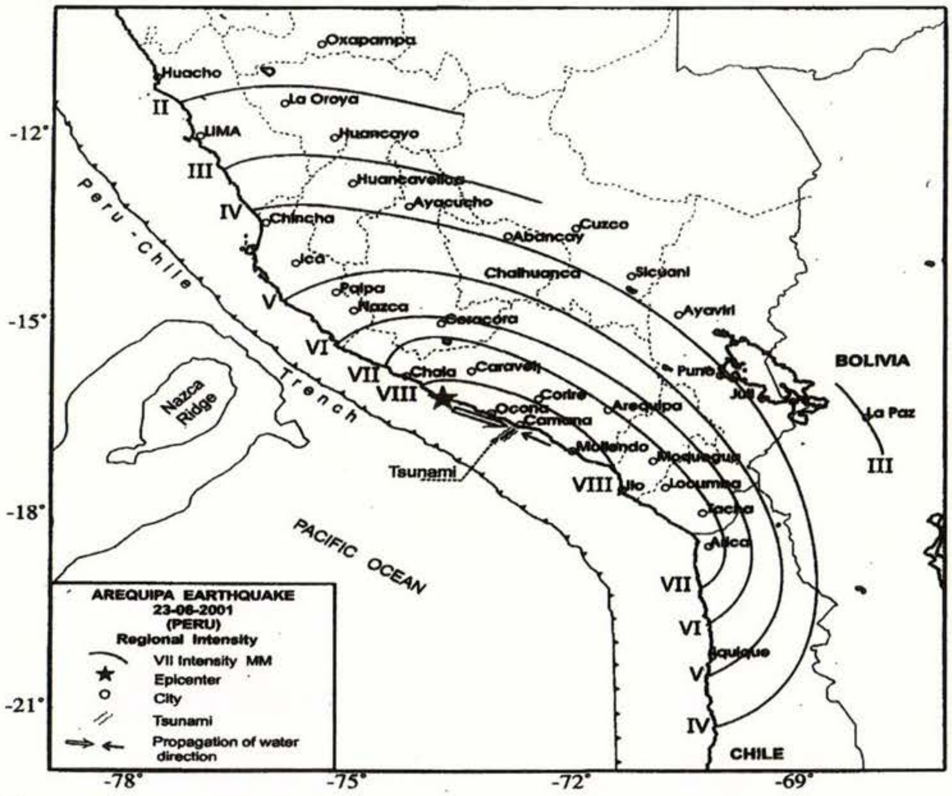
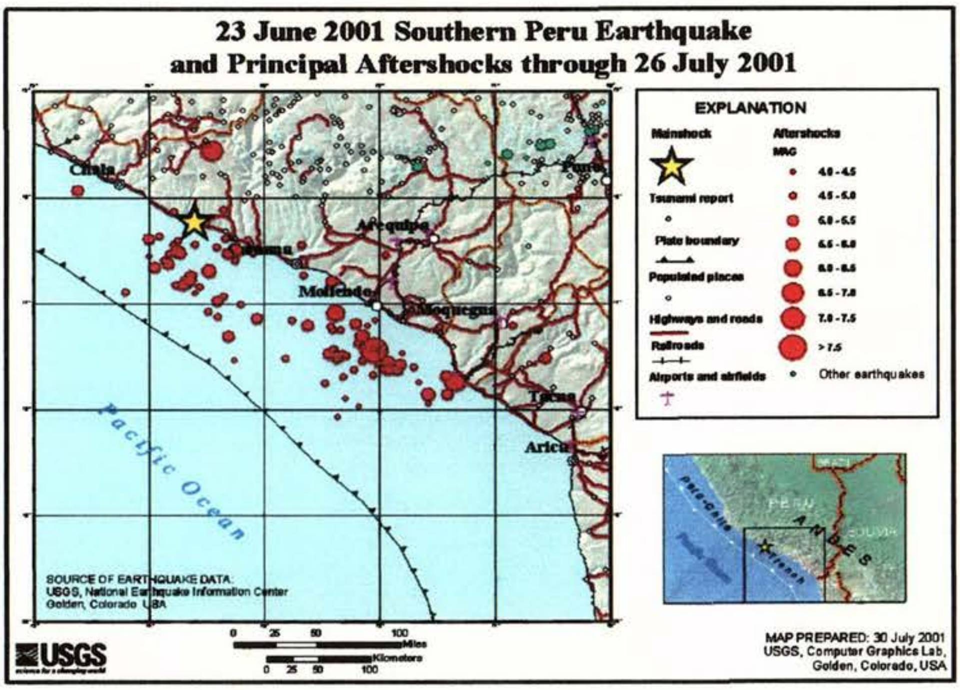


Figure 1 (b)

Plate tectonic setting of Peru and New Zealand, comparing the subduction zone setting of the eastern North Island to that of Peru (a); and a cartoon cross section of a subduction zone (b). In Peru the overriding plate is the South American continental plate and the subducting plate is the oceanic Nazca Plate. In the eastern North Island, the continental Australian Plate overrides the oceanic Pacific Plate. The southern Peru earthquake was centred just north of Arequipa on the Peruvian map. The subduction interface is the locked zone of contact between the two plates (marked "rupture area" on the figure) and great earthquakes are produced when then two plates let go and release many years of accumulated strain.



(a)



(b)

Figure 2

Isoseismal map of Modified Mercalli (MM) intensity produced by the southern Peru earthquake (a), and aftershocks recorded in the month following the earthquake (b). The sources of the maps are the Instituto Geofisico Del Peru and the US Geological Survey website, respectively.

Figure 3
Locations visited during our reconnaissance trip. The solid rectangle shows the surface projection of the 300 x 100km long zone of the subduction interface that is thought to have ruptured during the earthquake.

Figure 4
Reconnaissance team members. From left: Hector (Coco) Aleman (geophysicist), Robert Langridge (earthquake geologist), Mark Stirling (trip leader and seismic hazards scientist), and Rafael Benites (seismologist).

(a)

(b)

Figure 5
The Arequipa cathedral at the time of our visit, showing one spire absent as a result of the earthquake (a). In (b) the cathedral is shown during the actual earthquake shaking, moments before the spire fell through the cathedral ceiling (the picture is from the tourist brochure "Terremoto" which was being sold on the streets of Arequipa at the time of our visit).

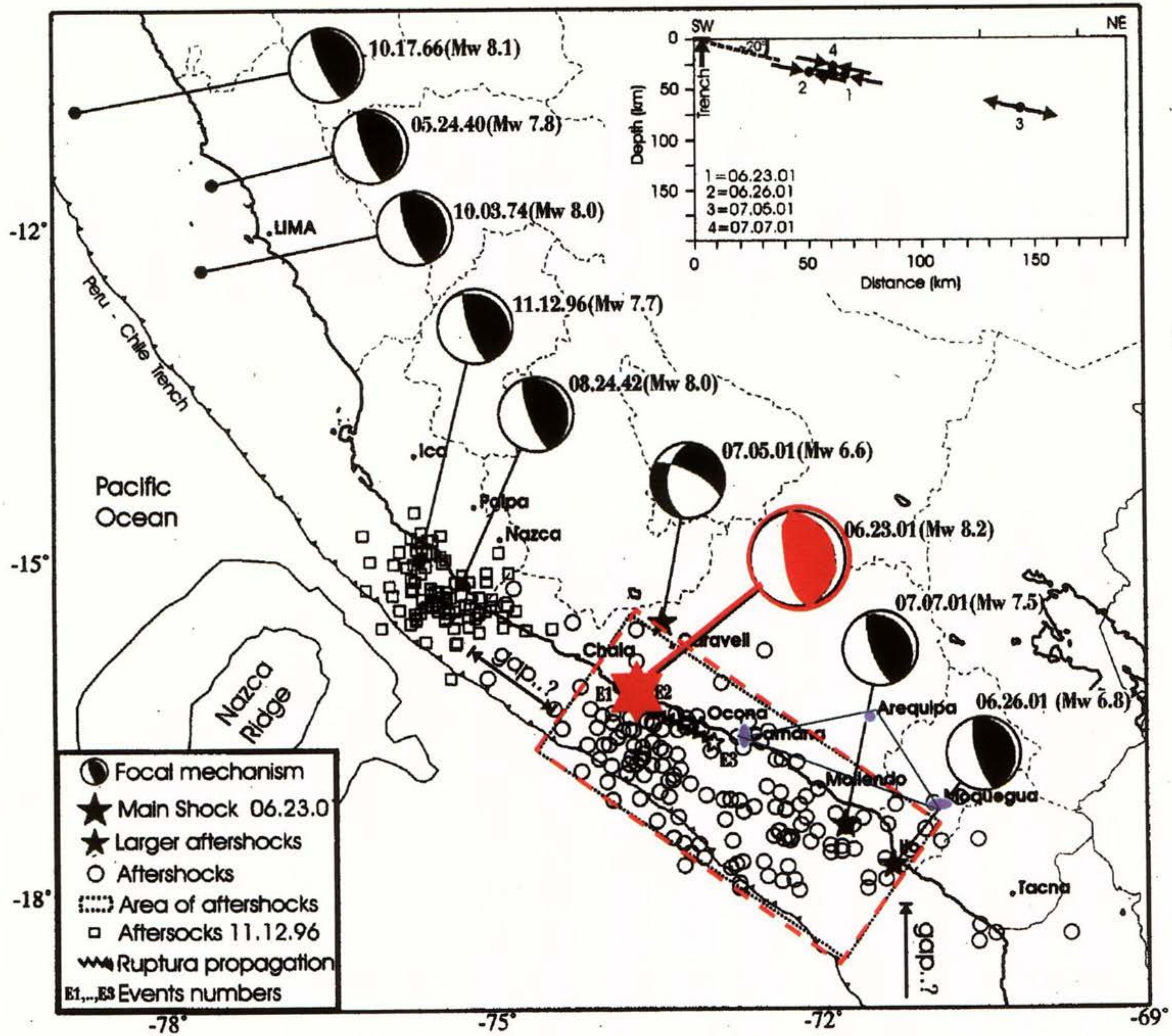


Figure 6
Historical subduction interface earthquakes in southern Peru since AD 1940. Focal mechanisms are lower hemisphere-equal area projections. The sources of the map is the Instituto Geofisico Del Peru.

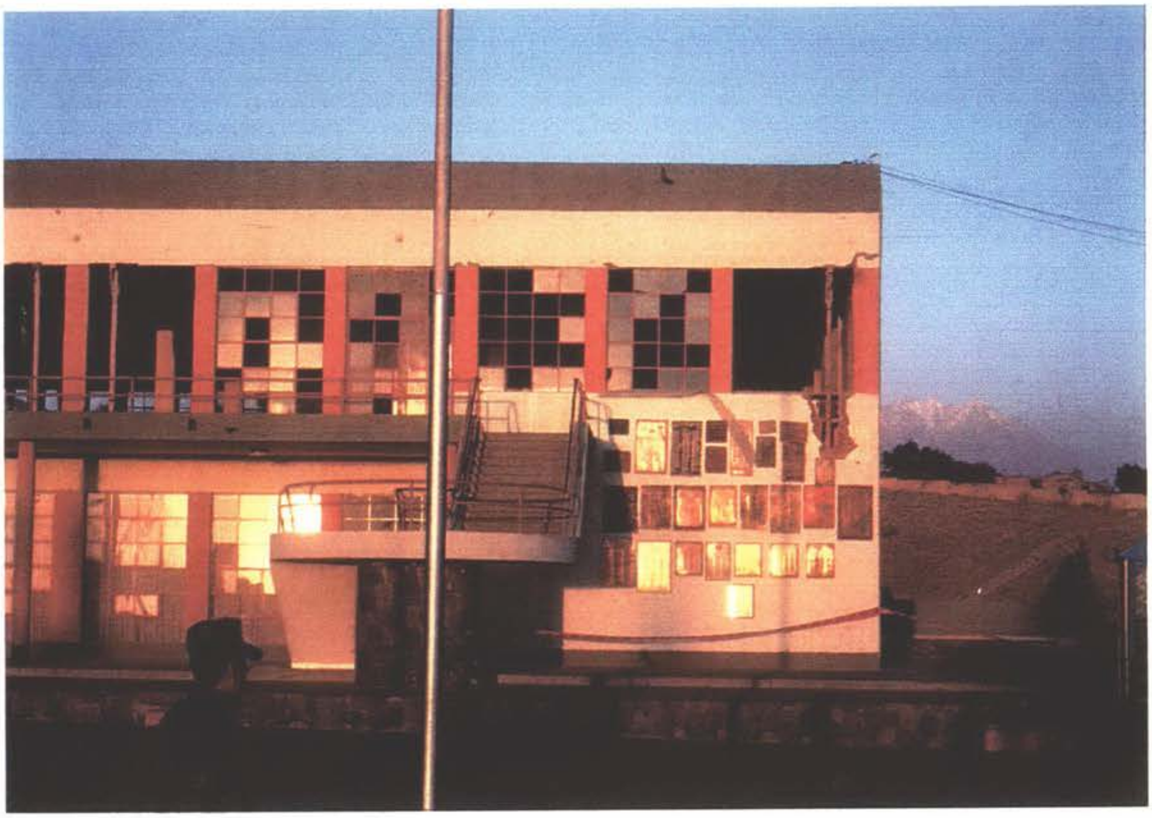


Figure 7
Damage to the top floor of the 1971-vintage Arequipa military mess. The broken glass and cracked pillars show that the building was not designed well enough to withstand the shaking, despite the relatively young age of the building.

Figure 8
Damage to the Pan American highway from failure of the slopes beneath the highway. Damage like this was widespread on the highways along the 300km long earthquake rupture zone, causing some considerable traffic jams.

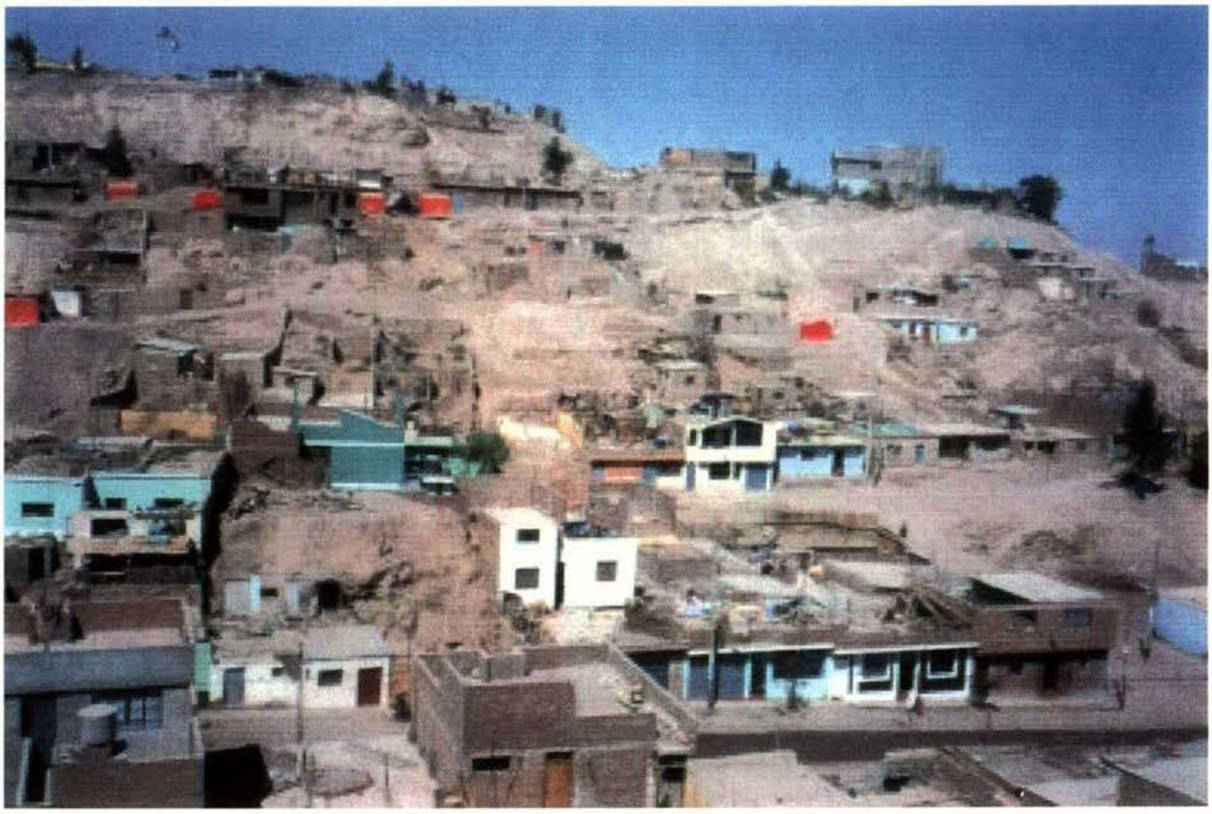


Figure 9
Sever damage to buildings on the steep hillslopes of Moquegua. These hillslopes, alongwith the valley bottoms, are underlain by alluvial sediments which would have amplified the shaking from the earthquake. In this photograph nearly all adobe buildings have been destroyed, with considerably less damage to the more substantially constructed buildings.

Figure 10
Damage to the Moquegua College, a building probably of similar age to the Arequipa military mess building in Figure7.

Figure 11
Undamaged buildings on granite rock in Mollendo. No damage was observed in the city, even in the case of adobe buildings (as can be seen in the lower centre of the photograph).

Figure 12
Rockfall of c.100m height in Ocona area.

Figure 13
Damage to the major bridge serving the township of Punta De Bom Bon.

Figure 14
Near total devastation to the coastal resort town of Camana by the tsunami.

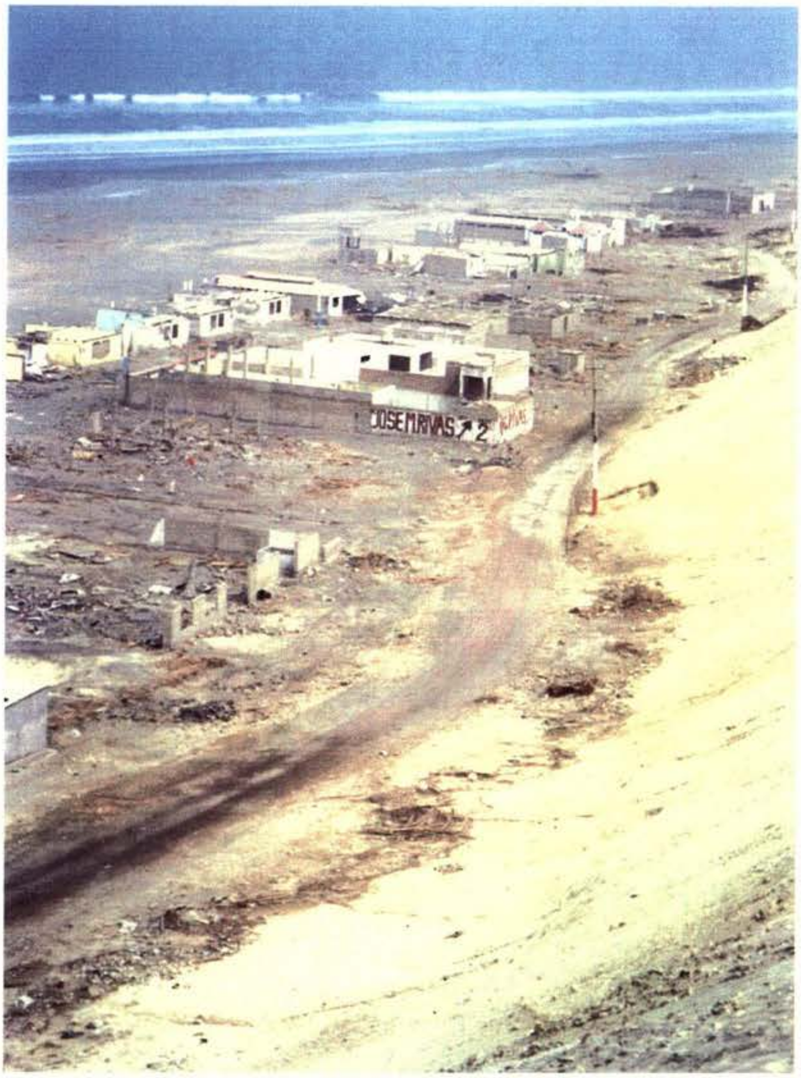


Figure 15
The settlement of Las Cuevas (southeastern continuation of Camana) as we saw it some five weeks after it was destroyed by the tsunami. Note the darkish line of water-washed debris at the base of the hill, which marks the maximum inland extent of the tsunami.

Figure 16
This photo gives an indication of the wave height reached by the tsunami. Eye witness accounts reported that the tsunami wave smashed through the roof of this disco and blew out the windows. The wave would therefore have been about 7m high, a height confirmed by the damage to the lamps of some tall lamp posts in the same area.

(a)

(b)

Figure 17
Possible evidence for coastal subsidence in Camana. The active beachfront was once 100 to 200m seaward of the ruined building shown in this photograph (a) but is now right at the building. This could be due to subsidence and also removal of sand by the retreating tsunami. The severe damage and southward lean to the building is largely due to the severity and obliquity of impact of the tsunami. The coastal promenade in (b) was once well back from the active beach front, but is now clearly at the active beachfront. In the 5 weeks following the earthquake it has been eroded and breached by the sea. This change in position of the active beachfront could also be due to coastal subsidence, and sand removal by the retreating tsunami.

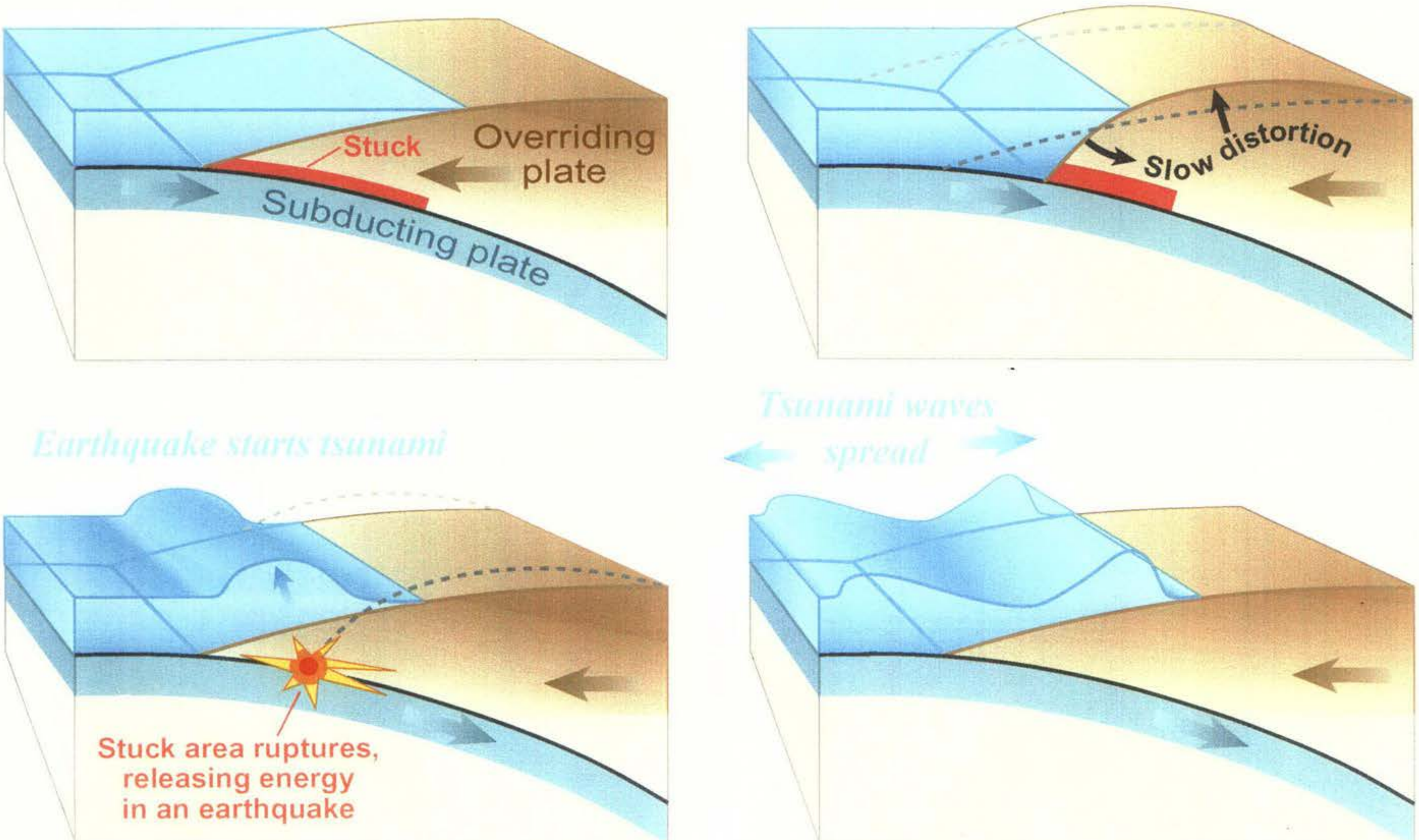


Figure 18
A four step cartoon showing the earthquake cycle of a subduction zone and how the tsunami is generated during a great earthquake.

Figure 19

The Pucchun croplands showing the up-to-1km inland extent of tsunami inundation. The light gray farmlands in the photograph are covered with tsunami sand and are absent of vegetation, whereas the dark (crop-covered) fields escaped inundation. A dashed line also defines this boundary.

Figure 20
Cobble gravel deposit formed by breaching of the natural beachfront bar during the tsunami.

(a)

(b)

Figure 21
Tsunami deposits. In (a), vegetation has been laid down in the direction of wave motion (i.e. left to right) and buried by about 2cm of sand (see pocket-knife excavation to the right of the photograph) and the light colour on the surface of the deposit is a salt crust left behind after evaporation of the standing seawater. Tsunami deposits were also laid down inside many buildings in the Las Cuevas-Camana area, with the added problem of being highly erosive before deposition. In this church building in Las Cuevas (b) the sand-laiden waters eroded the cement-veneered walls of the church enough to expose the underlying bricks.

Figure 22
Distal edge of the tsunami inundation at Puccun, about 1km inland. The inundation zone experienced crop loss, sand and gravel deposition, standing seawater and salinisation.

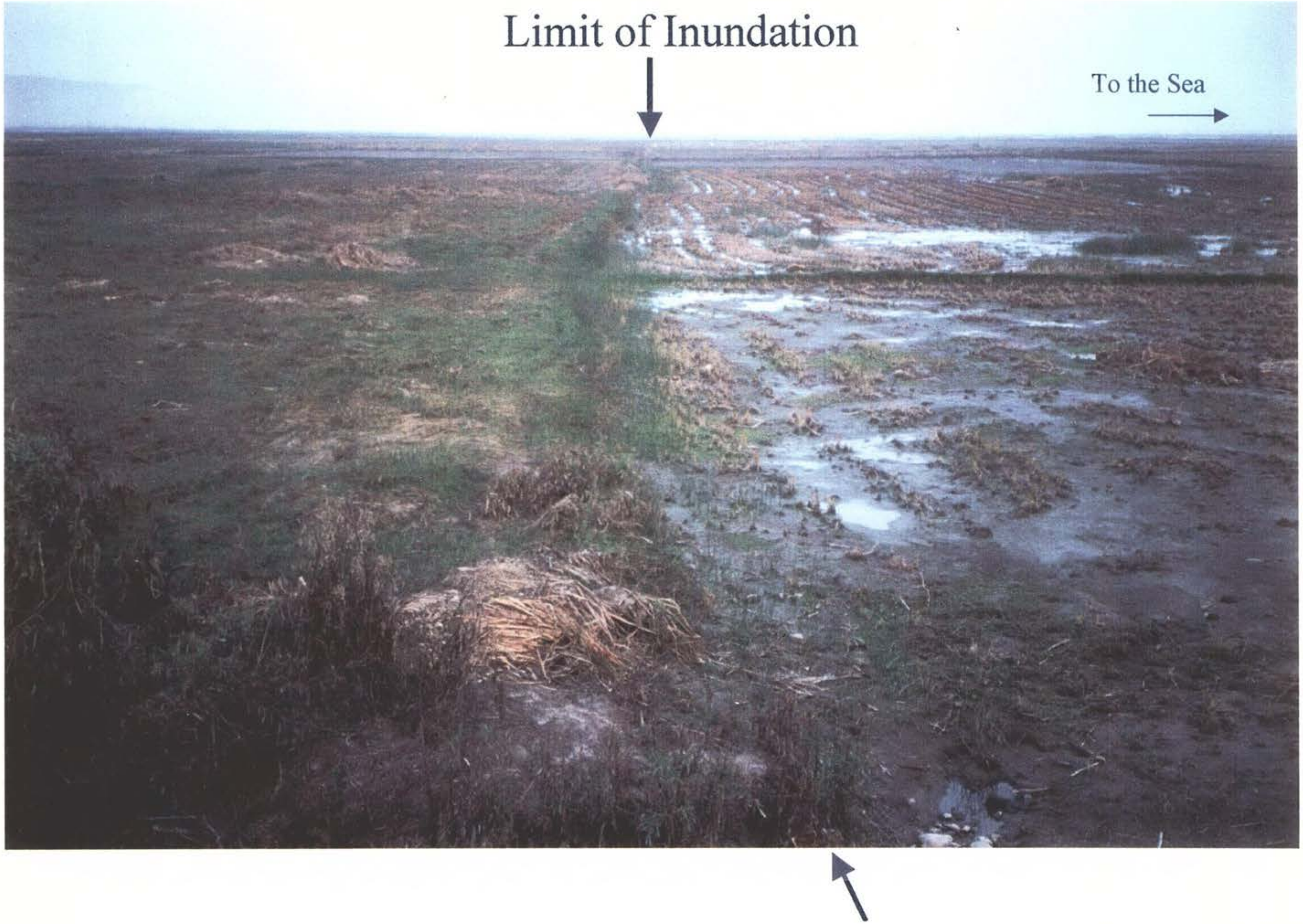
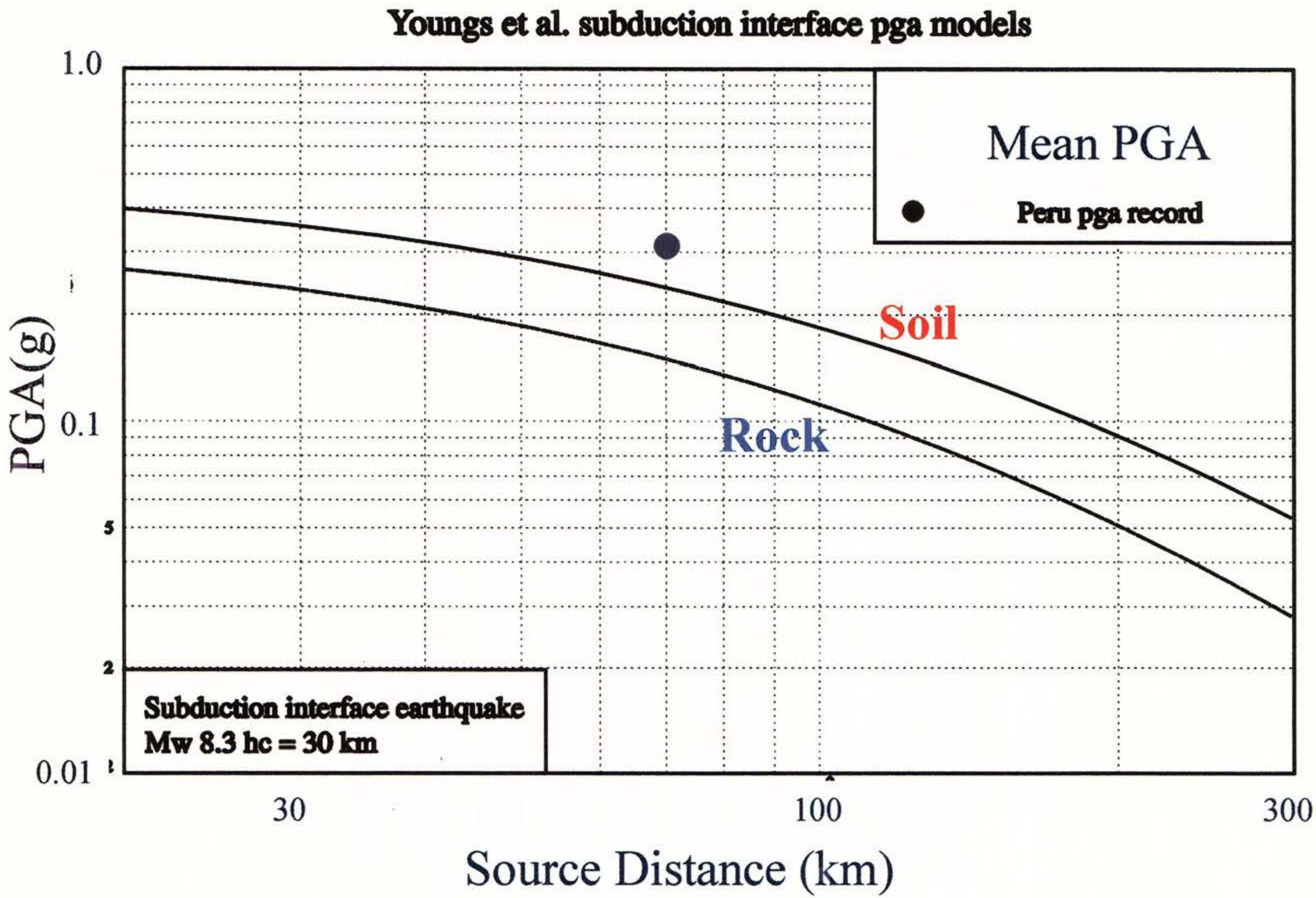


Figure 23
The Moquegua peak ground acceleration (soil site conditions) plotted on the graph of median ground motions predicted for the same size of earthquake from the Youngs et al (1997) subduction interface attenuation relationship.



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