Seismic Hazard Above the South America Subduction Zone in Southern Peru

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SUMMARY
Southern Peru lies above the South America subduction zone and is one of the most seismically active regions in the world. It was the site of one of the largest known earthquakes, the 1868 Arica **M** 9 earthquake and it is expected that the earthquake will be repeated in the future. We have estimated the probabilistic hazard for three major cities in southern coastal Peru using a seismic source model that has discrete seismic sources (e.g., crustal faults) and state-of-the-art ground motion prediction models. We have developed a segmentation model for the South America megathrust based largely on the tsunami record developed by Okal *et al*. (2006) and estimated recurrence intervals based on the historical seismicity record, which dates back more than 300 years. The Next Generation of Attenuation ground motion models were used for crustal faults and background seismicity in the hazard analysis. We have also selected and weighted current subduction zone ground motion models for use in the analysis. The probabilistic hazard is expectedly high in southern Peru with peak horizontal ground acceleration (PGA) values exceeding 0.6 g for a return period of 475 years. The seismic sources that generally control the hazard at this return period are both the megathrust and Wadati-Benioff zone.

Keywords: Peru, probabilistic seismic hazard, South America subduction zone

1. INTRODUCTION

We have evaluated the seismic hazard at three cities in southern Peru, Arequipa, Moquegua, and Tacna, using the probabilistic seismic hazard analysis (PSHA) methodology. Southern Peru is one of the most seismically active regions in the world (Figures 1 and 2) and the site of one of the largest known earthquakes, the 1868 moment magnitude (**M**) 9 Arica event. It is expected that the earthquake will be repeated in the future. More recent earthquakes have shaken southern Peru including the 2001 **M** 8.4 Arequipa and 2007 **M** 8.0 Pisco events (Figure 2).

Previous seismic hazard analyses of Peru have used an outdated seismic source zonation approach based on the historical earthquake record rather than specifically characterizing the South America subduction zone megathrust and crustal faults. In this study, the available geologic and seismologic data are used to evaluate and characterize discrete potential seismic sources, the likelihood of earthquakes of various magnitudes occurring on those sources, and the likelihood of the earthquakes producing ground motions over a specified level. It should be noted that there are very significant uncertainties in the characterization of seismic sources and ground motions in Peru due to the limited research in active faulting and strong motion seismology; these uncertainties have been incorporated into the PSHA.

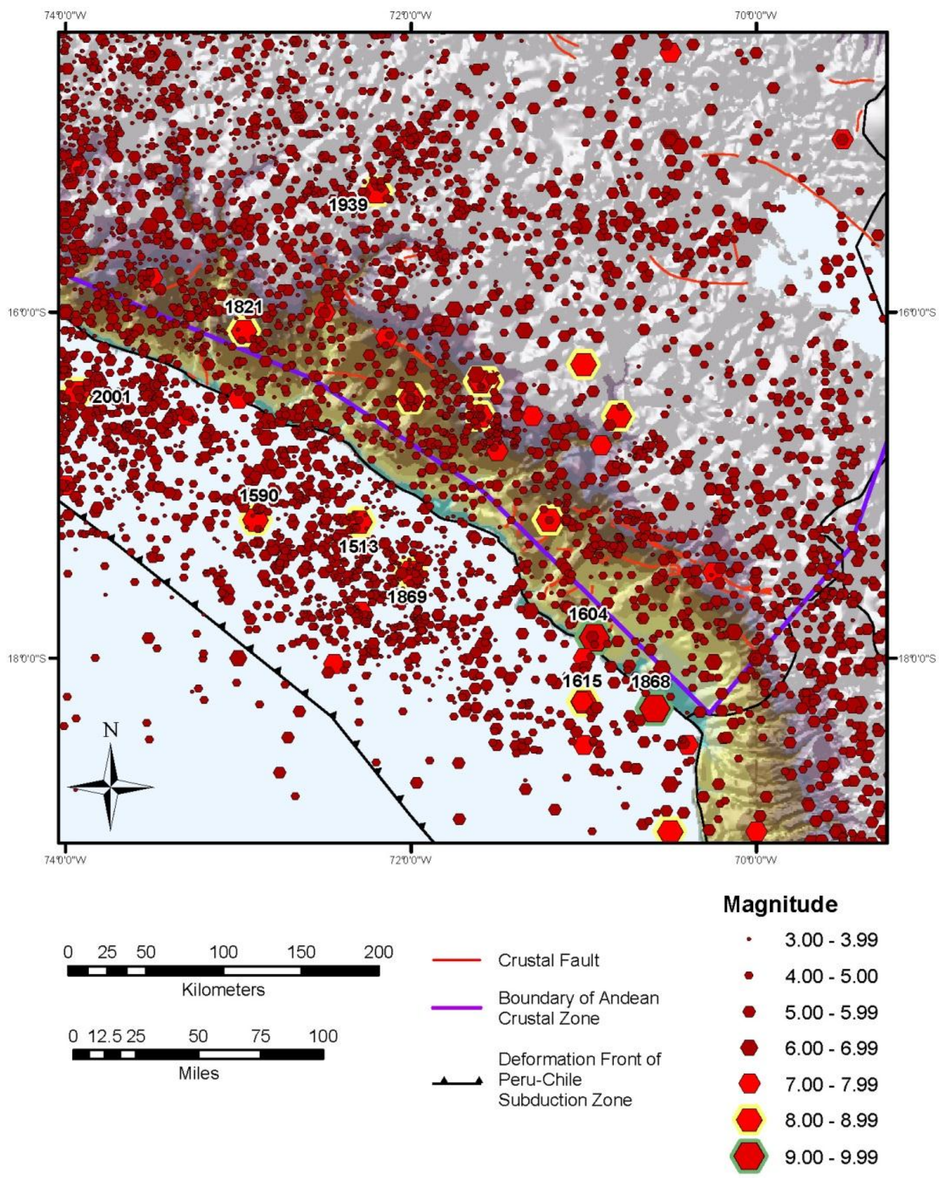


Figure 1. Historical seismicity of southern Peru, 1471 to 2011. Significant **M** ≥ 8.0 events indicated by year.

2. PSHA METHODOLOGY

The PSHA approach used in this study is based on the model developed principally by Cornell (1968). The occurrence of ground motions at a site in excess of a specified level is a Poisson process, if (1) the occurrence of earthquakes is a Poisson process, and (2) the probability that any one event will result in ground motions at a site in excess of a specified level is independent of the occurrence of other events.

For input into the PSHA, seismic sources need to be defined and ground motion prediction models selected. Two types of earthquake sources are characterized in this PSHA: (1) fault sources; and (2) areal source zones. The seismic sources considered in this analysis include crustal faults, background crustal seismicity, and the South America subduction zone, both the megathrust and the Wadati-Benioff (intraslab) zones. Fault sources are modeled as three-dimensional fault surfaces and details of their behavior are incorporated into the source characterization. Areal source zones are regions where earthquakes are assumed to occur randomly. Seismic sources are modeled in the PSHA in terms of geometry and earthquake recurrence. Uncertainties in the seismic source parameters, which were sometimes large, were incorporated into the PSHA using a logic tree approach. For the ground motion prediction models, we used global relationships for crustal and subduction zone earthquakes.

3. SEISMOTECTONIC SETTING AND HISTORICAL SEISMICITY

Tectonically, southern Peru is located on the South America plate, which overrides the actively subducting Nazca plate. At the latitudes of southern Peru, the Nazca plate is being subducted at a shallow dip (about 10° to 30°) to a depth of 100 km and at a rate of about 110 mm/yr. The Peru-Chile subduction zone has been the source of some of the largest earthquakes in the world including the largest event known, the 1960 **M** 9.5 Chile earthquake. In addition to great megathrust earthquakes, seismicity occurring in the crust of South America (above a depth of about 40 km) and within the Nazca plate Wadati-Benioff zone (intraslab) has been abundant (Figure 1). One of the largest intraslab earthquakes was the devastating 1970 **M** 7.9 earthquake in west-central Peru, which killed 70,000 people and injured 50,000.

Southern Peru is located in the "Big Bend" of the Peru-Chile subduction zone (Figures 1 and 2). This section of the subduction zone has a history of large destructive earthquakes including the destructive 1868 **M** 9 Arica and 1877 **M** 8-9 Tarapaca earthquakes. Most of these earthquakes have generated destructive tsunamis. Since 1471, a total of 42 earthquakes larger than or equal to approximately **M** 7 (or Modified Mercalli [MM] intensity IX) have been recorded and thought to have occurred in southern Peru (Figure 1). Twenty events occurred prior to this century and so there is a paucity of information on these events and their location uncertainties could be significant. There can be large uncertainties in magnitude estimates particularly for pre-1940 events. Significant earthquakes believed to be of approximate **M** 8 or greater are discussed below.

1604 Arequipa Earthquake
On 24 November 1604, a major earthquake struck the coast of southern Peru at about 1:30 p.m. local time. The magnitude of the earthquake has been estimated to be about **M** 9. The towns of Arequipa, Tacna, and Moquegua were shaken at MM VIII and MM VI effects were observed at Cuzco and Ica (Silgado, 1985). Arica was reportedly destroyed by the tsunami generated by this event. The 1604 earthquake was almost the size of the 1868 event but Okal *et al*. (2006) believe it did not rupture north of the Nazca Ridge as did the 1868 event.

1868 Arica Earthquake
A major earthquake, which also generated a great tsunami, occurred on 13 August 1868 at 4:46 p.m. local time (Figure 2). The maximum intensity assigned to the event is MM X. The event is thought to have lasted 5 minutes and damage was widespread. The cities of Arequipa, Tiabaya, Moquegua, and Locuillba were particularly hard hit.

1877 Earthquake
The 9 May 1877 Tarapaca (Iquique), Chile earthquake (Figure 2) unleashed a destructive tsunami that spread throughout the Pacific Basin. Locally there were 30 deaths in Iquique and 14 fatalities in Cobjia. The rupture length has been estimated at 450 km suggesting a magnitude of **M** 8.4 (Okal *et al*., 2006). Others have estimated a value between **M** 8 and 9.

2001 Arequipa Earthquake
The 23 June 2001 **M** 8.4 Arequipa earthquake in southern Peru ruptured a portion of the seismic gap that ruptured previously in 1868 (Figure 2). The event was felt throughout central and southern Peru and

northernmost Chile. The earthquake ruptured a 400 km length of the interface extending from Atico to Ilo that was 100 km wide. The event killed 80 people with 70 people missing and presumed dead.

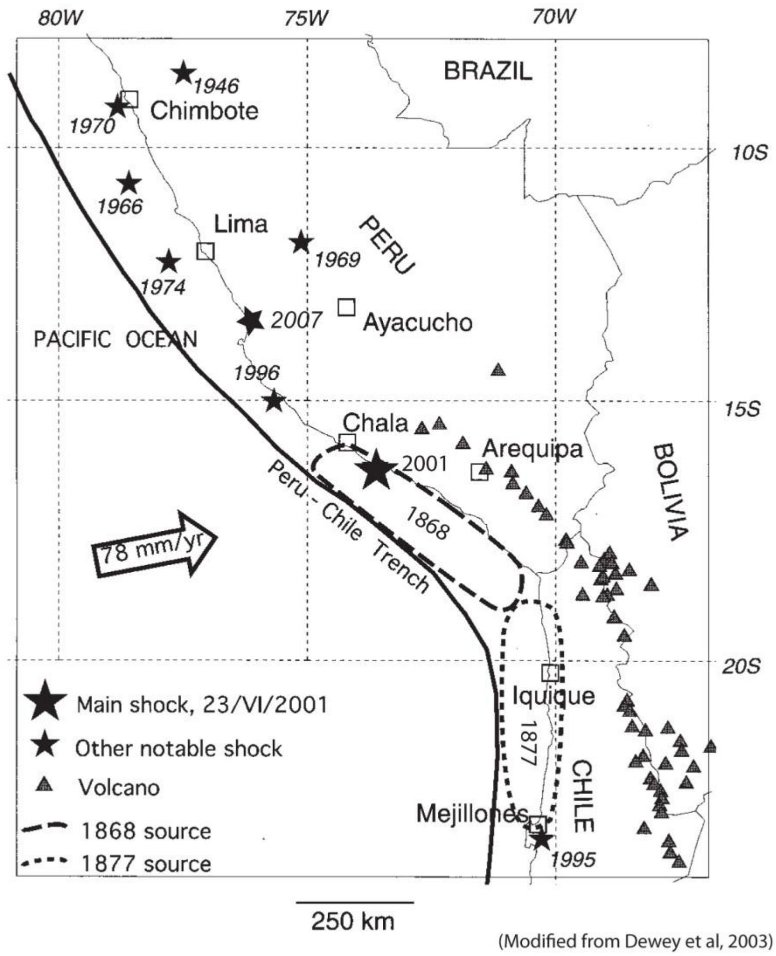


Figure 2. Significant historical earthquakes along the Peru-Chile subduction zone

4. SEISMIC SOURCE CHARACTERIZATION

Active and potentially active seismogenic crustal faults, the Peru-Chile subduction zone (both megathrust and intraslab zones), and background crustal seismicity are the seismic sources included in the PSHA.

4.1 Crustal Faults

Few active fault investigations have been performed in southern Peru and those that have been were at a reconnaissance level. Thus the inventory of active faults in southern Peru and Peru as a whole is significantly incomplete. Much of our characterization is based on a study we performed in 1994 (Woodward-Clyde Consultants, 1994; Fenton *et al*., 1995), whose results were published in *Database and Map of Quaternary Faults and Folds in Peru and its Offshore Region* (Macharé *et al.*, 2003).

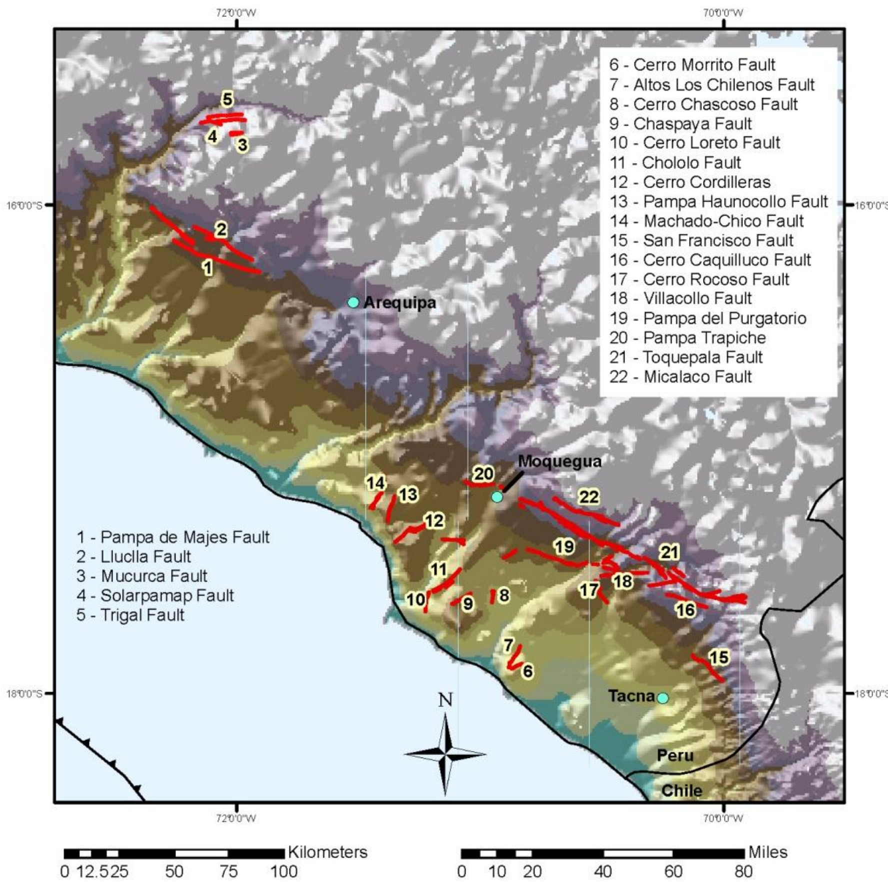


Figure 3. Crustal faults included in the PSHA

Consistent with current state-of-the-practice, we estimated the maximum magnitudes for the crustal faults based on empirical relations between fault rupture length and rupture area and magnitude developed by Wells and Coppersmith (1994). Considerable uncertainty often exists in the selection of the appropriate rupture length to be used in the analysis. In almost all cases, we have assumed no fault segmentation and that the whole length of the fault could rupture. Maximum magnitudes derived from rupture area-based estimates assumed a maximum seismogenic crustal thickness of 20 km based on examination of the contemporary seismicity.

The characteristic, maximum magnitude, and truncated exponential recurrence models were used for the crustal faults in the PSHA weighted 0.6, 0.3, and 0.1, respectively. The recurrence rates for faults within southern Peru are unknown, with the exception of the western part of the Pampa del Purgatorio fault where paleoseismic trenching shows a 200- to 300-year interval between the two most recent surface rupturing events. For all other faults, fault activity is expressed as an annual average slip rate (in mm/yr) rather than an interseismic interval.

4.2 Crustal Background Seismicity

Crustal background or random earthquakes are those events that can occur without an apparent association with a known or identified tectonic feature. Within the Andean crust of southern Peru, seismicity is distributed diffusely with no clear relationships with any geologic structures. These faults are often called "blind" or "buried" faults. The hazard from such sources is incorporated into the PSHA through inclusion of an areal source zone and Gaussian smoothing.

We estimate the maximum magnitude for the background crustal earthquakes to be between **M** 7.0 and 7.5, weighted 0.7 and 0.3, respectively. Earthquakes larger than **M** 6.5 to 7.0 will typically be accompanied by surface rupture in regions where the seismogenic crustal thickness is on the order of 15 to 20 km and thus repeated events of this size will produce recognizable fault-related geomorphic features at the earth's surface. However, the higher magnitudes used in this PSHA reflect the fact that crustal faults have received little attention in Peru and there are probably active faults in southern Peru that we have not accounted for.

In order to estimate probabilistic ground motions for the selected cities, recurrence parameters are required for the background seismicity occurring within South American crust as well as for the intraslab earthquakes within the subducting Nazca plate. Earthquakes in the historical catalog dating back to 1930 within the Andean crustal zone (Figure 1) were used in the crustal background recurrence estimates. Earthquakes shallower than 40 km were considered to be crustal events. The recurrence relationships were estimated following the maximum likelihood procedure developed by Weichert (1980) and estimated completeness intervals for the region. Dependent events, foreshocks, and aftershocks were identified using empirical criteria for the size in time and space of foreshock-mainshock-aftershock sequences. The resulting catalog for independent events was then used to develop a recurrence relationship. There were a total of 436 independent events of **M** ≥ 4.0 used to calculate the background crustal recurrence.

The resulting recurrence relationship for crustal background earthquakes, assuming the usual form of the Gutenberg-Richter relationship, is log N = -0.79 – 0.94 **M**. The recurrence curve is well constrained and predicts recurrence intervals for **M** 6.0 and greater and **M** 7.0 and greater earthquakes of about 7 and 61 years, respectively.

In addition to the traditional approach of using areal source zones with uniformly distributed seismicity, Gaussian smoothing (Frankel, 1995) with a spatial window of 15 km was used to address the hazard from background seismicity and incorporate a degree of stationarity. Minimum magnitude was **M** 4.0. We weighted the two approaches, an areal source and Gaussian smoothing, equally at 0.5 to compute the hazard from background seismicity in the PSHA.

4.3 Peru-Chile Subduction Zone

Megathrust

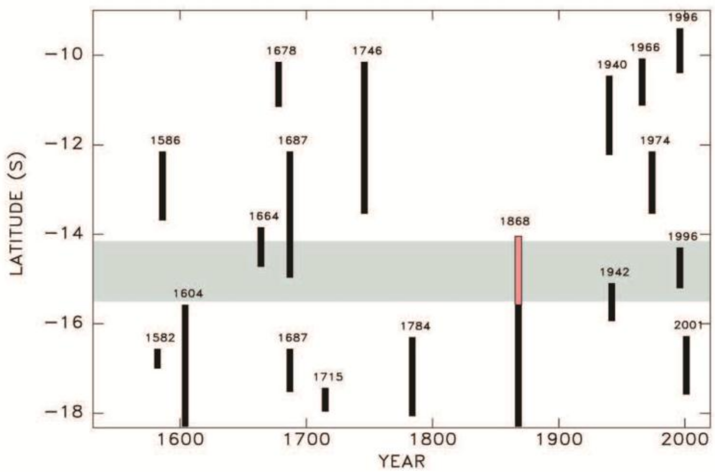
For this study, we developed a model of the Peru-Chile subduction zone that consists of three segments that impact southern Peru as listed in Table 1. The model is based on a modification of the model of Okal *et al*. (2006) for the Central and Southern Peru segments and includes the northernmost 1877 Chilean segment. The model is derived from the historical seismicity along the subduction zone (Figures 2 and 4).

Several investigators have recognized that the Peru-Chile subduction zone is segmented based on the historical record (Figure 4). Examination of the spatial-temporal distribution of the Peru-Chile subduction zone suggests that the Nazca Ridge is a "soft" segment boundary if a boundary at all. Hence, we adopted a model where the Southern Peru segment is represented by the 1868 rupture zone (Figure 2).

The seismic source parameters and their weights for our model for the subduction zone are listed in Table 1. We assumed that the maximum earthquakes have occurred already in historical times and have thus adopted the maximum magnitudes observed to date with their uncertainties.

Table 1. Peru-Chile Megathrust Model

Segments	Mmax (M)	Dip (degrees)	Maximum Depth (km)	Recurrence Intervals (years)
Central Peru (9.5 – 14.4°S)	8.8 ± 0.2	17 ± 3	40 ± 10	290 ± 100
Southern Peru – 1868 (14.4 – 18.5°S)	9.0 ± 0.2	17 ± 3	40 ± 10	260 ± 100
Northern Chile – 1877 (18.5 – 24.0°S)	9.0 ± 0.2	17 ± 3	40 ± 10	200 ± 100
Weights	0.2, 0.6, 0.2	0.3, 0.4, 0.3	0.3, 0.4, 0.3	0.3, 0.4, 0.3



(Source: Okal *et al*., 2006)

Note: 2007 Pisco earthquake not shown. The shaded band represents a segment boundary proposed by others coinciding with the Nazca Ridge.

Figure 4. Spatio-temporal distribution along the central and southern Peruvian subduction zone

The plate dips and maximum depths of the seismogenic megathrust along this portion of the subduction zone are similar and are based on observations of seismicity. We adopt a dip of 17° ± 3° for all three segments (Table 1). The maximum depth of the megathrust is not well constrained. Comte and Suarez (1995) suggested a maximum depth of 40 ± 10 km with no appreciable variations along strike. We adopt a range of 40 ± 10 km for the PSHA (Table 1).

In terms of recurrence intervals of the Southern Peru segment, only two known earthquakes have ruptured the whole segment in 1604 and 1868 (Okal *et al*., 2006) (Figure 4). Thus the single recurrence interval is 264 years. We adopt a value of 260 years but with a large uncertainty of 100 years (Table 1). We also adopt the Okal *et al*. (2006) recurrence interval of 290 years for the Central Peru segment although there are no repeat events for either the 1687 or 1746 earthquakes (Figure 4). Their value of 290 years is based on a possible repeat time of two cycles of activity. Finally, as noted by Nishenko (1991), there is no known predecessor of the 1877 event. Nishenko (1991) compares this segment with a similar-sized southern Chile segment to the south that has an estimated recurrence interval of 111 years and the 1868 segment (264 years). We adopt a broad distribution of 200 ± 100 years for the 1877 segment (Table 1).

Wadati-Benioff Zone

Based on the 1970 **M** 7.9 event, the intraslab earthquake within the subducting plate has been assumed to have a maximum magnitude of **M** 8.0 ± 0.2 beneath southern Peru. The closest approach of the Nazca plate to coastal cities and hence the intraslab region is at an approximate distance of 60 to 70 km. Unlike our megathrust model, we adopt a single intraslab region for the Peru-Chile subduction zone.

Similar to the approach taken for the crustal background seismicity, the recurrence was estimated for the intraslab zone assuming the truncated exponential model. A total of 441 earthquakes above **M** 4.5 was used in the well constrained regression. The *b*-value of 0.88 and *a*-value of -0.47 results in predicted recurrence intervals of **M** 7.0 and 8.0 and greater events of 15 and 115 years, respectively. The *b*-value was varied by ± 0.1 in the PSHA as was done for the crustal background zone.

5. GROUND MOTION PREDICTION MODELS

There are no vetted ground motion prediction models that are specific to Peru. Thus, in this evaluation, the recently developed Next General of Attenuation (NGA) models for crustal earthquakes in tectonically active regions by Abrahamson and Silva (2008), Chiou and Youngs (2008), Campbell and Bozorgnia (2008), and Boore and Atkinson (2008) were used in the PSHA. These models have been shown to be applicable to other regions worldwide.

Arango *et al*. (2012) evaluated a set of global and regional subduction ground motion models for their applicability to Peru-Chile. This evaluation utilized a recently compiled database of strong motion data from Peru and Chile. Using a maximum likelihood approach, Arango *et al*. (2012) favored, in order, the megathrust models of Zhao *et al*. (2006) followed by Youngs *et al*. (1997), and Atkinson and Boore (2003). We weighted the three models 0.4, 0.3, and 0.3, respectively, in the PSHA.

For the intraslab model, Arango *et al*. (2012) rated the Zhao *et al*. (2006) model the highest followed by Atkinson and Boore (2003). We weighted the models at 0.55 and 0.45, respectively. The hazard was calculated for soil site conditions. A V_S30 of 310 m/sec was used in the NGA models. The subduction zone models are for generic soil.

6. HAZARD RESULTS

The results of the PSHA are presented in terms of ground motion as a function of annual exceedance probability. This probability is the reciprocal of the average return period. Figure 5 shows the mean peak ground horizontal acceleration (PGA) hazard for the three cities. The values for mean PGA values at two return periods of building-code relevance are listed in Table 2. The probabilistic hazard is expectedly high in coastal southern Peru given the seismically active Peru-Chile subduction zone.

Table 2. Mean PGA Hazard on Soil (g's)

Cities	**Return Period (years)**	
	475	**2,475**
Arequipa	0.65	1.08
Moquegua	0.66	1.10
Tacna	0.64	1.05

Figure 5 also shows the hazard contributions by seismic sources for the three cities. At PGA, the hazard is controlled by the intraslab seismicity because of its high rate of occurrence. The megathrust also contributes to the PGA hazard at shorter return periods (Figure 5). The PGA hazard is similar at all three cities (Figure 5d) because the distances to the subduction zone are similar. At longer spectral periods, i.e., 1.0 sec spectra acceleration, the megathrust controls the hazard because of its capability to generate very large earthquakes (**M** ≥ 8.8) followed by the intraslab seismicity.

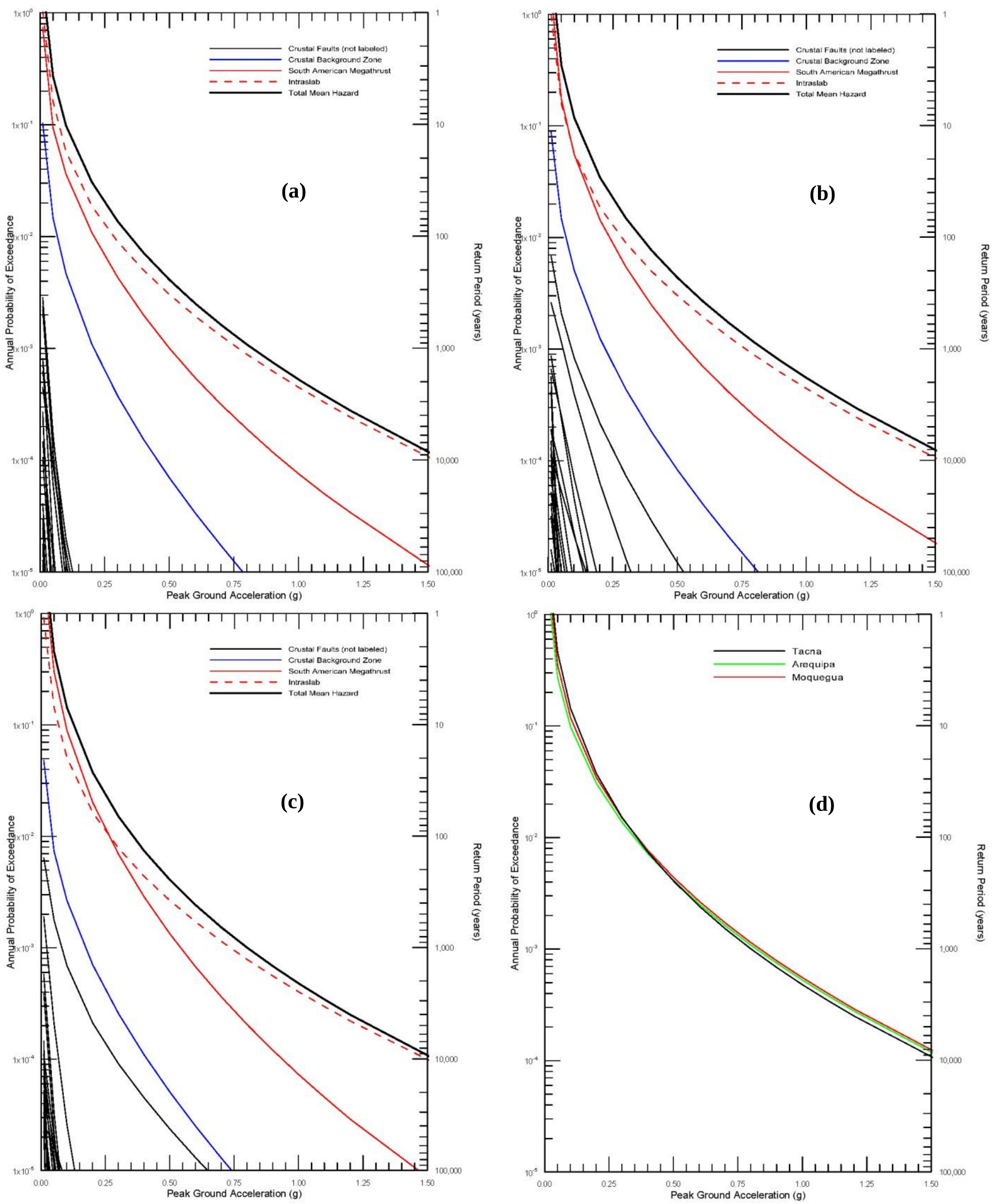


Figure 5. Seismic source contributions to mean PGA hazard: a) Arequipa; b) Moquegua; c) Tacna; d) mean hazard curves

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