A Report on the 24 August 2011 $M_w$ 7.0 Contamana, Peru, Intermediate-Depth Earthquake

by Hernando Tavera

INTRODUCTION

The seismic activity in Peru has its origin in the convergence process between the Nazca and the South American plates. Such convergence takes place at an average velocity on the order of 7–8 cm/yr (DeMets et al., 1980; Norabuena et al., 1999). This process is responsible for the largest damaging shallow interplate underthrusting earthquakes, the intraplate plate events in the dowgoing Nazca slab, and the shallow intraplate crustal events in the overriding South American plate. The interplate events, representing slip between the plates, are the largest earthquakes and can cause considerable damage along the coast from both ground shaking and tsunamis. Shallow crustal earthquakes, although not as large as the underthrusting events, in near-population centers can be damaging over small regions. Large intraplate earthquakes in the slab are not as common but can be a source of damage and concern especially if they are large. The recent 24 August 2011 earthquake is one of these intraplate events in the slab at ~150 km in depth that was well recorded in Peru and worldwide. Many of the large historic intermediate-depth slab earthquakes have not been well recorded with modern seismic or strong ground-motion instruments. Yet, they represent a significant hazard in the high cordillera region of Peru.

Peru has a long and continuous history of earthquakes. Every year, an average of 150 earthquakes are recorded and reported, with intensities of II–III [modified Mercalli (MM) scale] and magnitudes $M_L \geq 4.0$. Underthrusting earthquakes of larger magnitudes ($M_w \geq 7.0$) are less frequent but can cause significant damage over large areas, such as the event that occurred in the Pisco region on 24 August 2007 ($M_w$ 7.9; Tavera and Bernal, 2008; Perfettini et al., 2010). The earthquakes in the overriding plate causing crustal deformation at shallow depths are less frequent, but when they occur, they cause considerable damage in small areas, such as the events that occurred in the Alto Mayo region on 30 May 1990 and 5 April 1991, both with magnitudes of $M_w$ 6.0–6.5 (Tavera et al., 2001). Intermediate-depth earthquakes in the slab are rarely felt at the surface, but when they are large ($M_w \geq 7.0$), they often have a large radius of perception and can cause some damage to houses, soil liquefaction, and landslides in steep areas. An example is the earthquake analyzed in this study.

On 24 August 2011 at 17:46 UTC (12:46 local time), a strong earthquake with a moment magnitude of 7.0 occurred on the eastern border of the central region of Peru. The epicentral coordinates as estimated by the Geophysical Institute of Peru (IGP) were 07.56° S, 74.75° W, with a focal depth of 148 km. The epicenter is 37 km southeast of the city of Contamana (Loreto) and 93 km north-northwest of the city of Pucallpa (Ucayali). The shock was felt in an area with a 700-km radius. Despite the large magnitude of the earthquake, the reported damage was not extensive, likely due to the intermediate focal depth. In this region (Fig. 1), a large number of earthquakes occur in the depth range of 120–200 km with magnitudes less than $M_w$ 6.0, which are often not felt at the surface.

In central Peru, the slab seismicity displays a pattern as follows: (1) a 30° east-dipping segment, from the trench up to 300 km to the east, where it reaches 100 km in depth; (2) a flat-slab segment at a constant depth of about 100 km extending up to 650 km east of the trench; and (3) a poorly defined 30° east-dipping segment that extends to 240 km in depth.

Schneider et al. (1988) suggested that earthquakes in the depth range near 150 km may represent the possible resubduction of the oceanic plate after its transit as a flat segment. The 24 August 2011 earthquake occurs right where the slab begins to steepen and resubduct into the mantle, suggesting that in addition to slab pull forces, bending stresses may play a role in generating this earthquake (Fig. 1). In this note, we report the macroseismic observations, seismological parameters, and strong-motion accelerations of the 2011 Contamana earthquake and place it in the context of the Central Peru subduction process.

ISOSEISMAL MAP

The intensity map for the Contamana earthquake (Fig. 2) has been compiled using information from more than 120 cities and towns distributed throughout Peru. The isoseismal lines show a circular distribution of intensities typical of intermediate-depth earthquakes. A maximum intensity of V–VI (MM) was reached in the towns of Contamana (Loreto) and Pucallpa (Ucayali). Because of its size and focal depth (148 km), this earthquake displayed a large perception radius (700 km); thus, large parts of the Andean Cordillera felt strong shaking.
The event was felt with intensities of II–III (MM) in the cities of Lima, Piura, and Abancay. In addition, several reports indicated that the earthquake was felt in cities such as Quito, Loja, and Guayaquil (Ecuador); Rio Branco (Brazil); and La Paz (Bolivia). Furthermore, landslides and/or rockfalls were reported around the city of Jauja (Junin), where the main square and roads were damaged due to a landslide. It also produced cracks in 10 schools in Pucallpa and damage to houses made of adobe in Huánuco. Similar events occurred during 2010 with epicenters near Pucallpa ($M_w$ 5.8 and depth of 123 km), Bagua ($M_w$ 6.2 and depth of 121 km), and Ayacucho ($M_w$ 6.0 and depth of 110 km).

**AFTERSHOCKS**

The Contamana earthquake was followed during the first 24 h by 35 aftershocks with magnitudes between $M_L$ 3.5 and $M_L$ 5.0, all recorded at the Pucallpa station located 38 km from...
Figure 2. Isoseismal maps for the Contamana intermediate-depth earthquake in the modified Mercalli scale (see Table 1).
the epicenter. The largest aftershock, which occurred 1 h after
the mainshock (18:56 UTC), had a magnitude of $M_L 5.0$ and
a depth of 132 km, and its epicenter was near the mainshock
(epicenter at $07.75^\circ S, 74.21^\circ W$).

Figure 3 shows the mainshock and aftershocks during
the first 60 minutes recorded at the Pucallpa seismic station
(Fig. 3). Unlike other earthquakes in Peru at the same depth
and magnitude (e.g., 25 September 2005 Yurimaguas earth-
quake; Tavera, 2005), this is the first earthquake that has pro-
duced a large number of well-recorded aftershocks; however,
they could not be located because they were not registered
by a greater number of seismic stations.

**FOCAL MECHANISMS**

The focal mechanism of the mainshock has been estimated
from $P$-wave first-motion polarities (Brillinger *et al.*, 1980;
Udias and Buforn, 1988). Data were obtained from stations
at local, regional, and teleseismic distances, with a maximum
of 72 observations for the mainshock (Fig. 4). The solution
obtained for the mainshock corresponds to normal faulting with
nodal planes oriented in north-northwest and north-northeast
directions and a near-horizontal tensional axis oriented in an
east–west direction. The assumed fault plane trends north-
northeast and dips steeply (72°) toward the east, whereas the
auxiliary plane is near the horizontal axis (29°). The focal
mechanism solution suggests an extensional rupture within the
subducting slab, typical of the events that occur at intermediate
depths in the sub-Andean zone of Peru.

**OTHER SOURCE PARAMETERS**

Other parameters such as depth of focus, rupture length, and
seismic moment were determined from the ground-displacement
records obtained from 25 global seismic stations, all located at
distances between 30° and 90° (Fig. 5). To confirm the depth
of focus, we used the arrival time of $P$ and $pP$ waves (Stein and
Wysession, 2003) and travel-time tables of the International
Association of Seismology and Physics of the Earth’s Interior
(IASPEI; Kennett, 1991). We obtain an average depth of
152.4 ± 4.6 km, similar to that reported by the IGP and in-
ternational agencies.

For great earthquakes, the length of rupture can be calcu-
lated from the pulse duration ($T_r$) of ground displacement
using the relationship $T_r = L V_r (V_r = 0.7 \beta$; here, $\beta$ is the S-wave velocity at the focus; Stein and Wysession, 2003). $T_r$ has been identified in records of 20 stations from the global seismic network. We obtained an average rupture length of 22.5 ± 3.6 km, consistent with estimates made from the spatial distribution of aftershocks for earthquakes of similar magnitude and hypocenters in zones of plate convergence.

Also, the seismic moment was calculated from the area under the pulse of the ground-displacement record using the relation proposed by Chandra (1970), Fukao (1972), and Furumoto (1977) (see gray area in Fig. 5). After correcting for the radiation pattern, attenuation, and geometric spreading, we obtain a seismic moment of $4.7(\pm0.4) \times 10^{26}$ dyn cm, equivalent to a magnitude of $M_w$ 7.0, similar to that obtained with other methods.

**STRONG-MOTION RECORDS**

The main event was recorded by at least five digital strong-motion instruments, located at distances from 213 to 554 km from the epicenter (Fig. 2). The nearest station corresponds to Tarapoto (TAR), which recorded a maximum acceleration of 0.166g in the horizontal component. Basically, it corresponds to a single impulse in the S-wave train (Fig. 6), similar to that observed for the Pisco earthquake of 2007 in the record recorded at the Parcona strong-motion station located 138 km the epicenter of the 2007 event. For the 2007 earthquake, this unusual pulse was attributed to the complexity of the rupture process and the pattern of SH-wave radiation (Pulido et al., 2011). A similar situation could occur for this intermediate-depth earthquake; however, we note that the focal mechanism is different. The maximum accelerations recorded by the

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**Figure 4.** Focal mechanism of the Contamana earthquake obtained from the P-wave polarity. Solid circles correspond to compression, and open circles, dilatation. P axis, pressure axis; T axis, tension axis.

**Figure 5.** Three-component accelerograms of the Contamana and Pisco earthquakes recorded with digital strong-motion instruments at the Tarapoto and Parcona cities. Note that the record of high-amplitude peaks in both accelerograms is in the S-wave group. The Contamana earthquake presents an intermediate depth, and the Pisco earthquake, a shallow depth.
strong-motion instruments at different stations are presented in Table 1. According to the ranges of acceleration produced by these events in different seismic stations, it is important to consider its contribution to levels of ground shaking for seismic hazard studies.

Figure 7 shows the spectra amplitude response from the TAR record, where the highest values correspond to three peaks of 0.32g, 0.20g, and 0.24g for a 5% critical damping ratio, all being obtained between 0.1 and 1.5 s. This range of periods is associated with soft soils that are typical of the sub-Andean and jungle areas. The spectra amplitude response record at the Mayorazgo station (Lima) shows a value of 0.027g (5% critical damping ratio) corresponding to periods between 0.1 and 0.6 s (1.6–10 Hz).

This earthquake has produced partial damage to houses made of adobe and cracks in concrete houses for cities located around the epicenter. These values provide important information to consider in building regulations in Peru. This is the first intermediate-depth event for which records are available for ground acceleration; hence, they should be

### Table 1

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Epicentral Distance (km)</th>
<th>Maximum Acceleration (%g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarapoto</td>
<td>−06.496°</td>
<td>213</td>
<td>Z 13.30</td>
</tr>
<tr>
<td></td>
<td>−76.357°</td>
<td></td>
<td>N 15.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E 16.62</td>
</tr>
<tr>
<td>Milpo</td>
<td>−09.990°</td>
<td>366</td>
<td>Z 00.19</td>
</tr>
<tr>
<td></td>
<td>−77.610°</td>
<td></td>
<td>N 00.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E 00.031</td>
</tr>
<tr>
<td>Ancon</td>
<td>−11.510°</td>
<td>511</td>
<td>Z 00.55</td>
</tr>
<tr>
<td></td>
<td>−77.150°</td>
<td></td>
<td>N 00.91</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E 00.91</td>
</tr>
<tr>
<td>Lima</td>
<td>−12.055°</td>
<td>554</td>
<td>Z 00.51</td>
</tr>
<tr>
<td></td>
<td>−76.944°</td>
<td></td>
<td>N 01.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E 01.70</td>
</tr>
<tr>
<td>Huancayo</td>
<td>−12.044°</td>
<td>502</td>
<td>Z 00.10</td>
</tr>
<tr>
<td></td>
<td>−75.320°</td>
<td></td>
<td>N 00.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E 00.26</td>
</tr>
</tbody>
</table>

The maximum acceleration values are from the corrected strong-motion records.
considered when evaluating the risk due to intermediate-depth earthquakes.

CONCLUSION

The Contamana intermediate-depth earthquake was located in the eastern border of central Peru at a depth of 148 km. The earthquake occurred in the interior of the subducted Nazca plate beneath the Andean Cordillera and had a focal mechanism corresponding to processes of extension, consistent with the type of deformation present at these depths. The occurrence of this earthquake demonstrates the rebending of the Nazca plate after being held horizontally below the Andean Cordillera, a process that was associated with a possible fracture of the plate due to forces inherent in gravity (Schneider et al., 1988; Bernal and Tavera, 2001; Tavera and Buforn, 2001; see Fig. 8).

In Peru, these earthquakes are frequent in the sub-Andean zone of the northern and central regions and have produced major landslides and liquefaction processes that produced damage to roads, preventing communication for several days. In general, these intermediate-focus earthquakes do not show complex rupture processes because they do not require much time to accumulate and release enough seismic energy to cause further damage to surface. According to the seismic history of Peru, these earthquakes have magnitudes less than $M_w$ 7.5 and intensities less than VI (MM).

The Contamana earthquake presented a large radius of perception, probably due to the depth at which the event occurred (148 km); these are due to high intensities reaching and strongly shaking the mountain region of Central Peru. Similar seismic events occurred in Peru on 25 January 2010 in Pucallpa ($M_w$ 6.2, 115 km in depth), 18 May 2010 in Bagua ($M_w$ 6.2, 121 km in depth), and 23 May 2010 in Ayacucho ($M_w$ 6.0, 110 km in depth).

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