INTRODUCTION

The seismic activity in Peru has its origin in the convergence process between the Nazca and South American plates. Such convergence takes place at an average speed on the order of 7–8 cm/year (DeMets et al. 1980; Norabuena et al. 1999). This process is responsible for the offshore earthquakes with depths smaller than 60 km that take place off the coast of Peru (Dobath et al. 1990; Tavera and Buforn 2001), which are all associated with seismogenic contact. Moderate to large earthquakes occur on average at a rate of more than 60 per year and usually affect the towns near their epicenters. Earthquakes of larger magnitude ($M_w > 7.0$) have produced significant damage over broad areas, such as the event that occurred in southern Peru on 23 June 2001 ($M_w = 8.2$), which affected an area of $370 \times 70 \text{ km}^2$ between the towns of Atico (Arequipa) and Ilo (Moquegua) (Tavera et al. 2006).

The earthquake that is the subject of this article occurred on 15 August 2007 with a magnitude of $M_w 7.9$ and was named "the Pisco earthquake" because its epicenter was located 60 km west of Pisco city. The earthquake produced significant damage in Pisco city (approximately 80% of all structures) and minor damage in nearby towns, and it was assigned an approximate intensity of VII–VIII on the Modified Mercalli Intensity (MMI) scale in Pisco city. The epicenter of the Pisco earthquake and its aftershocks were located between the rupture areas of the 1974 Lima earthquake ($M_w 7.5$) and the 1996 Nazca earthquake ($M_w 7.7$). The earthquake also produced a tsunami, which originated south of the epicenter in the Paracas Peninsula.

Focal mechanisms for these earthquakes generally correspond to reverse motion with nodal planes oriented in a NNW-SSE direction and near horizontal plane dipping to the east, which corresponds to the subducting plate (Tavera and Buforn 2001).

ISOSEISMAL MAP

The intensity map for the Pisco earthquake (figure 1) has been compiled using information from more than 70 cities and towns throughout Peru. The isoseismal lines show an elliptical distribution typical of subduction earthquakes. A maximum intensity of VII–VIII (MMI) was reached in the cities of Pisco, Chincha, and Cañete (Ica). The earthquake was felt along the coastline of Peru from Piura (north) to Arequipa (south) and toward the continental interior as far as Ucayali (close to the border with Brazil). As an example, the isoseismal IV has a major axis of 600-km length in the NW direction and a minor axis of 450-km length in the SE direction. In nearby towns the majority of the damage occurred on old adobe and "quincha" buildings. In overall, 595 people were killed and 318 are missing, with more than 12 villages severely damaged in Ica, Lima, and Huancavelica (see figure 1). About 320,000 people were affected by the earthquake. More than 230,000 structures were damaged and 52,150 totally destroyed by liquefaction, mainly in Pisco city and towns within a radius of 150 km, especially those towns closer to the coast. On the Panamericana Sur road (the main road in coastal southern Peru), several cracks and landslides occurred between Pisco and Lima with directions parallel to the coast.

The earthquake was followed by a local tsunami. The highest sea elevation was 5–10 meters in Laguna Grande (30 km south of Paracas). The tsunami killed three people and a total of 12 persons are missing.

FOCAL MECHANISMS

Focal mechanisms of the mainshock and its eight largest aftershocks (table 1, A1–A8) have been estimated from polarities of $P$ waves (Brüllinger et al. 1980; Udias and Buforn 1988). Data were obtained from stations at local, regional, and teleseismic distances, with a maximum of 74 observations for the mainshock and a minimum of 23 for the aftershocks (table 1 and figure 2). The solution obtained for the mainshock corresponds to a thrusting fault with nodal planes oriented in a NNW-SSE direction and a pressure axis near the horizontal oriented in an ENE-WSW direction. One plane is nearly vertical ($78^\circ$) and the second plane is nearly horizontal dipping slightly to the ENE. Similar solutions have been obtained for the aftershocks A6, A2, A4, and A7. However, the aftershock A1 presents nodal planes oriented in the E-W direction and pressure axis in the N-S direction and dipping near 45°. The other aftershocks present nodal planes oriented in the NNE-SSW direction (A3, A5) with A8 oriented NEE-SWW. These solutions for the focal mechanisms suggest the development of a complex process of rupture during the earthquake.

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**DISTRIBUTION OF AFTERSHOCKS**

The recalculated hypocentral parameters for the mainshock and its eight largest aftershocks are shown in table 1. Figure 3 shows the spatial distribution of these aftershocks (squares) in three groups. The first group has four aftershocks around the mainshock (star) with depths of around 19 km and magnitudes between 5.0 to 5.9 ML (A1, A5, A7, and A8). The second group consists of three aftershocks with magnitudes between 5.6 and 6.3 ML (A2, A3, A4) and depths of 6 to 17 km localized 150 km SE of the mainshock (offshore Independence Bay—Ica). The eighth aftershock occurred near the coast, just south of Pisco, with a magnitude of 6.0 ML at a depth of 38 km. In the intervals between these groups there were no aftershocks of larger magnitudes. The aftershock distribution suggests at least two areas of energy liberation trending NW-SE and separated by about 150 km. Considering the temporal distribution of the aftershock sequence, the migration was to the SE. In general, the rupture propagation direction is parallel to the Nazca trench and the coastline.
TABLE 1  
Source parameters of the Pisco earthquake and its greatest aftershocks between 15 August and 19 August 2007, obtained from hypocenter determination and focal mechanism solutions.

<table>
<thead>
<tr>
<th>Code</th>
<th>Date</th>
<th>UT (GMT)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (km)</th>
<th>ML/Mw</th>
<th>T-axes (Trend°/Plunge°)</th>
<th>P-axes (Trend°/Plunge°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>08/15/07</td>
<td>23:40</td>
<td>-13.491°</td>
<td>-76.852°</td>
<td>18.4</td>
<td>7.0/7.9</td>
<td>80/67</td>
<td>245/33</td>
</tr>
<tr>
<td>A1</td>
<td>08/16/07</td>
<td>01:02</td>
<td>-13.395°</td>
<td>-76.802°</td>
<td>16.3</td>
<td>5.9</td>
<td>239/8</td>
<td>347/87</td>
</tr>
<tr>
<td>A2</td>
<td>08/18/07</td>
<td>05:16</td>
<td>-14.370°</td>
<td>-76.357°</td>
<td>11.6</td>
<td>5.8/6.3</td>
<td>162/16</td>
<td>51/87</td>
</tr>
<tr>
<td>A3</td>
<td>08/16/07</td>
<td>11:35</td>
<td>-14.498°</td>
<td>-76.468°</td>
<td>6.5</td>
<td>6.0</td>
<td>172/27</td>
<td>295/74</td>
</tr>
<tr>
<td>A4</td>
<td>08/17/07</td>
<td>06:18</td>
<td>-14.249°</td>
<td>-76.385°</td>
<td>17.0</td>
<td>5.6/5.5</td>
<td>156/20</td>
<td>65/89</td>
</tr>
<tr>
<td>A5</td>
<td>08/17/07</td>
<td>13:18</td>
<td>-13.608°</td>
<td>-76.882°</td>
<td>18.6</td>
<td>5.9</td>
<td>188/25</td>
<td>298/81</td>
</tr>
<tr>
<td>A6</td>
<td>08/18/07</td>
<td>02:52</td>
<td>-13.815°</td>
<td>-76.309°</td>
<td>38.2</td>
<td>6.0/5.9</td>
<td>66/27</td>
<td>246/27</td>
</tr>
<tr>
<td>A7</td>
<td>08/19/07</td>
<td>01:22</td>
<td>-13.717°</td>
<td>-76.893°</td>
<td>19.7</td>
<td>5.0</td>
<td>194/19</td>
<td>67/79</td>
</tr>
<tr>
<td>A8</td>
<td>08/19/07</td>
<td>20:11</td>
<td>-13.777°</td>
<td>-76.897°</td>
<td>19.6</td>
<td>5.6</td>
<td>85/30</td>
<td>321/72</td>
</tr>
</tbody>
</table>

**Figure 2.** Focal mechanisms of mainshock and eight of the largest aftershocks of the Pisco earthquake sequence. Lower hemisphere of focal sphere is shown. Black circles correspond to compression and white circles to dilatation. P = pressure axis, T = tension axis.

The distribution of 250 aftershocks (2.0 > ML > 4.0) that occurred within the week after the mainshock are plotted in figure 4 as circles. These aftershocks, located using stations in the National Seismic Network of Peru, are approximately distributed in a rectangular area of 170 x 130 km² oriented in a SE direction. The mainshock occurred in the northwest corner, and the spatial distribution of the aftershock sequence suggests the same migration toward the SE along the trench during the rupture process. The majority of aftershocks is distributed following the coastline and forming up to three groups: the first around the main event (G1), the second in front of Paracas Peninsula and to the south of Independence Bay (G2), and the third underneath the Paracas Peninsula (G3). These aftershock clusters are bordered by small areas that would have experienced aseismic ruptures. The figure 4 cross-section shows that the aftershock distribution occurs along interplate contact reaching the 100-km depth contour, and it is consistent with the average trend of the seismicity described in this region by Cahill and Isacks (1992), Lindo (1993), and Tavera and Buform (2001).

**MODELING P WAVES**

The waveform and amplitude of P waves were used to estimate the source orientation, the focal depth, the seismic moment, and the source time function (STF) of the seismic source when using the inversion method proposed by Nabelek (1984). The
\(P\) waves recorded on broadband stations localized at distances between 30° and 90° were compared with synthetic records generated by a combination of direct phases (\(P\) wave) and reflected phases (\(pP\) and \(sP\)). The amplitudes are adjusted considering the geometric spreading factor and attenuation (Futerman 1962). The fit between the observed and synthetic traces is minimized with the half mean square method. For elaborating the model, the parameters have been standardized to 5,000 amplitude and a 40° epicenter distance.

The parameters that define the source orientation from focal mechanism of the mainshock were initially fixed by using the \(P\)-wave polarity and the hypocenter parameters recalculated in this study. Figure 5 shows the solution using 10 \(P\)-wave records. After various iterations, the best fit between synthetic and observed is archived with a root mean square = 24. The solution corresponds to a focal mechanism with nodal planes trending in a NS direction, dipping 15° to the east. The focal depth is fitted to 15 km. The STF is complex and show two pulses of 30 seconds, separated by 60 seconds of quiescence. The second pulse shows major amplitude. The total duration of the rupture process is about 110 seconds with a seismic moment of \(2.3 \times 10^{31}\) Nm, equivalent to \(Mw = 8.1\).

**DISCUSSION**

The Pisco earthquake is the largest shallow (\(h < 60\) km) earthquake that has occurred in the last 250 years in the central region of Peru due to the subduction of the Nazca plate under the South American plate. The distribution of aftershocks forras a rectangular area approximately 170 × 130 km², parallel to the coast, which could be considered as the dimensions of the rupture area. This rupture area is located near the northern part of the aftershock region for the 1996 event (see figure 4; Tavera et al. 1998) and the southern part of the aftershock region of the 1974 event (Langer and Spence 1995), completely filling the seismic gap identified for the central region of Peru by Tavera and Bernal (2005), see figure 4. The geometry of the rupture area is in agreement with the isoseismal map that shows a distribution of energy in an elliptical area with the major axis parallel to the coast.
The complex rupture process of the Pisco earthquake can be analyzed on broadband seismic station records (Figure 5). Two wave sets can be observed (E1 and E2), separated by 60 seconds, that correspond to the two ruptures. In agreement with the signal amplitude of both wave sets (major in direction of EFI, TSUM, TRIS, etc.), the rupture front would have propagated to the SE.

Focal mechanisms obtained for the mainshock (P-wave polarity and modeling) and the aftershock A6 present thrusting solutions with a horizontal plane dipping to the ENE and horizontal pressure axes striking in ENE-WSW direction, which is in agreement with focal mechanisms for the largest earthquakes that have occurred in Peru between the trench and the coastline (Figure 1). The other largest aftershocks’ pressure axes strike in the NNW-SSE direction (A3, A5, A8) and in the NS direction (A1). All solutions suggest the development of a complex rupture process during the Pisco earthquake.

The stress regime obtained from the focal mechanisms of the Pisco earthquake sequence (Table 1) may be associated with the convergence motion between the Nazca and South American plates. In this region, the plate contact surface is larger than in the south (Cahill and Isacks 1992; Tavera and Buforn 2001); this implies bigger ruptures even if the subduction earthquake magnitude is similar in both regions.

According to Figure 4, the Pisco earthquake rupture process begins south of the 1974 Lima earthquake rupture area (gray area) and propagated in a SE direction 170 km (from Pisco to Independence Bay, below the Paracas Peninsula) in the SE direction. The A1 aftershock shows nodal planes trending EW and dipping 45° that could be associated to some crustal fault location that separates the 1974 and 2007 rupture zones (Figure 4). The largest aftershock happened five hours after the mainshock and had its epicenter offshore Independence Bay with a similar focal mechanism as the mainshock but with the fault plane dipping near 50°, greater than the mainshock. This suggests the fault plane or contact surface geometry between plates is different and could be associated with tortion of the plates in this region. The A6 aftershock had a focal mechanism similar to the mainshock and its hypocenter (Paracas Peninsula) suggests that the displacement of the plate shows on a low-angle plane at 38-km depth. The other mechanisms present a diversity of orientation and dips for the fault planes, which confirms the complex earthquake rupture process. This suggests that the rupture velocity was smaller than observed for other Peru subduction earthquakes with similar or greater magnitude; for example, the earthquake of 23 June 2001 in southern Peru with a $M_w = 8.2$ magnitude and a complex unilateral rupture process during 90 seconds (Kikuchi and Yamanaka 2001; Bilek and Ruff 2002; Dewey et al. 2003; Tavera et al. 2006). Figure 4 also shows two aseismic areas (gaps) that didn’t experience any rupture: the first one is located in between the area covered by the after-shock distribution of 1996 (Nazca) and 2001 (Arequipa), and the second one is located south of the 2001 earthquake rupture zone.
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