SOURCE PARAMETERS OF THE AREQUIPA EARTHQUAKE OF JUNE 23, 2001

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INTRODUCTION

The western border of South America is one of the most important sismogenic regions in the world. In this region did occur the most damaging earthquakes known and reported in the news. One of these earthquakes occurred in June 23rd, 2001 (Mw=8.1-8.2) and produced death and damages in the whole southern region of Peru. This earthquake was originated by a friction process between Nazca and Sudamericana Plates and affected an area of about 300km x120km defined by the distribution of more than 220 aftershocks recorded by a local seismic network that operated 20 days. The epicenter of the main shock was localized in the northwestern extremity of the aftershock area and this suggests that the rupture propagated towards the SE direction. The P-wave modelization for teleseismic distances permited to define a focal mechanism of reverse type with nodal planes oriented NW-SE and a possible fault plane dipping gently toward the NE. The STF suggest a complex process of rupture during 85 seconds with 2 succesive sources, the second one of greater size, and located approximately 100-120 km toward the SE direction. It was estimated a rupture velocity of about 2 km/seg on a 28°-dipping plane to the SE (1xx°). A second event happened 45 seconds after the first one with an epicenter 130km farther to the SE and a complex STF. This event and the second source of the main shock gave origin to a tsunami with waves from 7 to 8 meters that propagated almost orthogonally to the coast line affecting mainly the Camana area.

From all the aftershocks, three presented magnitudes greater or equal to Mw=6.6, two of them occurred in front of Ilo and Mollendo (June 26th and July 7th) with focal mechanisms similar to the main seismic event. Aftershock of July 5th corresponded to a normal mechanism at a focal depth of 75km, with a probable origin inside the Nazca plate under the friction zone. The aftershocks of June 26th (Mw=6.6) and July 5th (Mw=6.6) show plain STF with short duration. The aftershock of July 7th (Mw=7.5) with duration of 27 seconds suggests a complex process of energy release with the possible occurrence of a secondary shock with lower focal depth and focal mechanism of inverse type with a great lateral component. Plain focal mechanisms and composite ones were calculated for the aftershocks, and all of them show characteristics similar to the main one.

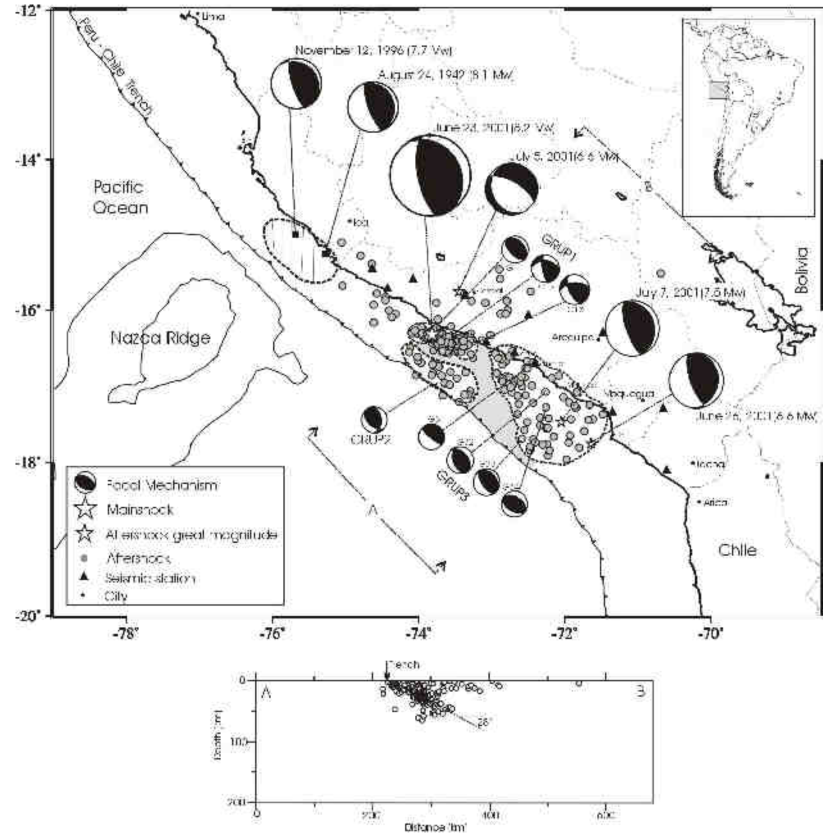
The June 23rd earthquake induced major damages in the whole southern Peru. The damage estimation in towns of Arequipa, Moquegua allow to consider maximum intensities from 6 to 7 (MSK79). In Alto de la Alianza and Ciudad Nueva zones from Tacna, the maximum intensity was of 7^- (MSK79).

Discussion and Conclusion

The southern Peru region was affected after 133 years by an Mw=8.2 earthquake that occurred in June 23rd, 2001. Preliminary studies allowed to consider this earthquake as a recurrence of the one of August 1868, that was assigned Mw=9.0, a rupture length of about 500km and intensities of about X-XI (MM) (Dorbath et al, 1990; Comte and Pardo, 1991). Later, Tavera et al. (2001), Kikuchi and Yamanaka (2001), Tavera et al. (2002), Giovanni et al. (2002), Bilek and Ruff (2002), and Dewey et al. (2003) demonstrated that June 2001 earthquake presented a lower magnitude (Mw=8.2), rupture length of 300km and maximum intensity of VII-VIII (MM), therefore it is not a recurrent earthquake.

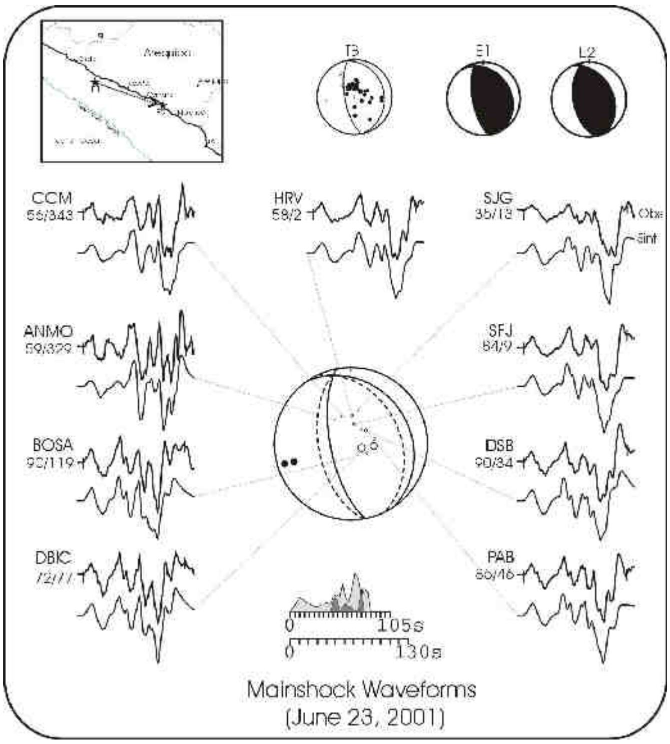
The focal depth was estimated to 23km and from the waveform inversion to 29 km (Table 3), approaching those values of USGS (33 km); Kikuchi and Yamanaka (2001), 32 km and Giovanni et al (2002), 20 km. The earthquake magnitude was estimated by the IGP to ML (d)=6.9 and from waveform inversion to Mw=8.1 similar to those reported by other international agencies (mb=6.7, GS; Ms=8.2, GS; Mw=8.4, HRV; Mw=8.2, Kikuchi and Yamanaka (2001); Mw=8.2, Giovanni et al (2002); Mw=8.4, Bilek and Ruff (2002)).

The relocation of 220 aftershocks with magnitudes ML between 2.4 and 4.8 allowed to define a rupture area of about 300km x 120 km with the epicenter of the main shock located in the NW extremity of this area, that suggest an unilateral propagation of the rupture toward the SE, as suggested by Giovanni et al, (2002) and Bilek and Ruff (2002). According to the aftershock distribution, the rupture stopped abruptly in front of Ilo town, producing two aftershocks with magnitude Mw=6.6 y 7.5, and thus delimiting the initiation of a new area of energy accumulation. The aftershocks form three clusters, the first one concentric fully around the main shock, the second one near the trench and the third, spread in the SE end. In between those clusters can be observed the presence of another area that would not have experienced rupture and on the contrary the displacement would have taken place in aseismic way.



Spatial distribution of June 23rd 2001 earthquake and aftershock series. The focal mechanisms were obtained from the P-wave model and polarity. The crosshatched area corresponds to aftershocks of the 1996 November aftershock (Tavera et al, 1998) and the shaded one to the asperity of the aftershock area of the 23rd of June earthquake. The discontinuous line indicates the various aftershock swarms. In the lower part is presented a vertical cross section with the aftershocks, indicated as A-B. Triangles are indicating the seismic station disposed during this study.

The focal mechanisms obtained for the main shock and major aftershocks correspond to reverse type with NW-SE nodal planes, being the possible fault plane the one dipping gently to the NE. The focal mechanisms corresponding to lower magnitude already events, whither composed or simple are similar to the main shock one, even if cluster GRUP1 presents some lateral component. The 5th of July aftershock, with epicenter inside the continent located NE to the main shock, presents a normal focal mechanism with NW-SW planes and a possible fault plane nearly vertical. This earthquake focal depth has been estimated to 75km, therefore it should be associated to the Nazca plate internal deformation, below the friction level, and suggests a depth zone in which compression stresses change to extension. In northern Chile, this zone this located to 60 km of depth approximately (Comte and Suarez, 1995).



Synthetic (sint) and observed (obs) waveform corresponding to the main shock obtained with inversion after the Nabelek method (Nabelek, 1984). The record amplitude has been normalized to a gain of 5000 and a distance of 40°. The inversion window is indicated with vertical lines on the record. The station identification is found at the extreme left side of the record and below the epicentral distance and azimuth in degrees. The focal sphere corresponds to its projection in the lower hemisphere, after P and T axis represented by black and white circles. The SFT is presented below the focal mechanism, just as the record scale. In the upper part is presented the focal mechanisms corresponding to both seismic events (E1, E2) and the solution after Tavera et al (2002) thanks to the P-wave polarity (TB). The upper left side figure shows the epicenter localization of 2 seismic events associated to the rupture process of the 23rd of June 2001 earthquake.

The STF characteristics suggest that the main shock presented a very complex process of rupture during 85 seconds. During this time period occurred two main ruptures, the first one at the onset of the earthquake that lasted 25 seconds before to slowly propagate until to produce a major rupture of 45 seconds approximately 100 km in the SE. As suggested by Giovanni et al (2002) and Bilek and Ruff (2002), in between both sources is encountered an asperity, but in this case of lower size. A second event, complex too, occurred 40 seconds after the first one, with its epicenter localized 120-130km toward the SE respecting to the beginning of the rupture. This second event and the second source of the main event produced the greatest energy release in front of Camana town, just as suggested by Kikuchi and Yamanaka (2001), Giovanni et al (2002) y Bilek and Ruff (2002). This whole rupture process developed on a surface dipping about 28° with a velocity of 2 km/seg. The rupture velocity explains the lasting time of the shock and perhaps the damage extent and induced effects in surface that were not so big compared to the earthquake size. The June 26 and July 5th aftershocks, presents one SFT very simple and of short duration. For July 7th aftershock, the SFT lasted 27 seconds and suggested an occurrence due to a complex rupture process. A second event, with epicenter located to the west of first one, produced 7 seconds after with duration of 23 seconds. The first event presented an 18km-depth and the second one a 12km-depth consistent with its epicenter localization and that could suggest the propagation of the rupture to the west. The second event focal mechanism is of reverse type with a big lateral component that suggests the occurrence of a more complex rupture processes that could implicate the two internal plates. In Table 3 is presented a summary of the source parameters obtained in this study for the main shocks and its great aftershocks.

The results obtained in this study demonstrate that the June 2001 earthquake has produced one of the most complicated rupture processes known for Peruvian earthquakes. The local tsunami characteristics are complex too and gave birth to the waves that affected to Camana town. Data collected from 15 people, confirmed the formation of marine currents that circulated parallel to the coastline, from Chala to Atico toward the SE, and from Mollendo and Matarani toward the NW, apparently with major velocity and that could have run into each other near from Camana and facilitate the formation of waves that propagated oblique to the coastline. This could explain the 32km-inland flooding de 32 km of beaches south of Camana. Obviously the tsunami characteristics could be explained by the complex pattern of the main shock rupture.

Considering the rupture propagation to the SE, to the margin of the engineering parameters, major damages and effects should be produced in towns and villages of the southern Peru. In terms of acceleration, the accelerometer located in Huancavelica city (420 km to the NE of the epicenter of the earthquake) has registered an acceleration of 11.6 cm/seg^2; whereas, the accelerometers of the Arica-Chile city (455 km to of epicenter of the earthquake) registered a acceleration of 284 cm/seg^2, which suggests it energy propagated in direction SE, coherent with the damage assessed in the southern region. The intensity estimations show that in this area the maximum intensity was about 6^+ to 7^- MSK79, excepted in the districts of Alto de la Alianza and Ciudad Nueva where the major percentage of damages occurred for the houses because of the low quality level of the build work. Similar damages occurred in Moquegua, but in this case the houses were mainly old ones built with mud and without any building techniques. Lower damages were reported in Arequipa and near town areas. The presence of geologically inadequate grounds to build houses and public edifices played a major role in the increase of damages induced by the earthquake (sewers, water pipes, public phones and electrical maintenance).

The June 23rd earthquake is one of the most important shocks that occurred in this region, as well as one of the most complex one in terms of rupture process. This magnitude Mw=8.1 shock showing a rupture length of 300 km, cannot be seen as a repetition of the August 1868 earthquake. This earthquake presented magnitude of Mw=9.0 and one length of rupture of 500 km; that is to say, 200 km but that the earthquake of the 2001. This new energy accumulation zone should give birth to a new high magnitude earthquake in the future.

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