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Identification of High Frequency Pulses from Earthquake Asperities Along Chilean Subduction Zone Using Strong Motion

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Abstract—The Chilean subduction zone is one of the most active of the world with $M = 8$ or larger interplate thrust earthquakes occurring every 10 years or so on the average. The identification and characterization of pulses propagated from dominant asperities that control the rupture of these earthquakes is an important problem for seismology and especially for seismic hazard assessment since it can reduce the earthquake destructiveness potential. A number of studies of large Chilean earthquakes have revealed that the source time functions of these events are composed of a number of distinct energy arrivals. In this paper, we identify and characterize the high frequency pulses of dominant asperities using near source strong motion records. Two very well recorded interplate earthquakes, the 1985 Central Chile (Ms = 7.8) and the 2007 Tocopilla (Mw = 7.7), are considered. In particular, the 2007 Tocopilla earthquake was recorded by a network with absolute time and continuos recording. From the study of these strong motion data it is possible to identify the arrival of large pulses coming from different dominant asperities. The recognition of the key role of dominant asperities in seismic hazard assessment can reduce overestimations due to scattering of attenuation formulas that consider epicentral distance or shortest distance to the fault rather than the asperity distance. The location and number of dominant asperities, their shape, the amplitude and arrival time of pulses can be one of the principal factors influencing Chilean seismic hazard assessment and seismic design. The high frequency pulses identified in this paper have permitted us to extend the range of frequency in which the 1985 Central Chile and 2007 Tocopilla earthquakes were studied. This should allow in the future the introduction of this seismological result in the seismic design of earthquake engineering.

1. Introduction

Large interplate thrust earthquakes frequently occur along the Chilean coast. A large number of earthquakes of magnitude greater than $M = 8.0$ have been observed since the sixteenth century (Montessus de Ballore, 1911–1916; Lomnitz, 1970, 2004; Comte *et al.*, 1986; Beck *et al.*, 1998; Madariaga, 1998; Comte and Pardo, 1991; Barrientos, 2007). These earthquakes have large rupture areas, over 100 km in length (Kausel and Ramírez, 1992). Seismologists usually consider that the rupture of these large events are controlled by the presence of asperities or barriers (Kanamori and Stewart, 1976; Das and Aki, 1977). These terms have been widely used in a variety of contexts that usually refer to geometric complexities of the fault zone. In this paper we will define "dominant asperities" as the zones where the principal seismic waves (pulses) are generated. The pulses studied are similar to those observed in shallow continental earthquakes where these pulses can be identified from the kinematic inversion of earthquakes (Heaton, 1990) or directly from strong motion data (Hall *et al.*, 1995; Makris, 1997; and others).

The few well studied Chilean earthquakes present complex slip distributions that are not distributed homogeneously on the seismogenic plate interface, as show the results of kinematic inversion for the 1985 Central Chile (Ms = 7.8) earthquake (Mendoza *et al.*, 1994) and the 2007 Tocopilla (Mw = 7.7) earthquake (Delouis *et al*., 2009; Peyrat *et al*., 2009). Also, seismic source studies of historical Chilean earthquakes show more than one important energy release or asperity (Malgrange *et al.*, 1981; Beck *et al.*, 1998). This complexity manifests itself in the form of complex radiated pulses. In this paper the pulses of large interplate Chilean earthquakes are correlated with the concept of "dominant asperities". The characteristics and location of these pulses are important for seismic engineering design, especially

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for large earthquakes where the seismic demand can be different in two different zones with the same rupture area. This is a key characteristic for seismic design, where the non-linear behavior of structures is considered. Therefore, seismic energy distribution associated to the arrivals of high frequency pulses turns out to be an important issue in order to estimate seismic hazard.

Two large and very well recorded Chilean earthquakes are studied: the Central Chile of March 1985 and the Tocopilla of November 2007 events. The first has been very well studied in the low frequency (of 5 to 350 s periods), but comprehensive studies have not been done at higher frequencies. For the 2007 Tocopilla traditional studies have already been done. In this paper we characterize the pulses generated by dominant asperities using strong motion data.

2. *The 1985 Valparaiso (Central Chile) Earthquake*

2.1. *1985 Central Chile Earthquake Rupture*

The Central Chile region has been shaken by several earthquakes that have repeatedly ruptured the same zone since the sixteenth century. All these earthquakes have their epicenter off shore in front of Valparaiso city (Comte *et al.*, 1986), the 1971 and 1985 earthquake pair being the last example, Fig. 1. The Ms = 7.5 earthquake of 8 July 1971 occurred to the North of Valparaiso and stopped at a barrier or asperity situated almost in front of the city (Malgrange *et al.*, 1981). The 1985 Valparaiso earthquake started with a $m_b = 5.2$ event located 7 km northwest and 10 s before the main shock (Comte *et al.*, 1986). Moreover NEIS reported that another event of magnitude $m_b = 6.7$ occurred 13 s before the Ms = 7.8 earthquake. All these shocks occurred in a small cluster in front of the Chilean coast (Comte *et al.*, 1986). The complex rupture of this earthquake has been studied by different authors (Houston and Kanamori, 1986). Some of these works will be discussed in the present paper; for more details we refer to the Barrientos and Kausel (1990) paper that presented a comprehensive review.

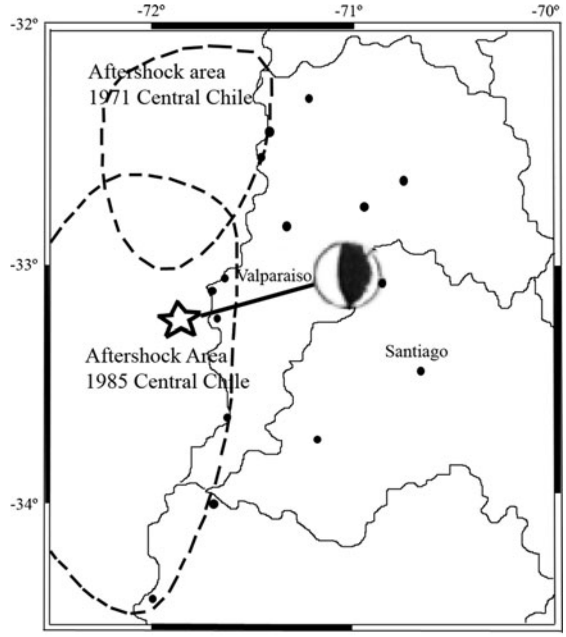

Figure 1
The *star* indicates the epicenter and the "beach ball" the mechanism of the 1985 Central Chile earthquake. We show with *dashed lines* the aftershock areas for this earthquake and the 1971 Central Chile event. The *points* indicate the location of accelerographic stations that recorded the 1985 Central Chile earthquake (modified from Comte *et al.*, 1986; Malgrange *et al.*, 1981)

Christensen and Ruff (1986) studied the P and PP phases radiated by the Valparaiso earthquake and concluded that this event was actually composed of two events; the first one occurred 16 s before the principal event at a depth of 10–40 km. The aftershocks extended 75 km to the North and 125 km to the South of the epicenter. Monfret and Romanowicz (1986) studied the Rayleigh waves and they proposed that the rupture propagated 100–150 km to the south or southeast. Zhang and Kanamori (1988) analyzed the long period surface wave spectra (150–300 s) and estimated that the rupture propagated 160 km to the south with strike N10°E. Korrat and Madariaga (1986) proposed that the rupture started at a barrier in the northern part. They showed that the rupture started with a foreshock 10 s before the main shock. Using the area of foreshocks and aftershocks Pardo *et al.* (1986) estimated an area of rupture of 200 km by 90 km, located in a plane of dip 10°E. Barrientos (1988, 1997) studied the static deformation identifying two important zones of permanent displacement separated by more than 50 km (Fig. 2). CHOY and DEWEY (1988) studied in detail the P + pP + sP wave forms and concluded that the principal earthquake was composed of three events, the first occurring 27 s before the main shock, and the second, occurring 17 s before the main shock. HOUSTON (1987) and HOUSTON and KANAMORI (1987) studied the P spectra and concluded that the Chile earthquake showed a higher frequency than other shocks of similar magnitude. Finally MENDOZA *et al.* (1994) studied near-source strong motion records, teleseismic body waves and long period Rayleigh waves and proposed from kinematic seismic inversion that there were two principal zones of energy release as shown in Fig. 3.

In summary, all these different studies show that the Valparaiso earthquake had a complex initiation, with one or more small foreshocks and the presence of at least two large zones of seismic radiation or asperities, one of them near the hypocenter and the other about 50 km to the south.

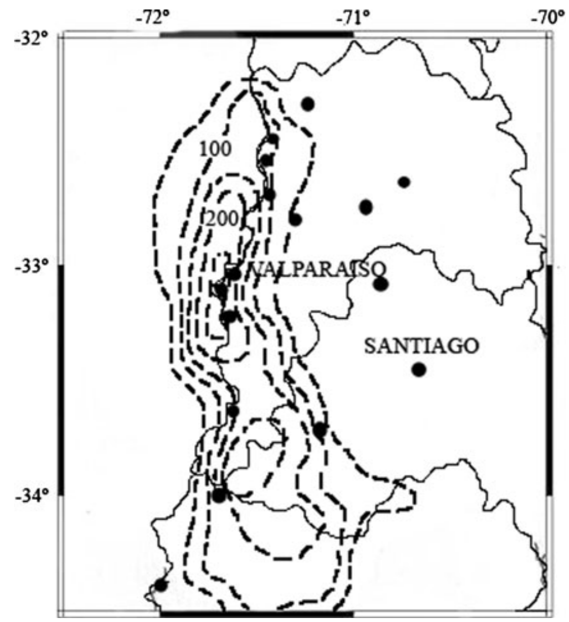

Figure 2
1985 Central Chile earthquake. Surface projection of observed permanent displacements. The *points* correspond to the location of the accelerographic stations (modified from BARRIENTOS, 1988). The *segmented lines* correspond to the surface projection of slip due to the earthquake in centimeters

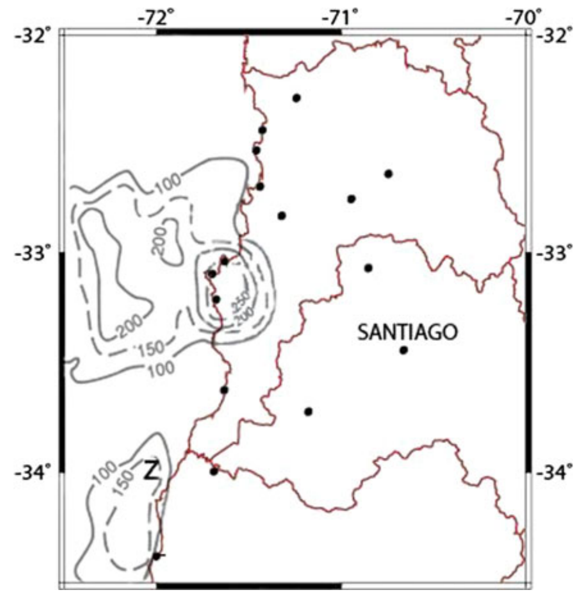

Figure 3
1985 Central Chile earthquake: inferred dislocation model. The *points* correspond to the location of accelerographic stations (modified from MENDOZA *et al.*, 1994)

2.2. *Strong Motion Database of the 1985 Central Chile Earthquake*

For a long time, the 3 March 1985 Central Chile earthquake was the best recorded subduction earthquake worldwide (EERI, 1986). More than 20 free field accelerograms were recorded at close epicentral distances (Fig. 4) by SMA-1 analog accelerographs. The uncorrected records were processed by SARAGONI *et al.* (1986) and Celebi (1987). Because these analog records were hand digitized, it was only possible to obtain a good signal in the range 0.1–25 Hz.

In this paper we study the displacement records integrated from the digitized accelerograms. We corrected for the base line and filtered the traces using a Butterworth bandpass filter of fourth order between 0.1 and 25 Hz. In this frequency range the instrumental response is approximately flat and therefore the correction for instrumental response is not necessary (BOORE and BOOMER, 2005). Unfortunately these accelerograms have no common time nor trigger with buffer memory. For these reasons an acausal filter is used.

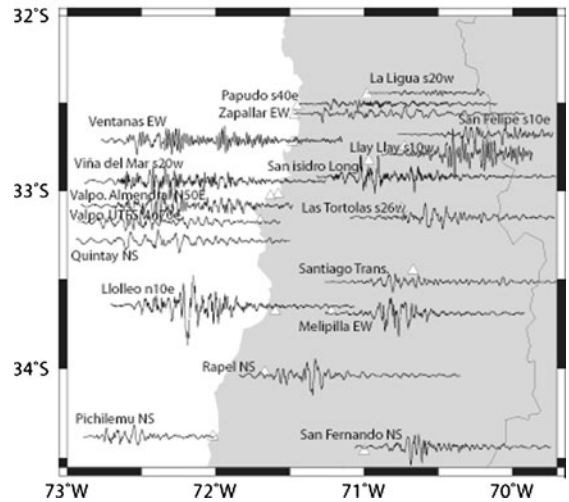

Figure 4
Displacement records of one of the horizontal components recorded at each accelerographic station available for the 3 March 1985 Central Chile earthquake located between 32°S and 34.5°S

3. *Identified High Frequency Displacement Pulses of the 1985 Central Chile Earthquake*

3.1. *High Frequency Filter*

The identification of high frequency pulses is the main objective of this paper. For this reason the records were filtered between 0.1 and 25 Hz allowing the characterization of pulses associated to the earthquake rupture that apparently were not studied in previous works, except by Mendoza *et al*. (1994) who filtered the strong motion data between 0.133 and 0.5 Hz in order to do a kinematic inversion of the earthquake. We think that it is possible to use a broader range filter than that used by Mendoza *et al*. (1994) in order to obtain higher frequency characteristics of the earthquake. For example, in Fig. 5 we show the San Isidro Longitudinal and Zapallar EW, records located northward of the main rupture, filtered using both a broad bandpass filter (0.1 to 25 Hz) and a narrow bandpass filter (0.133 to 0.5 Hz). For the San Isidro Long record the two filters show the same important zones of large amplitude, indicated with numbers 1, 2 and 3 in Fig. 5. However, in the Zapallar EW record a zone of large amplitude is not clear using the narrow bandpass filter, the second pulse (2 in the Fig. 5) is only shown using the broader bandpass filter.

3.2. *High Frequency Pulses of the 1985 Central Chile Earthquake*

In this section we show similar pulses observed at selected accelerograms of Fig. 4. Figure 6 shows the displacement records of the San Isidro Longitudinal and San Felipe S10°E components of the 3 March 1985 earthquake. The pulses in both records show similar shapes. Encircled are shown the three main pulses—S1, S2 and S3—that are evident in all the records. The traces have not been rotated and only horizontal components are shown. The three pulses shown in Fig. 6 can also be clearly seen in other records, depending on the distance to the dominant asperities and the polarity of the seismic source.

Figure 7 shows two displacement records obtained at the Papudo and Zapallar coastal stations. The records have not been rotated, because the other horizontal component of Papudo was unfortunately not recorded. The EW component for Zapallar was selected because the pulse S1 is best observed. Pulse S1 is clearly observed with a similar shape in both traces. Pulses S2 and S3 cannot be clearly distinguished.

Pulses S1 and S3 have durations shorter than 10 s, much less than the total duration of the earthquake (more than one minute) and also less than the rise time of 14 s proposed by Mendoza *et al*. (1994). Pulse S2 is composed of two subpulses, so that the corresponding zone of the fault may represent a zone of even more complex rupture process. The difference in time between the arrivals of each pulse indicates that they were not generated at the same place. Therefore, during the 1985 earthquake, at least three important zones of energy release shown as displacement pulses are observed. This result is in agreement with the observation made by other authors who proposed a heterogeneous distribution of earthquake slip (Barrientos, 1988, 1997; Mendoza *et al*., 1994).

The soils in which these records were obtained are not similar. Despite that, they show similar displacement shapes, as can be seen in the records of Rapel

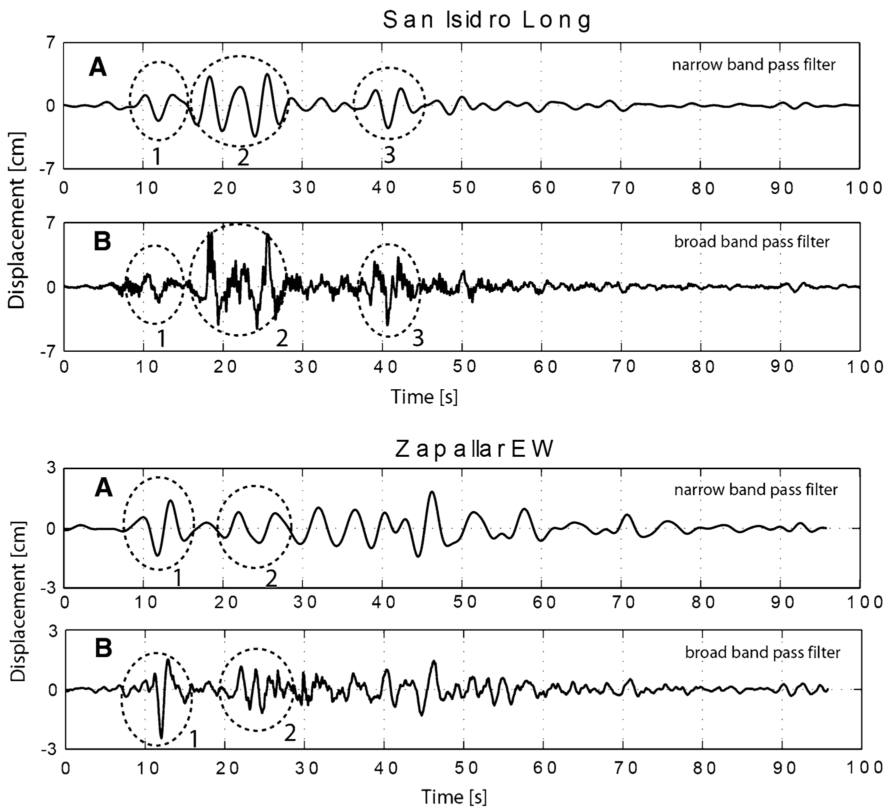

Figure 5
Identified pulses of the San Isidro Long and Zapallar EW displacement records of 1985 Central Chile earthquake, filtered using **a** a narrow bandpass filter and **b** a broad bandpass filter

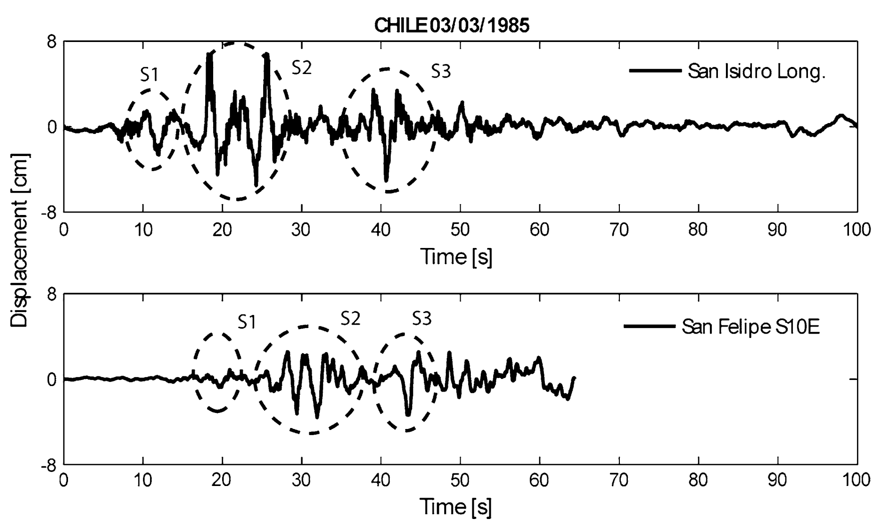

Figure 6
Displacement records for San Isidro Long and San Felipe S10°E 1985 Central Chile earthquake. Identified pulses *S1*, *S2*, and *S3* are *encircled.* Pulses in both records have similar shapes

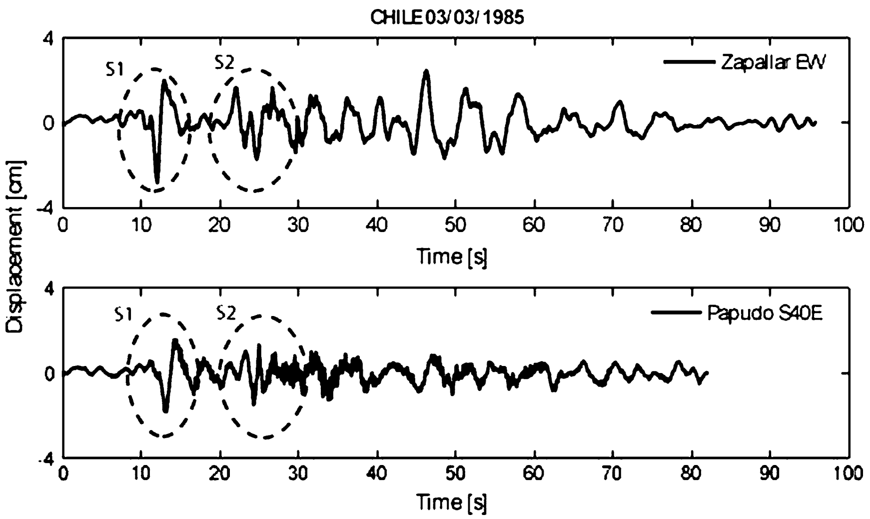

Figure 7
Displacement records of Zapallar EW and Papudo S40°E 1985 Central Chile earthquakes. Identified pulse *S1* is clearly observed with similar shapes in both traces. Pulses *S2* and *S3* cannot be clearly distinguished

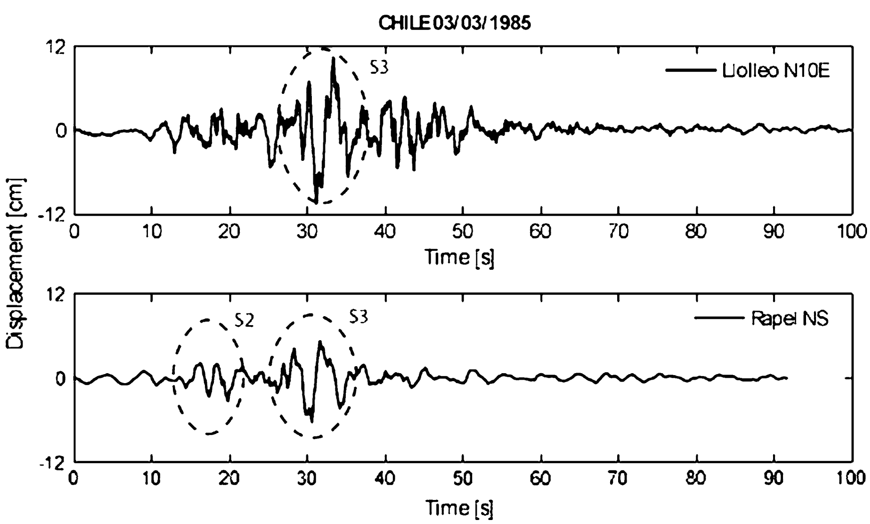

Figure 8
Displacement records for Llolleo N10E and Rapel NS, 1985 Central Chile earthquake. Similar identified pulse shapes can be observed in both records. In Rapel trace two pulses are seen, the first is not clearly observed in Llolleo. The traces have not been rotated because the pulses are well observed in the original components

and Llolleo (Fig. 8) recorded in different soils (Llolleo on sand and Rapel on rock), with shear wave velocities given in Table 1. This difference of soil types clearly indicates that the pulse shape is not due to the soil effect.

The first pulse (S1) can be observed on the displacement records of San Isidro, San Felipe, Zapallar and Papudo, with the strongest amplitudes on the coastal records in the EW direction. On the other hand, in records located south of the rupture the pulse of greater importance corresponds to the third pulse (S3), observed on the displacement traces of San Isidro and San Felipe. Figure 8 shows the displacement records of Llolleo N10°E and Rapel

Table 1

Stratigraphy of Chilean soils where some accelerograms were recorded in the 1985 Central Chile earthquake (Araneda and Saragoni 1994)

Station	Layer 1		Layer 2		Layer 3		Bedrock versus V_s (m/s)
	Thickness (m)	V_s (m/s)	Thickness (m)	V_s (m/s)	Thickness (m)	V_s (m/s)	
Papudo	4	150	12	830			
Zapallar	1	*	2	280	27	660	
San Felipe	2	250	5	315	107	640	1,940
San Isidro	0.33	175	5.7	720	54	845	2,460
Llolleo	0.35	*	4.85	140	14	400	
Rapel	3	2,130	9.5	3,155			

(*) V_s Unspecified

S wave velocities and layer thicknesses are shown

NS emphasizing the importance of pulse S3. The predominant direction of pulse S3 is NS.

A maximum displacement of about 10 centimeters observed for this earthquake was recorded at the Llolleo station. This displacement is a very small value for an $M = 7.8$ earthquake, however this is because the displacement corresponds to dynamic high frequency waves (0.1–25 Hz) and the permanent and long period waves have been filtered out.

Figure 9 compares the displacement traces at Rapel NS and San Felipe S10°E. These stations are located more than 200 km apart and on completely different soils. However, it can be observed that the second and third pulses are practically identical. In this figure, the Rapel and San Felipe traces have been shifted by 12.2 s in order that the second pulses coincide and by 13 s to adjust the third pulse (S3). The shape of both pulses is similar in both traces. The shifts were made with respect to the start of the records.

3.3. *Discussion of High Frequency Pulses of the 1985 Central Chile Earthquake*

The presence of multiple subevents during the 1985 Central Chile earthquake is also supported by the rupture initiation of this earthquake which is marked by the presence of two foreshocks that occurred several seconds before the start of the main shock; the last one occurred approximately 17 s before the main shock with a magnitude Mw = 6.6 (Choy and Dewey, 1988; Christensen and Ruff, 1986; Mendoza *et al*., 1994).

Unfortunately the lack of absolute time in the records does not permit us to identify which foreshock is registered in the accelerograms, but the pulses shown are similar to other pulses observed in events of comparable magnitudes. For example, in the 4 April 1985 Ms = 7.2 and the 3 March 1985 Ms = 6.4 earthquakes, the pulses of these events are shown in Figs. 10 and 11, and are similar to pulses observed in the records of the 1985 Central Chile main event. Therefore the pulse generated by the Ms = 6.4 foreshock may be the first pulse recorded in the accelerograms. This interpretation is in agreement with those who proposed that the foreshocks were generated in the northern part of the rupture zone (Choy and Dewey, 1988), because this can explain the larger amplitude of the first pulse in the accelerograms located to the north of the rupture.

Considering these observations, it can be concluded that the event of 3 March 1985 is the result of the sum of subevents of smaller magnitudes, difficult to identify separately, starting some 10 s after the beginning of the first event activated by the rupture front of the earthquake as it propagated along the plate interface. Considering a rupture velocity of the order of 3 km/s, the separation of about 10 s between pulses S1, S2 and S3 implies distances between dominant asperities of about 30 km. The separation time between the S1 and S3 pulses is in agreement with the separation between the dominant asperities proposed by Barrientos (1988, 1997) and Mendoza *et al*. (1994).

The largest amplitudes in the records of this earthquake are not necessarily due to waves coming

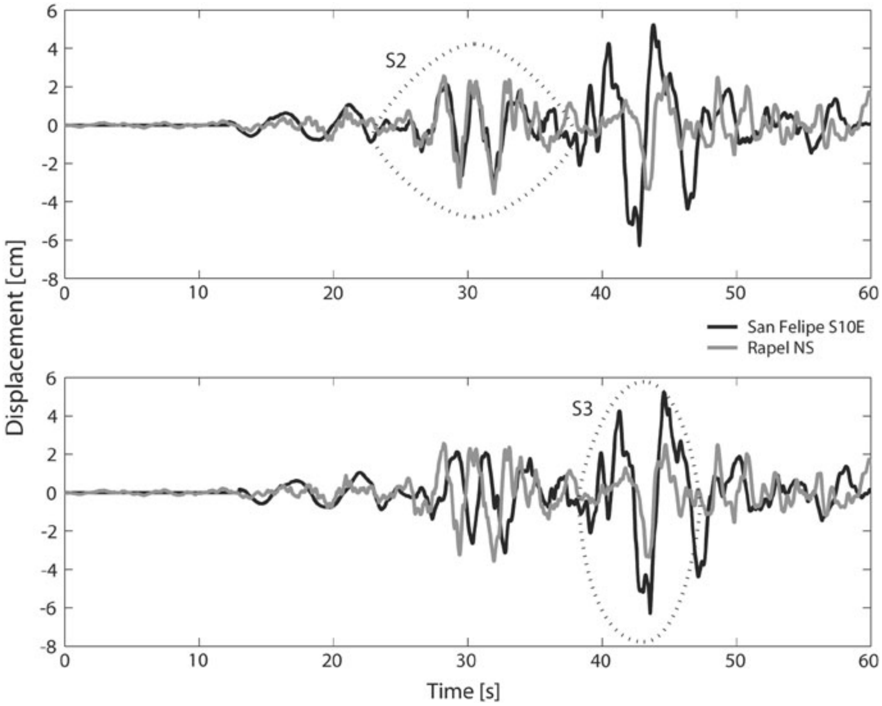

Figure 9
Superposition of identified pulses of San Felipe S10°E and Rapel NS for the 1985 Central Chile earthquake. In the *upper* figure record, the Rapel trace has been shifted by 12.2 s to make the pulses in *S2* coincide. In the *bottom* figure, Rapel trace has been shifted 13 s to superimpose both *S3* pulses' traces. The shifts were made with respect to the start of the records

from the hypocentral zone. Therefore, the attenuation of waves does not correlate with hypocentral and epicentral distances or shortest distance to the fault as is usually assumed in empirical attenuation formulas used to assess seismic hazard. These formulas should consider the location and associated magnitude of each dominant asperity and the radiation pattern of these ruptures. For seismic hazard assessment the consideration of the key role of dominant asperities can reduce the estimation of the seismic hazard by reducing the scattering of commonly used attenuation formulas.

The Central Chile interplate zone has ruptured during large earthquakes in the years 1575, 1647, 1730, 1822, 1906, and 1985 (Comte *et al.*, 1986). For this reason, a future earthquake can be expected to strike this zone in about 60 years, with a rupture mechanism that includes the same dominant asperities which have invariant location (Irikura *et al.*, 2004). This assumption and the identified pulses make the seismic hazard assessment to be more deterministic in this region.

Since most of these conclusions were obtained from a set of accelerographic stations without absolute time, these results will be validated by considering the better recorded 2007 Tocopilla earthquake.

4. *Tocopilla Earthquake*

4.1. *Rupture of the 2007 Tocopilla Earthquake*

The 2007 Tocopilla earthquake occurred in Northern Chile, Fig. 12, in a region that, because of desert characteristics, has been practically uninhabited. However, from the analysis if historical earthquakes it has been possible to reconstruct the seismic history of the region (Montessus de Ballore, 1911–1916; Kausel, 1986; Comte and Pardo, 1991). In the zone of Tocopilla, the last important earthquake with a large tsunami, occurred in 1877 with a 400 km long intensity VIII Mercalli isoseismal (Kausel, 1986). This isoseismal is assumed to

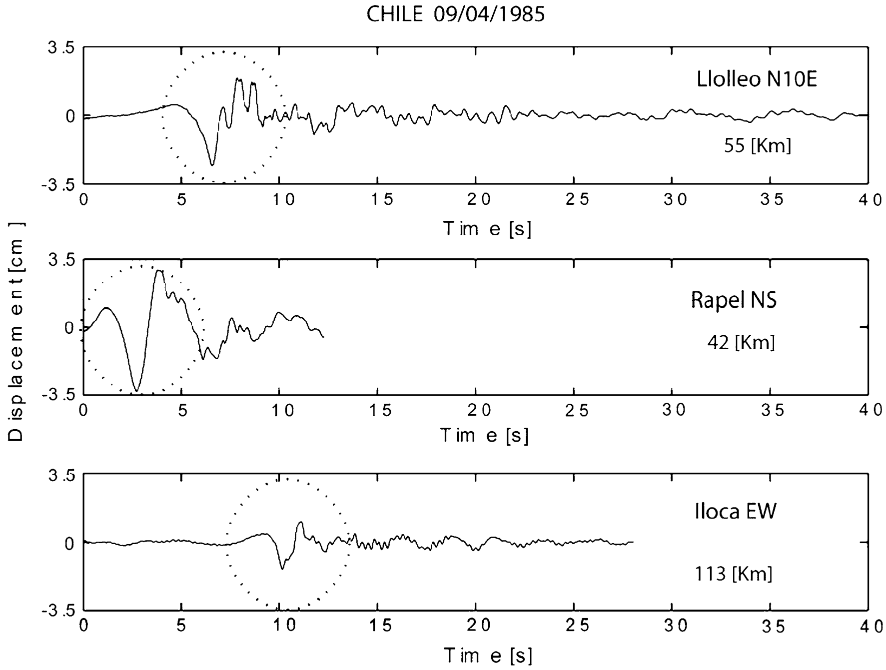

Figure 10
Displacement records of the 9 April 1985 aftershock, Ms = 7.2 for Llolleo N10°E, Rapel NS and Iloca EW. A similar pulse is identified in the three *encircled* records. The *numbers* correspond to the hypocentral distance

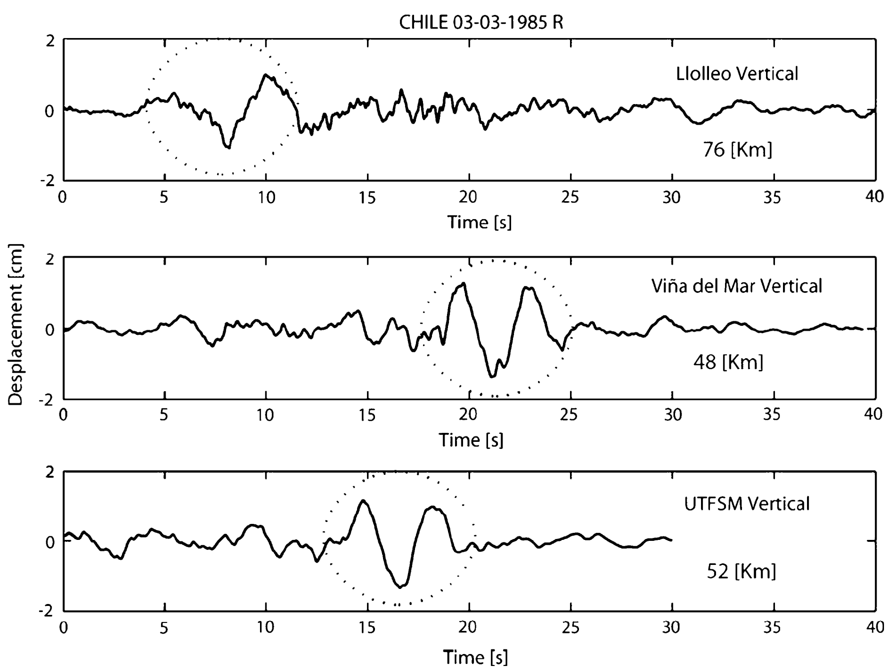

Figure 11
Vertical displacement records of the 3 March 1985 1-h-later aftershock Ms = 6.4 for Llolleo, Viña del Mar and UTFSM stations. The *encircled* pulses have similar shapes in the three records. The *numbers* correspond to the hypocentral distance

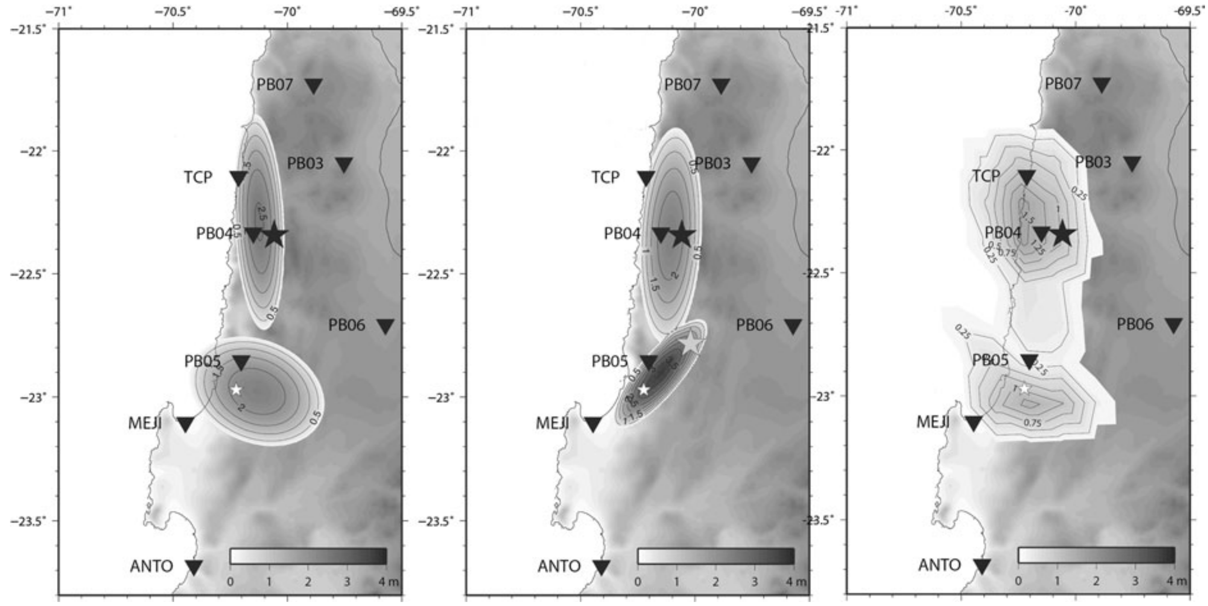

Figure 12
Slip distributions from the inversion of near field displacements obtained with three different techniques using strong motion data for the 2007 Tocopilla earthquake (modified from Peyrat *et al*., 2009)

represent the area of rupture of the earthquake (Kausel and Ramírez, 1992).

The uncertainty of the concurrence of large historical earthquakes makes it difficult to estimate the seismic hazard in the zone where only one paleoseismological study is available (Vargas *et al*., 2005). In addition, in the twentieth century no large earthquake occurred in this region except for a relatively small event of M 7.3 in December 1967 (Malgrange and Madariaga, 1983). For this reason, the recent very well recorded Tocopilla earthquake is a unique opportunity for studying the potential destructiveness of north Chilean earthquakes pulses. This will also corroborate our conclusions about the high frequency pulses of the 1985 Central Chile earthquake obtained from accelerograms without absolute time.

The hypocenter of the 2007 Tocopilla earthquake is located at a depth of around 45 km with a continental epicenter, and with a rupture that propagated to the South. The kinematic inversion models show two well defined zones of energy release (Delouis *et al*., 2009; Peyrat *et al*., 2009), Fig. 12. The inversions shows that the second event occurred about 23 s after the main shock in the southern part of the rupture area, at a distance of 49 km, with an azimuth of 175° with respect to the first event (Peyrat *et al*., 2009). GPS and interferometric data also confirm the two important zones of release of energy (Bejar-Pizarro *et al*., 2008).

4.2. Strong Motion Database of the 2007 Tocopilla Earthquake

The recent 2007 Tocopilla earthquake was a very well recorded earthquake as shown in Fig. 13. Several accelerographic stations recorded this Mw = 7.7 event at short distance (Peyrat *et al*., 2009). More than 20 digital accelerograms with absolute time are available for the study of the high frequency behavior of this earthquake. The base line was corrected and the traces were filtered using a second order lowpass causal Butterworth of cut frequency of 0.08 Hz. The instrumental response is flat and no correction was necessary (Boore and Boomer, 2005).

The high quality of data of the 2007 Tocopilla earthquake, allow one to observe very low frequency

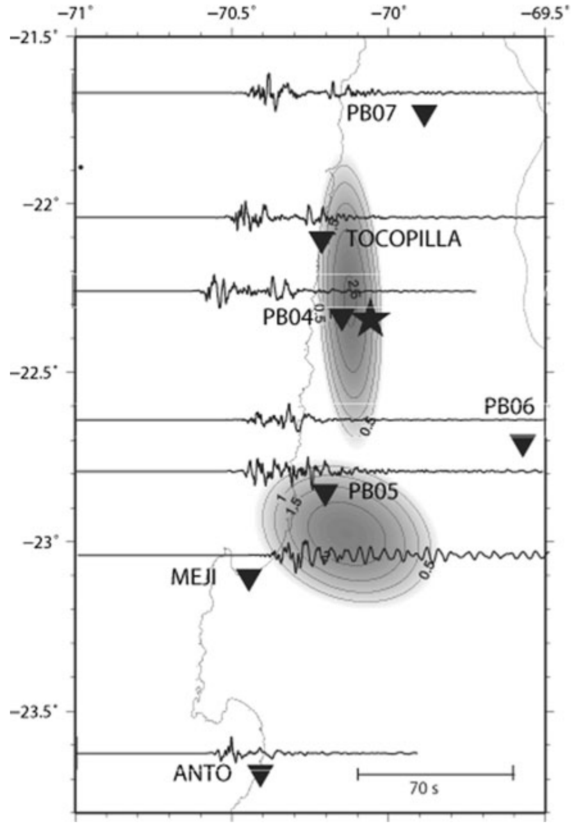

Figure 13
EW displacement data of the 2007 Tocopilla earthquake and slip distribution of near field proponed by Peyrat *et al*. (2009). The strong motion data were filtered using a second order lowpass causal Butterworth of cut frequency of 0.08 Hz and doubly integrated

waves in the accelerograph that correspond to waves of intermediate and near field. These waves have large amplitudes and if they are not removed the high frequency pulses observed in this work can not be distinguished clearly.

The low frequency filter has a cut off frequency of 0.08 Hz smaller than that used in the 1985 Central Chile earthquake, because, for this last earthquake, the instrumental quality did not allow observers to recover waves larger than 10 s (0.1 Hz).

4.3. Identified High Frequency Displacement Pulses of the 2007 Tocopilla Earthquake

The first and second event of this earthquake was observed directly in the original acceleration records and more clearly in the doubly integrated accelerograms shown in Fig. 14. In the northern stations the two arrivals have been encircled. In the southern stations the two pulses can not be distinguished because the direction of rupture propagation is to the south and the arrival of the two energy pulses is almost simultaneous at all stations. This is a clear example of strong motion directivity effects. Other authors have also observed these two pulses in the strong motion records using a narrower filter (Peyrat *et al*., (2009) used a 0.01–0.1 Hz bandpass).

4.4. Discussion of High Frequency Pulses of the 2007 Tocopilla Earthquake

In a more detailed analysis of the strong motion records it is possible to observe additional similar pulses recorded at different stations. For example, using P waves, a cascade rupture type is shown for the 2007 Tocopilla earthquake. In Fig. 15 the vertical components near the epicenter are shown. This zoom is for the early seconds corresponding to the P wave displacements of the first dominant asperity. It is possible to observe three similar waves in all stations. These waves are generated by three subevents where the first and second events are superposed in the southern stations because of the hypocenter location of these subevents and its rupture propagation to the south. This rupture type is in agreement with the cascade model proposed by Ellsworth and Beroza (1995). The cascade rupture characteristic is observed with clarity because we filtered out the long period components that have the largest amplitude and hide the details of source.

The shape and amplitude of the identified pulses of the 2007 Tocopilla earthquake are similar to those of the 1985 Central Chile earthquake validating the previous result for the 1985 earthquake. Since these pulses are a typical characteristic of Chilean interplate thrust earthquakes they should be considered for the seismic design.

5. Discussions and Conclusions

High frequency pulses from doubly-integrated accelerograms of two large magnitude Chilean thrust

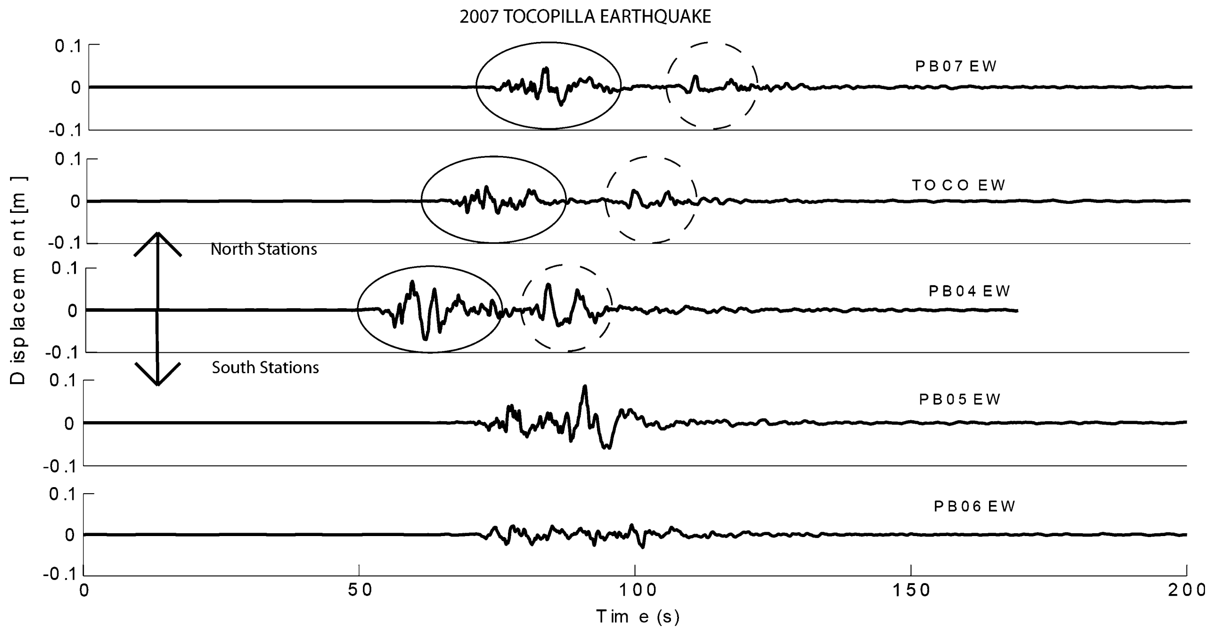

Figure 14
The north stations show the two principal *encircled* pulses. For the south station the arrival of these pulses is almost simultaneous

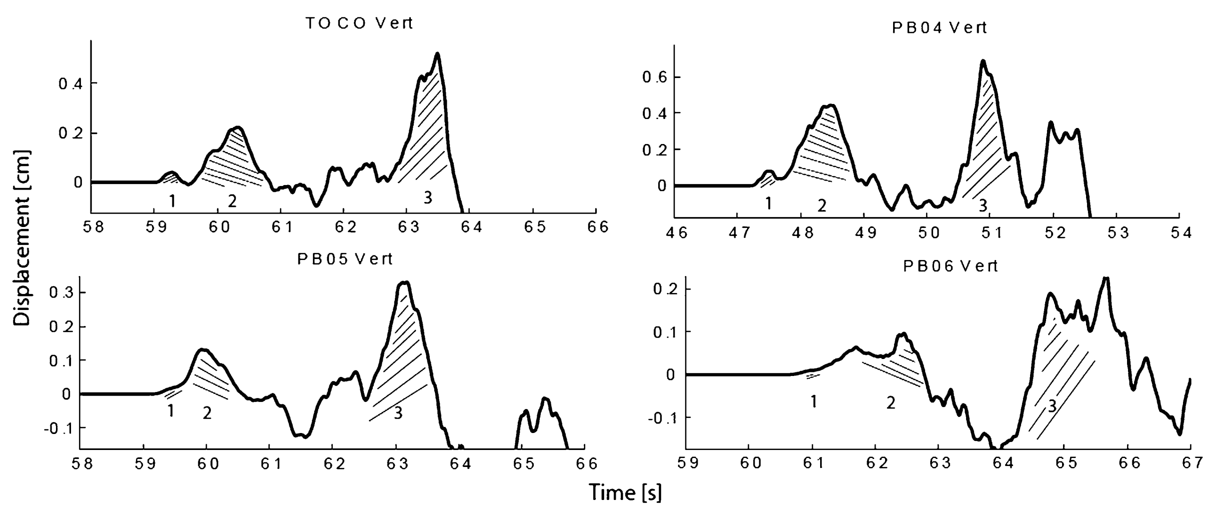

Figure 15
First seconds of vertical component of P wave arrivals, where it is possible to identify three pulses. The first pulse of the P wave is superposed with the second one due to the south rupture propagation (the PB06 displacement was multiplied by −1)

earthquakes were identified from many accelerographic stations. These pulses are generated by the dominant asperities of the studied earthquakes. These pulses have periods between 1 and 5 s, small amplitudes, and different arrival times. The shape and amplitude of identified pulses are similar for the 1985 Central Chile main earthquake (Ms = 7.8) and the two main aftershocks as well as for the 2007 Tocopilla earthquake (Mw = 7.7).

The observed pulses contain the main seismic source properties. The amplitude of these pulses may be controlled by geometrical attenuation which could explain the smaller amplitude of these pulses in comparison with those of shallow earthquakes (Hall *et al.*, 1995; MAKRIS, 1997; SOMERVILLE *et al.*, 1997) since the latter ones have probably smaller dominant asperity distances.

In other subduction earthquakes, like the 1985 Michoacan Mexico and 2007 Pisco Perú events, more than one dominant asperity have been observed (HOUSTON and KANAMORI, 1986; TAVERA and BERNAL, 2008) and the strong motion data show similar pulses to those identified in this paper (ANDERSON *et al.*, 1986; TAVERA *et al.*, 2009).

The peak amplitude of these earthquake records are not necessarily due to waves coming from the hypocentral area. Therefore, the attenuation of waves do not correlate well with hypocentral and epicentral distances or shortest distance to the fault as is usually assumed in empirical attenuation formulas used to assess seismic hazard. These formulas should consider the location and associated magnitude of each dominant asperity and the radiation pattern of these ruptures. For seismic hazard assessment the consideration of the key role of dominant asperities can reduce the estimation of the seismic hazard by reducing the scattering of commonly used attenuation formulas.

The Chilean subduction seismic zone is one of the most active in the world. For this reason a future potential earthquake can be expected in central Chile Central and north Chile within the next 60 years (KELLEHER, 1972; NISHENKO, 1985; COMTE *et al.*, 1986). Considering that the earthquake rupture may have similar dominant asperities with an invariant location (IRIKURA *et al.*, 2004) and similar pulses like those identified in these papers, the seismic hazard assessment turns out to be more deterministic in the region.

The characteristics and arrivals of the identified pulses are important for seismic engineering design, especially for large earthquakes where the seismic demand can be different in two different sites for the same rupture area. This is a key characteristic for seismic design, where the non-linear behavior of structures is considered. Therefore seismic energy distribution associated to the arrivals of high frequency pulses turn out to be an important issue to estimate the seismic hazard potential.

The low destructiveness of large subduction thrust earthquakes observed in several sites, like the 1985 Central Chile event (EERI, 1986), the epicentral zone of the 1985 Michoacan, Mexico (ASTROZA *et al.*, 1986), the 2007 Pisco, Perú (ASTROZA *et al.*, 2007) and the 2007 Tocopilla, Chile (ASTROZA et al., 2008) events, which is the scope of seismic hazard assessment, may be due to the characteristics of the pulses associated to dominant asperities (small amplitude and different arrival times).

The high frequency pulses identified in this paper have permitted observers to extend the range of frequency in which the 1985 Central Chile and 2007 Tocopilla earthquakes were studied (MENDOZA *et al.*, 1994; PEYRAT *et al.*, 2009). The study in the high frequency range of large magnitude earthquakes will allow the introduction of new seismological results in earthquake engineering design in the future.

The displacement pulses observed in this work could be correlated with the source time function of the 1985 Central Chile and 2007 Tocopilla earthquakes, but as the frequency range of the pulses and the source function time are different the correlation is not obvious, but this certainly exists.

Future works that allow one to correlate the possible geological barriers with the zones that produce the high frequency pulses is very important for seismic design. For example, understanding the role of the Mejillones peninsula in the release or stop of seismic energy, and the influence the O'Higgins sea mount that is subducted about 100 km to the north of Valparaiso, are questions that should be studied in the future.

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