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Evidence for Earthquake Interaction in Central Chile: the July 1997-September 1998 Sequence

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Abstract. Seven $Mw > 6$ events occurred between July 1997 and January 1998 along the shallow dipping subduction zone of Central Chile. We used body waveform modeling and master event relocation to study them. During July 1997, typical shallow interplate thrust events located close from each other followed a southward migration path and were located close from each other. On 15 October, the largest shock of the series (Mw=7.1) occured at 68 km depth. From the directivity, we found that its rupture plane was almost vertical with a downward rupture. It was a down-dip compressional mechanism which is rare in Chile. Then, several thrust events occurred above it, along the plate interface. The rupture zones of the July 1997 events followed a cascade pattern with strong stress interaction. The slab push event of 15 October does not seem to have been triggered by static stress transfer from the July swarm.

Introduction

Seven events of magnitude $M_w > 6$ occurred between July 1997 and January 1998 over an area that extends for more than a hundred km between roughly 30°S and 31.5°S in Central Chile (see Figure 1). These events were spread over an area that overlaps the northern part of the rupture zone of the great $M_w = 7.9$ Illapel earthquake of 1943 [*Lomnitz*, 1970]. Starting with an event of magnitude $M_w = 6.7$ on July 6, 1997, the interplate seismicity migrated southward during July 1976, 4 events of $M_w > 6$ occurring during this period of time. A few weeks later, on October 15, 1997 the largest event occurred, this was a very unusual intermediate depth, slab push event of $M_w = 7.1$.

In the Illapel region, the Nazca plate subducts under North-Central Chile with a velocity of 9.5 cm/yr in the 80^o NE direction [*Tichelaar and Ruff*, 1991]. In this region, subduction is shallow and the slab flattens under the South American plate [*Barazangi and Isacks*, 1976]. [*Tichelaar and Ruff*, 1991] found that the dip of the down-doing Nazca plate in this area was $16 + / - 2^o$ and that the interface was coupled down to 48-53 km depth. The geometry of the slab shows flexure points so that the state of stress of this area is probably very complex. This region roughly corresponds to the Illapel gap where the last great thrust event occurred on April 6, 1943 ($M_w = 7.9$) [*Lomnitz*, 1970; *Beck et al.*, 1998]. We modeled the seismicity that began with the $M_w = 6.7$ July 6, 1997 earthquake using teleseismic body waveform inversion, and we relocated the seismicity using a master event method. We find that this sequence of events shows signs of correlation of several relatively large events over a large zone in a relatively short period of time.

Data Analysis

Seven $Mw > 6$ events from July 1997 to January 1998 were modeled using very broad band, P and SH waveform data from the IRIS and GEOSCOPE networks. In order to avoid upper mantle triplications and core arrivals, we used teleseismic stations in the range $30^o < \Delta < 90^o$. We selected a set of stations that gave us the best azimuthal coverage as possible, and modeled the earthquakes as single point double-couple sources. In the inversion we solved simultaneously for focal mechanism, focal depth and source time function using the CMT solutions as a priori models. The velocity structure near the source and beneath the stations was approximated by a half space with standard upper mantle wave speeds. We worked with displacement seismograms and, in order to avoid problems with low and high frequency noise, we filtered the displacement records with band-pass Butterworth filters of order 3 between $0.02H_z$ and $0.16H_z$.

We used a master event relative location technique [*Fitch*, 1975] in order to relocate 127 events of $M > 4.5$ in the region from 29^o to 33^o S in the period from March 1997 to September 1998. We assumed that travel time residuals could be adequately fitted by first-order perturbations of ray trajectories. This is probably the case in our relocations because our slave events were close to the master event. As we could not get accurate depth estimates from relocation, we used EDR depths for the events with $4.5 < M_w < 6$. For larger events we used the depths determined from body-wave modeling. The 71 best relocations are shown in Fig. 1. For $M > 6$ events, we hand-picked arrivals times of P waves from teleseismic very broad band data. For $4.5 < M < 6$ events, we used the arrival times tables from EDR (Earthquake Data Reports) of the USGS.

As observed in Figure 1, most of the events we studied were typical shallow interplate thrust earthquakes (from 9 to 50 km depth, increasing from West to East). Their fault planes have dips that coincide with that of the downgoing slab. The 15 October 1997 event ($M_w = 7.1$) was an exception (see its fault plane solution in Figure 2). This event was a "slab push" earthquake with a down dip compressional mechanism that took place inside the Nazca plate slab at 68 km depth. There is some evidence for directivity in the SH waves of Figure 2. SH waves at stations WVT, HKT and

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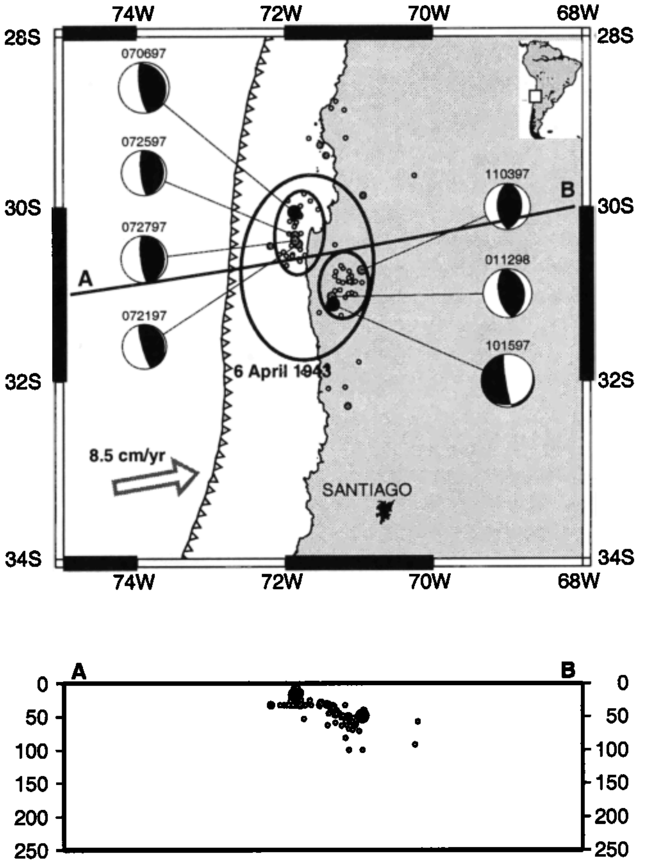

Figure 1. Focal mechanisms of all modeled events ($M_w > 6$) of the 1997 swarm in the Illapel gap of Central Chile. Large symbols indicate the events for which depth was determined by body waveform modeling. The smaler dots show all relocated earthquakes for the period from 1977 to 1999. At the bottom we show a cross section along the line AB, parallel to the direction of convergence of the Nazca and South American plates. The upper limit of the relocated earthquakes probably define the plate boundary, but it is poorly defined because of the lack of depth control of relocated events.

CMB that leave the source along the vertical fault plane have much larger amplitudes than those observed at stations SDV or SJG. From this observation we conclude that the actual fault plane for this events was the almost vertical nodal plane with rupture beginning at the top of the slab and propagating downwards. Slab-push earthquakes of this magnitude, near the plate interface are very unusual for Chile. The only other one we know was reported by [*Astiz and Kanamori*, 1986] in Southern Chile, but was actually a much deeper event than this one.

Earthquake Migration and Interaction

The high level of seismicity in such a reduced area during few months is very unusual in Central Chile except in aftershock sequences. As shown in Figure 3 the events spread over a region of more than 100 km along the strike of subduction zone. After the occurrence of these events, seismicity almost stopped in the area. For this reason we think that these events constitute a closely related swarm of seven $M_w > 6$ earthquakes. In fact, we can describe the sequence of 1997-1998 Central Chile events as two swarms shown in Figure 4. The first swarm included four $M_w > 6$ earthquakes that occurred during July 1997 and began with the July 6 $M_w = 6.7$ event in the northern part of the rupture area of

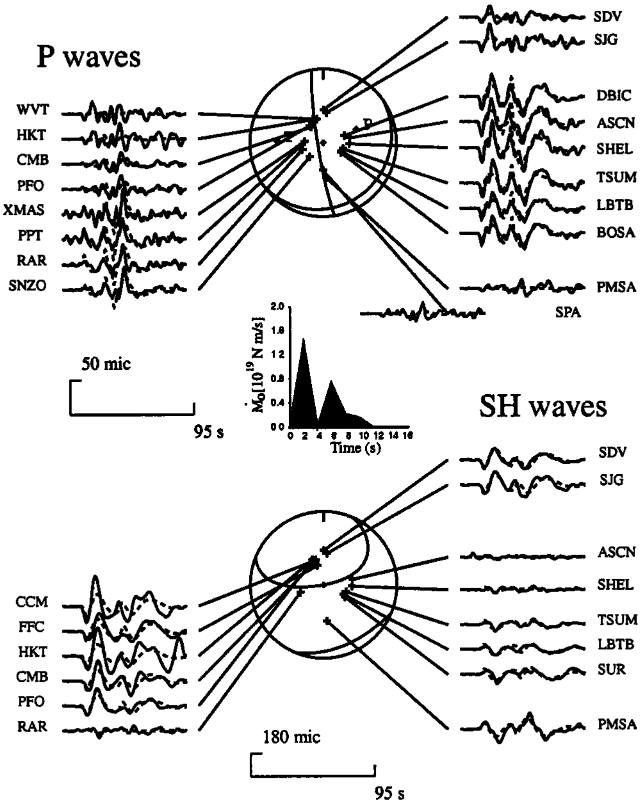

Figure 2. Body wave modeling of the slab push event of October 15, 1997, the largest event of the swarm. Solid lines are observed displacements and the dotted lines are synthetics. The P axis is subparallel to the downgoing slab. Larger amplitudes at stations WVT, HKT and CMB as compared to those at SDV and SJG suggest downward directivity on the subvertical plane.

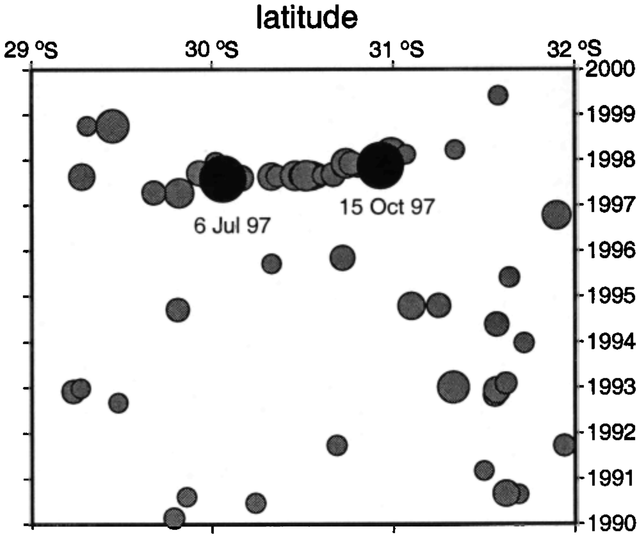

Figure 3. Seismicity listed in the NEIC catalog plotted as a function of time and latitude. Before 1997, seismicity was diffuse between 29°S and 32°S and not very strong. Between July 1997 and January 1998, there were seven $M_w > 6$ earthquakes in a region 130km long.

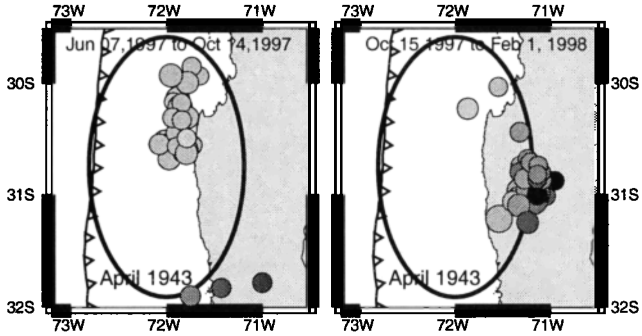

Figure 4. Maps of relocated seismicity with magnitude greater than 4.5 for different periods of time. During July seismic activity was high and followed a southward migration. Then, the region became quiet until October 15, 1997 when the large slab-push earthquake occurred. It was then followed by shallower interplate seismicity.

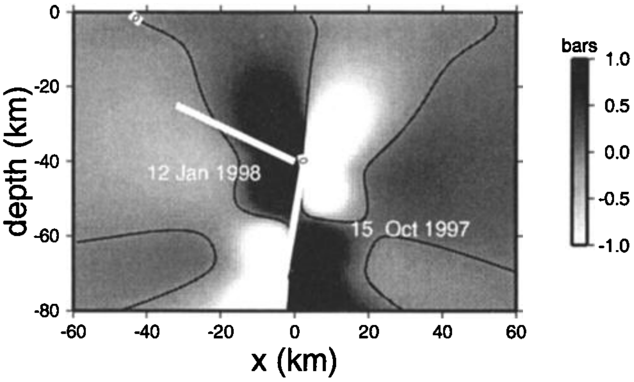

Figure 6. Incremental Coulomb stress field created by the October 15, 1997 slab-push earthquake on faults oriented like the plate interface in the Chilean subduction zone. The white lines indicate the fault zone of the October 15 earthquake and that of the large shock of January 1998. The thin black line is the contour of zero Coulomb stress change.

the great thrust event of 1943 (see Fig. 4). The July swarm followed a cascade pattern propagating southward, offshore, under the accretionary prism in Chile. The July seismicity ended near the future location of the October 15 event. After two and a half months of quiescence, the second swarm began with the October 15 $M_w = 7.1$ slab push event. It occurred inland, inside the downgoing slab, just below the end of the coupling zone defined by [*Tichelaar and Ruff*, 1991]. The second swarm continued after the October 15 event with two medium sized thrust events of $M_w = 6.2$ and $M_w = 6.6$, that took place on the plate interface just above the October $M_w = 7.1$ event on 3 November 1997 and 12 January 1998.

We studied the possible Coulomb stress interaction between the different earthquakes in the swarm [*King et al.*, 1994]. The July swarm of thrust events on the subduction interface followed a clear cascade from North to South. Coulomb stress calculations give a clear positive answer to the question whether these events were triggered by the southwards transfer of stresses along the plate interface.

Many studies have shown that changes in Coulomb failure stress change produced by a group of events can affect the spatial distribution of earthquakes which are more likely to occur where the Coulomb stress increases on optimally oriented faults. [*King et al.*, 1994] showed that even very small Coulomb stress increases of the order of 0.01 MPa may trigger earthquakes. As shown in Figure 5, however, the change in Coulomb stress computed after the July events can not explain the occurrence of the 15 October earthquake. Actually, as seen in this Figure, Coulomb stress did not increase but decreased on the plane of the the 15 October earthquake.

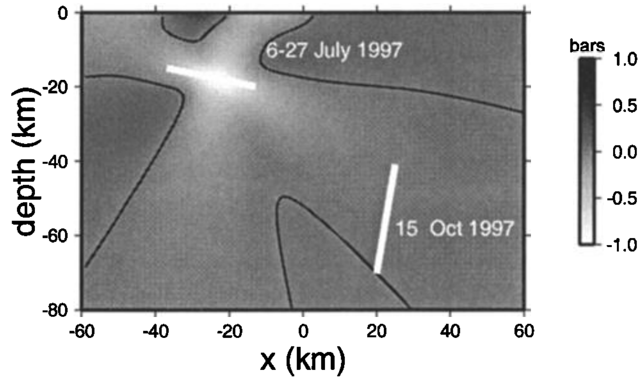

Figure 5. Incremental Coulomb stress field created by the July 1997 earthquakes on faults oriented like that of the slab-push event of October 15, 1997. The lines indicate the inferred fault zone of the July interplate swarm and that of the October event. The thin black line is the contour of zero Coulomb stress change.

Finally, as shown in Figure 6, the Coulomb stress change produced by the 15 October slab push interplate event clearly favored the occurrence of the 3 November and 12 January 1998 thrust event on the plate interface just above the 15 October earthquake. Thus stress modeling show some interaction inside each swarm, but not between the two swarms.

Discussion

The southward migration of seismicity suggests a relation between the July thrust events swarm and the occurrence of 15 October 1997 slab-push event. But we cannot explain its slab-push mechanism which is opposite to the local change in Coulomb stress. [*Astiz and Kanamori*, 1986] and [*Dmowska et al.*, 1988] proposed that slab-push events occur after very large events that decouple the interplate area. We do not think this is the case here because the July swarm was too small to decouple the plate interface, although it may be argued perhaps that the 15 October event was a very late response to plate decoupling produced by the 1946 Illapel earthquake.

It may also be that the occurrence of the slab-push event of October was independent of the July 1997 events and the 1946 Illapel earthquakes. As we discuss below, slab push events are not that rare in Peru, Mexico and Chile. In this case, it is possible that the October event was due to local stress perturbations produced by the unbending of the subducting slab under central Chile.

Like in Central Chile, subduction in Central Peru is characterized by a complex geometry [*Barazangi and Isacks*, 1976]. In 1940 and 1966, two $M_s = 8$ thrust events occurred there [*Abe*, 1972] and were followed in May 1970 by a large destructive normal faulting event. Several aftershocks in June and July 1970 studied by [*Stauder*, 1975] show the same slab push mechanism as the October 15, 1997 Chilean event. As in low-dipping areas of Central Chile and Peru, in Southern Mexico the Cocos plate subducts with a shallow dip angle. Among a large number of mexican events modelled by [*Pardo and Suárez*, 1995] we found the July 2, 1968 $m_b = 5.7$ earthquake that occurred at the end of the coupled zone, inside the slab at 48.1 km depth, and had a slab-push mechanism like that of the October 15, 1997 event. More recently, [*Cocco et al.*, 1997] studied the Zihuatanejo, Mexico, earthquake of December 10, 1994, an intermediate-depth slab-push earthquake ($\simeq$ 50 km) located 30km inland, inside the subducted Cocos plate on a subvertical fault.

Conclusion

The 1997-1998 North Central Chile swarm began with four typical shallow thrust events which occurred during July 1997. Their rupture zone followed a southward cascade pattern propagating toward the location of the most interesting earthquake, that of October 15 $M_w = 7.1$ which had a slab push mechanism which is very rare in Chile. It occurred down-dip of the great 1943 Illapel earthquake, at intermediate depth inside the downgoing slab of Nazca plate, at the end of the coupled zone. Its fault plane was subvertical and its rupture propagated downward. Clearly, we need now to look for more slab push events in other regions to try to understand their occurrence: are they induced by shallow dipping subduction zones or do they occur in any kind of subduction zone?

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