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A seismological study of the 1835 seismic gap in south-central Chile

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Abstract

We study the possible seismic gap in the Concepción–Constitución region of south-central Chile and the nature of the $M = 7.8$ earthquake of January 1939. From 1 March to 31 May 1996 a seismic network of 26 short period digital instruments was deployed in this area. We located 379 hypocenters with rms travel time residuals of less than 0.50 s using an approximate velocity distribution. Using the VELEST program, we improved the velocity model and located 240 high precision hypocenters with residuals less than 0.2 s. The large majority of earthquakes occurred along the Wadati–Benioff zone along the upper part of the downgoing slab under central Chile. A few shallow events were recorded near the chain of active volcanos on the Andes; these events are similar to those of Las Melozas near Santiago. A few events took place at the boundary between the coastal ranges and the central valley. Well constrained fault plane solutions could be computed for 32 of the 240 well located events. Most of the earthquakes located on the Wadati–Benioff zone had "slab-pull" fault mechanism due to *tensional* stresses sub-parallel to the downgoing slab. This "slab-pull" mechanism is the same as that of eight earthquakes of magnitude around 6 that are listed in the CMT catalog of Harvard University for the period 1980–1998. This is also the mechanism inferred for the large 1939 Chilean earthquake. A very small number of events in the Benioff zone had "slab-push" mechanisms, that is events whose *pressure* axis is aligned with the slab. These events are found in double layered Wadati–Benioff zones, such as in northern Chile or Japan. Our spatial resolution is not good enough to detect the presence of a double layer, but we suspect there may be one.

Keywords: Subduction; Intermediate depth earthquaques; Nazca plate; Cocos plate; Flat subduction; Compression; Extension; Flexure

1. Introduction

Chile is one of the most seismically active areas in the world; on an average, a destructive earthquake of magnitude larger than 8 has occurred every 10 years in the historical period from the beginning of the 17th century. Although several of these earthquakes require a careful re-evaluation, every single segment of the country has been the site of at least an event of magnitude 8 in the last 130 years. Since the early 1970s, several sites along the coast were pin designated by seismologists (see, Nishenko (1985) for a statistical evaluation) as probable sites of future large events (seismic gaps). We define a seismic gap as a zone where large earthquakes occurred in the past, but that has been quiet for decades.

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An obvious seismic gap, that of south-central Chile between 35 and 37° S, which had the last large subduction earthquake of magnitude 8.5 on 20 February 1835, has been overlooked in some previous studies because a major shock, the Chilean earthquake occurred there on 25 January 1939. This is probably the most damaging seismic event in Chile's seismic history. Recent work by Campos and Kausel (1990) and Beck et al. (1998) has shown that the 1939 earthquake was not a subduction event but an extensional intraplate shock. In this study, new information about the seismicity and seismotectonics of the Concepción–Constitución area is presented and analyzed.

1.1. Historical seismicity of the Concepción–Constitución area

The historical seismicity of central Chile has been studied by numerous authors including Darwin (1851), Perrey (1854), Montessus de Ballore (1916), Greve (1964), Lomnitz (1971), Comte et al. (1986) and Beck et al. (1998). From their analysis of local reports, geological information, levelling changes, seismic data, etc., a reconstruction was made of the seismic history of the Chilean subduction zone from 32 to 39° S in Fig. 1. Although this data is not quantitative enough, the rupture extents are agreed upon by most recent authors (see, e.g. Beck et al., 1998; Comte et al., 1986; Madariaga, 1998). The area from 35 to 37° S has suffered at least three large events in 1730, 1751, 1835 and, partly, in 1928. Although there are some doubts about the southern termination of the 1928 event, it is clear that the southern part of the Concepción–Constitución region has had no major subduction earthquakes since 1835. The 1939 earthquake, as will be discussed later, did not take place in the plate boundary.

The southern part of central Chile was the site of the great earthquake of 22 May 1960 of magnitude larger than 9.5 (Fig. 2, and studies by Astiz and Kanamori, 1986; Barrientos et al., 1992; Cifuentes, 1989; Plafker and Savage, 1970; Vita-Finzi and Mann, 1994). As seen from Fig. 2, the 1960 earthquake bounds the Concepción–Constitución gap from the south. Although many scientists studied the rupture zone of this event in detail, they concentrated their efforts mostly on the central and southern parts of the fault area, where large permanent coastal subsidences

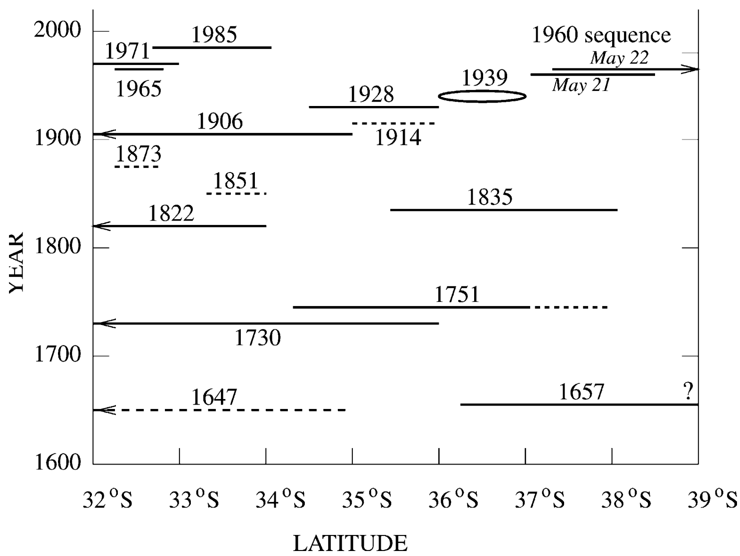

Fig. 1. Time-space plot of the large earthquakes that took place along the Chilean subduction zone from 30 to 39° S. Earthquake rupture zones, inferred from local damage data as well as field observations by numerous authors, are indicated by horizontal lines. The whole area has ruptured repeatedly since 1647, the largest earthquakes being that of 1730 and that of 22 May 1960. The area of the Chilean earthquake of 1939 is indicated by a balloon since this event is not a subduction zone shock, but an earthquake that broke the downgoing slab under the central valley of Chile. The vertical broken lines show the approximate size of the seismic gap.

and upheavals of up to 10 m were observed. The northern end of the earthquake rupture zone, is poorly known because it is situated in a very sparsely populated area south of Concepción. Most authors agree, however, that rupture did not extend north of the Arauco Peninsula. Cifuentes (1989) relocated a sequence of nine foreshocks that occurred in the last 33 hours before the main 1960 event. All these foreshocks had epicenters south of latitude 37.1° S (Arauco Peninsula) showing a progression of seismic activity to the south, toward the initiation of the 1960 main shock. The first event in this sequence had a magnitude $M_W = 8.1$ and ruptured about 150 km to the south (Cifuentes, 1989; Plafker and Savage, 1970). Therefore, the region north of 37° S was not affected by this sequence. An additional indication that the 1960 earthquake stopped well south of Concepción city is that several large thrust type events of $M \simeq 7.0$ took place near the Arauco Peninsula in 1974–1975 (Cifuentes, 1989).

Two important magnitude 8 earthquakes immediately to the north of the Concepción–Constitución area are those of 1985 south of Valparaíso (Comte et al., 1986; Korrat and Madariaga, 1986) and that of Talca on 1 December 1928 (Beck et al., 1998; Greve, 1964; Lomnitz, 1971) as shown in Fig. 2. The 1928 event produced extensive damage along the coast from Cauquenes in the south (36° S) to Pichilemu in the north (34.5° S) and in the central valley cities of Talca, Curicó and San Fernando (Bobillier, 1930). In their recent re-evaluation of large Chilean earthquakes, Beck et al. (1998) used three old seismograms from stations KEW, DBN and TNT and determined the depth and mechanism of the 1928 event. According to these authors, this earthquake was a shallow dipping thrust event with a centroid depth less than 20 km. The 1985 Valparaíso earthquake covered only partially the rupture zone of the great 1906 thrust earthquake, which in turn with the 1928 earthquake difine the northern boundary of the 1835 Concepción–Constitución seismic gap (Fig. 1). Thus, our study area is well defined by major events to its north and south (Fig. 2).

The 25 January 1939 Chilean earthquake took place in the gap between the 1928 and 1960 shocks. Two lines of evidence show that the 1939 event was not a plate boundary earthquake: Gutenberg and Richter (1941) determined the depth of this earthquake as 70 km from depth phases recorded at Pasadena, and recently, Campos and Kausel (1990) and Beck et al. (1998) studied P wave recordings of the 1939 earthquake from Europe and north America and determined its depths as 80–100 km in an almost vertical normal fault. Therefore, the 1939 event did not break the plate interface between the 1928 and 1960 earthquakes; thus, the Concepción–Constitución area has been considered the oldest seismic gap in Chile (Barrientos, 1987), with its last large earthquake dating back to 1835 (Fig. 1).

1.2. Instrumental seismicity

A good estimate of the seismicity of the zone between 35 and 37° S can be obtained from the recent homogeneous catalog of relocated earthquakes computed by Engdahl et al. (1998). The seismicity of the area from 30 to 40° S contained in their catalog is shown in Fig. 3. Earthquakes tend to concentrate in a narrow band along the coast and the central valley of Chile. The increase in depth of the events as the subducted plate descends below Chile is also clearly evidenced by the gray scale that describes depth. Shallow events (white) only occur near the trench along the coast, and in the vicinity of the volcanic axis of the Andes. All other shallow events occur in Argentina in the northern part of the provinces of Neuqu rsquo;enand Mendoza. Events in the Concepción–Constitución area are mostly concentrated in a narrow band of intermediate depth (deep gray) events. Coastal earthquakes are rare, especially between 34.5 and 36° S where the 1 December 1928 earthquake occurred. Clustering of aftershocks of the 1985 earthquake north of 34.5° S as well as that around the Arauco peninsula is observed, most likely corresponding to aftershocks of a series of events two of them with $M_W > 7$ that occurred south of the Arauco Peninsula (37.3° S) between 1974 and 1975.

Fig. 3 confirms that the region between 34.5 and 37.5° S is a place of relative quiescence of shallow seismicity for events about $M_W > 5.2$. This is even clearer in Fig. 4 where the seismic moment tensors (CMT Harvard catalog) of all available earthquakes since 1976 are shown. Again, apart from aftershocks of the Valparaíso earthquakes of 1971–1985 situated north of 34.5° S, there are no shallow fault plane solutions from 34.5 down to 36.5° S. This absence of mechanisms is very conspicuous since this is the only area of Chile where such a quiescence can be observed.

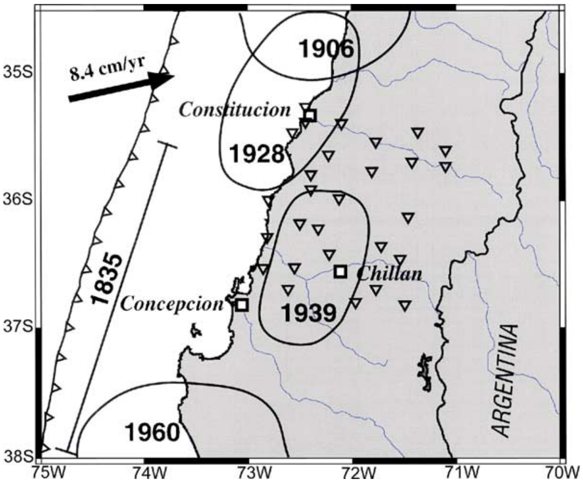

Fig. 2. Source areas of the largest $M \sim 8$ Chilean earthquakes of the last 95 years. The ellipsoidal patches define the estimated source areas for these events. The estimated fault length of the great 1835 earthquake is indicated by a solid line. The 1939 Chilean earthquake is not a thrust earthquake. Inverted triangles correspond to seismic stations deployed during the period 1 March to 1 June 1996.

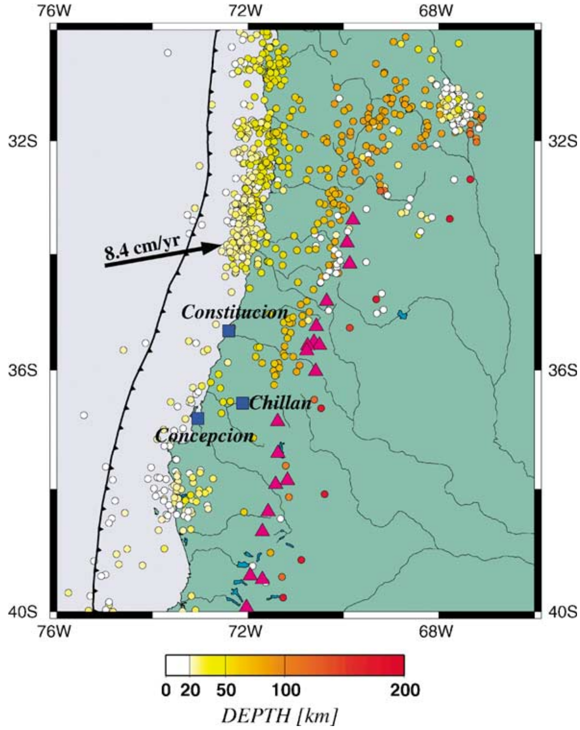

Fig. 3. Seismicity of $M > 5$ in the Concepción–Constitución since 1980 determined from the new seismic catalog of Engdahl et al. Engdahl et al. (1998). The Concepción–Constitución region looks less seismic than the rest of central Chile. Active volcanoes are indicated by triangles.

On the other hand, frequent activity is reported at intermediate depth in the CMT catalog as shown by the eight mechanisms along the central valley. This alignment of events correspond very well with the same north–south line of activity observed in Fig. 3.

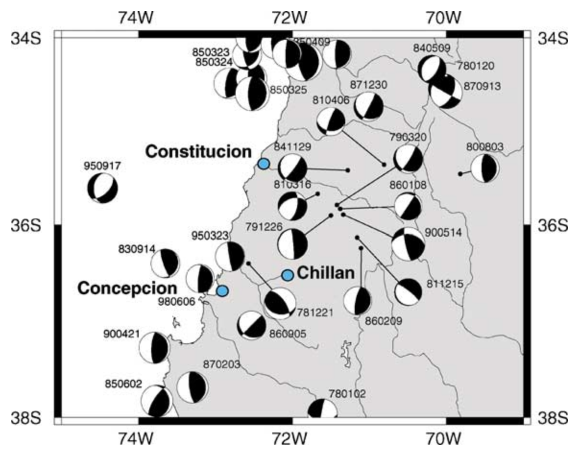

Fig. 4. Mechanisms of all the earthquakes contained in the centroid moment tensor catalog produced by Harvard covering the period from 1976–2000.

2. Seismic field experiment

From 1 March to 1 June 1996 a seismic field experiment was carried out in the Concepción–Constitución area (35–37° S) with the goal of studying the current seismicity of this region. A total of 25 portable, digital seismic stations were deployed recording in trigger mode. Time was periodically checked with GPS receivers. The stations are listed in Table 1 and shown in Fig. 2. The distribution of stations is homogeneous, with an average distance between sites of about 30 km. Quiet good quality sites were relatively easy to find in the coastal ranges that have granitic or granodioritic outcrops. In the central valley, on the other hand, where sediment cover is very thick at places, the best sites were found in isolated hills of the valley.

Table 1
Seismic stations deployed in the 1996 campaign

Station	Longitude	Latitude	Elevation
CAUQ	−72.39466858	−35.89466858	229
CAU2	−72.39783478	−35.89466858	273
PEHU	−71.10083008	−35.70283508	512
FLOR	−72.59183502	−35.56666565	165
CONS	−72.45549774	−35.36116791	88
CON2	−72.45383453	−35.36116791	235
NAME	−72.22566986	−35.74066544	402
PICH	−72.09566498	−35.49266815	426
ITAT	−72.81766510	−36.39016724	16
QUEL	−72.12633514	−36.08499908	230
VLSC	−71.81083679	−35.86883163	234
SNIC	−72.21666718	−36.52016830	100
SJAV	−71.77050018	−35.63916779	166
SNCL	−71.36299896	−35.56100082	277
QUIN	−71.42416382	−35.79616547	253
DIGU	−71.45766449	−36.23116684	450
NIPA	−72.59166718	−36.62799835	256
THER	−71.49266815	−36.91600037	1162
CARM	−71.96666718	−36.90000153	265
PINT	−71.77083588	−36.79666519	525
FLRD	−72.61916351	−36.79650116	52
TOME	−72.85766602	−36.63116837	391
SNFB	−71.53849792	−36.56000137	425
CACH	−71.72166443	−36.45750046	410
TORE	−72.32533264	−36.32149887	175
QUIR	−72.50433350	−36.28049850	585
COBQ	−72.80783081	−36.09749985	31
ARME	−71.09716797	−35.69866562	457

The network recorded almost continuous seismic activity directly under the stations. As we have discussed in previous sections, world wide data (Fig. 3), as well as the CMT catalog of Harvard University (Fig. 4), indicate a lack of activity near the coast of the Concepción–Constitución area. This is certainly not the case for smaller events as our results show a continuous distribution of seismicity that extends from the trench situated about 100 km off-shore all the way down to about 150 km under the Andes.

Of the thousands of events that triggered stations of our network, only a few were retained. Quality requirements for keeping an event in the final database were adjusted as the data was being processed. Finally, a set of 379 events was selected for hypocentral determination using the HYPO71program. Among these 379 events, 240 earthquakes were located with a root mean square (rms) residual less than 0.5 s, had more than 10 readings of either P or S wave arrivals, and with depth error less than 10 km.

The most difficult part of the earthquake location procedure is determining an appropriate P wave velocity model for the area under study. In Chile, where few stations work permanently, knowledge about the velocity structure of the crust and upper mantle is scarce. From experience gathered by the central Chile seismic network in Santiago and previous microseismic studies in South America (e.g. Cunningham et al., 1986) we decided to use a simple one dimensional model of the velocity structure. Locations obtained from such a model do not differ significantly from those computed with a more sophisticated 3D velocity model. Three different crustal models extracted from previous experiments in Chile were used as initial models. The S wave velocity models needed for location were derived assuming a constant v_P/v_S ratio of 1.752. This value was determined by averaging the t_P/t_S arrival times for all earthquakes at all the stations. It was later verified constructing a Wadati diagram from 3276 phases read for a selection of 88 earthquakes. The rms error of the v_P/v_S ratio is estimated as ± 0.0031.

Once the locations were computed with HYPO71, the VELEST program (Ellsworth, 1977; Roecker, 1981) was used to perform a series of runs following the procedure indicated by Kissling et al. (1994). The final structure and the final hypocenter locations of the best 240 shocks with rms less than 0.2 s are shown in Fig. 5 and listed in Table 2), respectively. Do to the unique nature of the data set, Table 2 will be available in electronic form (http://www.dgf.uchil.cl).

This final set of retained events is plotted on plan view in Fig. 6. The shocks in this figure are coded with a gray scale so that darker circles indicate deeper depths with a maximum of 180 km. It is clearly observed that the dominating trend is for earthquakes to get deeper the farther they are from the Peru–Chile trench. This trend of the seismicity is better defined by looking at the two vertical cross-sections, the lines A–A′ and B–B′ normal to the trench defined on Fig. 6. The cross-sections are shown on Fig. 7. We observe that the great majority of the seismicity aligns along a more or less narrow Wadati–Benioff zone that plunges with increasing dip angle below the central valley. This trend indicates that more than 90%of the events belong to the downgoing slab.

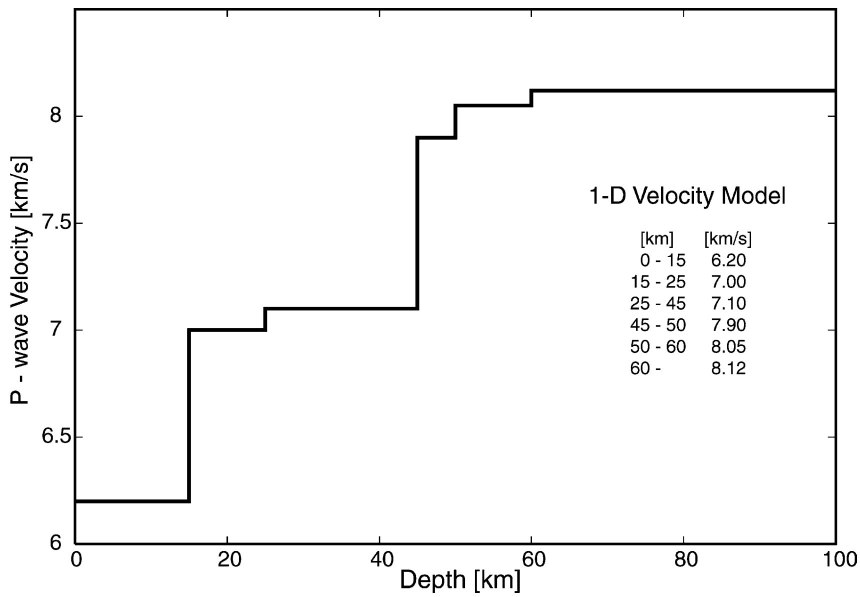

Fig. 5. The 1D velocity model obtained from the set of earthquakes located with our temporary seismic network.

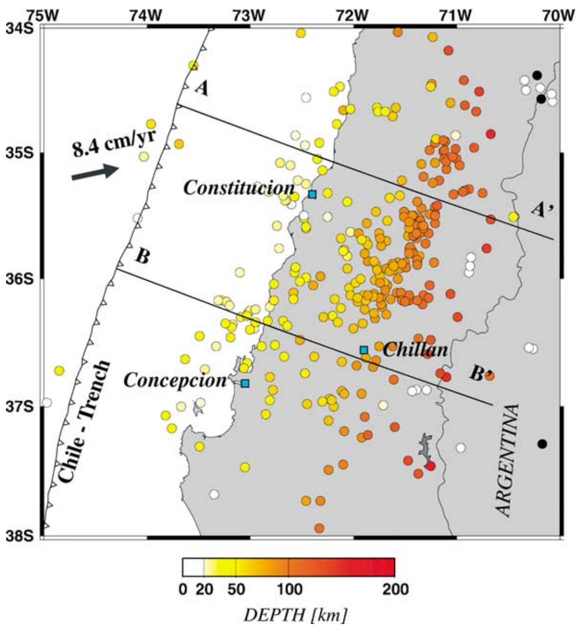

Fig. 6. Distribution of final selection of earthquakes obtained during our experiment in the Concepción–Constitución area. These events were very well located according to a set of different criteria. The two lines marked A–A′ and B–B′ are the orientation of the cross-sections plotted on Fig. 7.

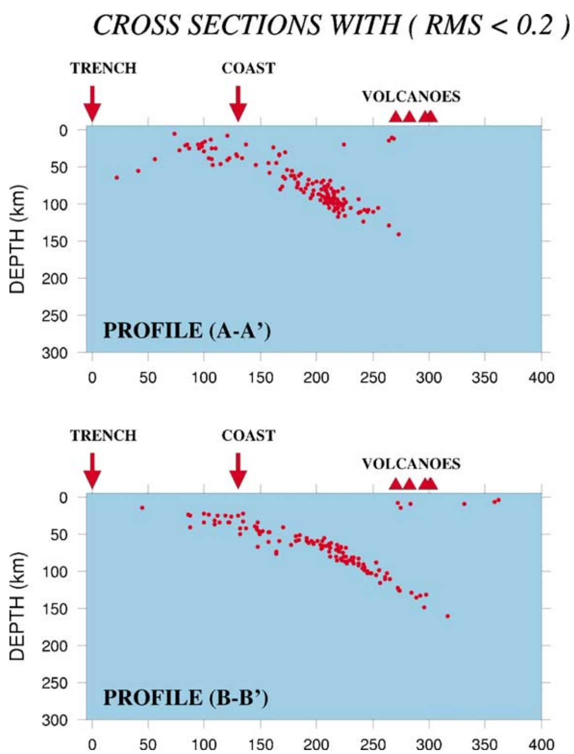

Fig. 7. Distribution of the final selection of earthquakes located during our experiment in the Concepción–Constitución area plotted along two profiles indicated on Fig. 6.

Table 2
Selected events from the 1996 campaign

Date	Time			Latitude	Longitude	Depth
	Hour	Minutes	Seconds			
22/3/1996	00	01	46.03	−71.74000	−36.13267	77.38
23/3/1996	02	34	24.76	−71.85033	−33.04483	128.92
23/3/1996	03	44	5.47	−71.86133	−35.56183	73.65
23/3/1996	21	01	18.40	−71.42200	−35.56900	91.09
24/3/1996	05	54	52.12	−72.35250	−37.72800	92.79
24/3/1996	15	54	58.28	−72.50750	−34.04483	57.88
24/3/1996	16	01	22.86	−72.37800	−36.04883	70.99
25/3/1996	02	54	42.17	−72.84333	−36.92433	38.23
25/3/1996	04	31	45.55	−73.97800	−35.01233	25.23
25/3/1996	09	34	30.46	−72.59033	−36.57400	40.11
25/3/1996	09	57	25.48	−71.35083	−35.63917	102.26
27/3/1996	03	45	19.71	−71.74800	−36.57267	88.57
27/3/1996	07	27	51.01	−72.79083	−36.75000	53.13
28/3/1996	00	26	10.96	−70.89750	−35.92167	5.96
28/3/1996	01	03	59.25	−71.78750	−34.70483	33.86
28/3/1996	10	43	1.73	−71.60233	−34.70450	67.21
28/3/1996	11	04	59.20	−71.75000	−34.63817	43.19
28/3/1996	12	09	12.85	−71.21550	−34.92850	98.45
28/3/1996	17	53	48.92	−71.52633	−34.04567	94.24
28/3/1996	19	47	21.72	−72.30450	−35.99183	72.45
29/3/1996	22	19	43.65	−71.49567	−35.46983	88.97
29/3/1996	22	42	50.66	−72.37300	−36.58850	53.71
30/3/1996	00	48	20.79	−71.35300	−35.49783	92.78
30/3/1996	02	11	4.48	−72.59817	−35.10117	22.45
30/3/1996	17	35	3.11	−72.67283	−36.33033	35.38
30/3/1996	18	43	30.32	−73.78350	−37.17517	32.58
30/3/1996	22	10	11.18	−73.80317	−37.05200	35.69
30/3/1996	22	26	46.32	−71.09817	−34.91933	100.57
31/3/1996	00	26	13.85	−74.13200	−35.53450	18.27
31/3/1996	01	04	37.55	−72.03900	−32.79367	118.72
31/3/1996	03	58	59.61	−71.03800	−33.43383	111.63
31/3/1996	05	21	48.90	−70.98450	−35.27767	111.54
31/3/1996	07	49	18.66	−71.11017	−33.73183	105.99
31/3/1996	09	16	15.08	−71.72450	−36.22217	82.00
31/3/1996	12	42	3.27	−72.10767	−34.44350	37.25
31/3/1996	16	41	18.74	−71.62750	−36.52483	95.24
31/3/1996	17	53	40.83	−72.12050	−36.63350	62.22
31/3/1996	23	09	59.34	−71.86483	−35.70417	59.71
1/4/1996	00	21	33.87	−70.98683	−32.13950	138.63
1/4/1996	00	31	42.55	−71.41950	−37.51717	126.25
1/4/1996	05	28	11.07	−72.75667	−35.76483	19.23
1/4/1996	05	56	32.61	−70.89533	−35.27850	108.57
1/4/1996	06	24	51.05	−71.77383	−35.90733	68.19
1/4/1996	08	47	40.05	−71.79683	−36.31917	83.56
1/4/1996	10	51	15.66	−72.28883	−36.30783	61.17
2/4/1996	10	15	18.04	−73.02650	−36.26667	25.46
2/4/1996	11	18	36.45	−71.37417	−35.58850	95.82
2/4/1996	13	46	4.23	−71.60050	−36.79583	104.15
2/4/1996	21	32	30.54	−70.15567	−34.34883	0.30
3/4/1996	00	56	59.68	−70.71133	−34.82867	154.45
3/4/1996	01	06	50.66	−70.91950	−34.42800	123.63

Table 2 (*Continued*)

Date	Time			Latitude	Longitude	Depth
	Hour	Minutes	Seconds			
3/4/1996	03	13	54.16	−73.08367	−35.95250	13.72
3/4/1996	17	53	40.56	−71.80033	−36.28350	73.92
4/4/1996	08	16	19.73	−71.46433	−36.16267	103.55
4/4/1996	12	20	55.93	−71.35600	−36.87100	4.69
5/4/1996	00	58	45.37	−72.05817	−35.92183	59.28
5/4/1996	01	56	27.93	−72.59867	−36.11783	62.11
5/4/1996	06	39	22.10	−70.69983	−35.76750	142.70
5/4/1996	17	39	44.69	−71.56017	−35.99933	85.26
5/4/1996	19	54	32.30	−71.38083	−35.84650	102.53
6/4/1996	02	23	49.49	−71.75850	−36.65517	90.67
6/4/1996	09	58	2.74	−72.94117	−36.38183	25.08
6/4/1996	10	47	16.02	−73.93850	−34.73700	52.35
6/4/1996	23	40	3.85	−71.26567	−35.60067	102.63
7/4/1996	02	27	21.59	−71.77367	−34.67633	40.47
7/4/1996	06	28	48.18	−71.02500	−35.03967	112.48
7/4/1996	15	23	24.40	−71.57567	−34.66850	63.65
7/4/1996	19	47	22.05	−71.27500	−36.46167	126.52
8/4/1996	07	55	34.98	−74.92783	−38.01233	18.36
8/4/1996	17	29	37.77	−71.54150	−35.27333	61.57
8/4/1996	18	19	26.58	−71.58000	−36.10467	90.30
9/4/1996	02	04	42.54	−70.38217	−32.22750	164.89
9/4/1996	05	10	1.27	−71.99567	−36.38233	66.19
9/4/1996	06	01	29.15	−71.68450	−35.90450	84.03
9/4/1996	11	34	2.11	−71.59967	−35.93433	75.54
9/4/1996	18	41	34.45	−72.37633	−35.03117	48.03
9/4/1996	19	53	38.51	−72.12333	−36.87917	70.77
9/4/1996	21	37	20.06	−71.58517	−35.83917	75.83
10/4/1996	03	58	21.42	−72.45417	−36.98333	58.93
10/4/1996	08	15	8.10	−71.20883	−34.46767	57.93
10/4/1996	09	22	43.23	−72.27633	−37.12250	66.66
10/4/1996	10	48	22.37	−71.39300	−35.68217	94.09
10/4/1996	23	23	33.07	−72.05500	−36.05267	61.49
11/4/1996	00	02	49.80	−72.76200	−36.53033	39.47
11/4/1996	01	25	48.98	−71.42000	−35.75950	100.62
12/4/1996	20	02	51.87	−71.40217	−35.65717	94.05
13/4/1996	13	26	52.31	−72.25167	−37.48867	91.88
13/4/1996	13	34	16.49	−71.44233	−35.73533	99.94
13/4/1996	14	43	22.02	−71.24683	−34.93800	101.89
14/4/1996	09	25	4.51	−71.74333	−35.65950	68.27
14/4/1996	10	58	50.86	−71.71550	−36.26067	81.88
15/4/1996	00	49	23.24	−71.18967	−35.39467	119.28
15/4/1996	01	59	27.72	−72.20800	−37.01617	61.76
15/4/1996	03	51	57.11	−72.18217	−36.29867	51.67
15/4/1996	16	25	4.06	−72.47717	−36.00167	45.20
15/4/1996	22	21	55.16	−71.92450	−37.05983	102.16
16/4/1996	01	07	35.75	−71.08850	−35.11217	104.32
16/4/1996	03	00	44.45	−72.16617	−34.79333	41.68
16/4/1996	06	18	56.80	−71.90100	−36.12317	64.79
16/4/1996	13	45	4.69	−71.68350	−35.70117	69.76
16/4/1996	23	37	20.58	−70.91050	−35.31933	110.61
17/4/1996	06	21	53.36	−71.45967	−35.64350	75.70
17/4/1996	07	16	4.83	−71.72717	−35.72917	80.80

Table 2 (*Continued*)

Date	Time			Latitude	Longitude	Depth
	Hour	Minutes	Seconds			
17/4/1996	09	48	26.95	−72.83917	−37.05150	43.27
17/4/1996	11	11	6.71	−73.25900	−33.60967	69.69
17/4/1996	11	46	49.81	−72.48183	−35.51267	40.55
17/4/1996	21	17	55.11	−72.28267	−31.13767	155.88
17/4/1996	21	44	2.02	−71.85450	−35.85750	78.70
17/4/1996	23	29	1.89	−72.08183	−36.89400	71.07
18/4/1996	00	46	18.07	−71.14650	−35.22000	106.61
18/4/1996	01	54	48.59	−70.84183	−34.64867	121.32
18/4/1996	11	02	36.27	−72.34383	−37.93283	109.26
18/4/1996	14	11	8.14	−71.35700	−36.19850	107.50
18/4/1996	18	52	13.25	−72.03050	−35.63083	15.24
19/4/1996	03	06	51.18	−71.37700	−35.61383	100.71
19/4/1996	10	34	24.21	−71.35017	−35.17950	95.21
19/4/1996	12	03	10.32	−72.64867	−35.36700	28.48
19/4/1996	12	18	53.50	−72.69750	−35.09767	17.67
19/4/1996	18	32	40.28	−71.60983	−35.89333	84.12
19/4/1996	20	25	13.81	−71.37917	−36.48167	105.02
20/4/1996	02	08	3.30	−72.51233	−34.86700	17.68
20/4/1996	03	53	54.76	−71.14817	−36.78650	150.69
20/4/1996	08	59	0.35	−75.01483	−36.95267	11.54
20/4/1996	09	27	4.84	−71.38250	−35.57533	94.05
20/4/1996	09	60	18.20	−71.24850	−35.22050	88.12
20/4/1996	10	37	50.31	−71.26617	−36.04050	108.55
20/4/1996	13	14	55.95	−71.12200	−34.97933	104.73
20/4/1996	13	31	52.51	−71.43350	−35.79583	98.56
20/4/1996	17	51	5.00	−71.19183	−35.55200	103.37
20/4/1996	21	21	59.68	−72.49717	−35.93633	34.62
20/4/1996	23	55	38.20	−71.35417	−35.59233	93.74
21/4/1996	04	04	54.14	−72.58333	−36.15950	43.69
21/4/1996	09	34	24.13	−71.10117	−34.90183	103.75
21/4/1996	10	59	15.71	−73.04500	−37.42767	42.02
21/4/1996	15	58	23.16	−70.86917	−35.89150	4.51
21/4/1996	18	20	25.91	−73.35033	−36.52500	12.81
21/4/1996	20	38	55.15	−71.46750	−35.79033	93.54
22/4/1996	00	57	36.50	−72.22750	−36.94500	60.19
22/4/1996	06	33	37.32	−72.22083	−36.96067	62.66
22/4/1996	07	09	7.11	−70.72333	−35.47667	130.91
22/4/1996	07	14	14.56	−72.11350	−35.68750	56.84
22/4/1996	07	54	35.61	−72.88567	−36.53817	41.18
22/4/1996	09	45	34.48	−71.96500	−36.17217	65.59
22/4/1996	10	06	7.29	−71.98100	−36.68483	87.37
22/4/1996	11	35	31.22	−69.74600	−31.91617	350.77
23/4/1996	05	05	31.14	−73.42717	−36.71400	19.10
23/4/1996	06	18	33.80	−72.50983	−35.92967	29.05
23/4/1996	06	59	25.10	−72.05350	−35.82117	26.19
23/4/1996	19	24	53.21	−71.81933	−36.12183	80.39
23/4/1996	19	30	52.08	−71.13417	−35.01867	100.92
24/4/1996	00	24	5.83	−71.96133	−36.03900	58.00
24/4/1996	03	21	19.59	−72.53833	−36.02550	46.93
24/4/1996	08	49	41.97	−71.32000	−36.12817	107.01
24/4/1996	08	52	42.88	−71.79633	−36.01600	68.03
24/4/1996	17	36	25.22	−71.95533	−35.64700	77.71

Table 2 (*Continued*)

Date	Time			Latitude	Longitude	Depth
	Hour	Minutes	Seconds			
24/4/1996	18	41	49.32	−71.93783	−36.91467	87.13
25/4/1996	06	29	27.06	−71.73717	−36.15450	88.67
25/4/1996	17	12	3.57	−73.57233	−34.32450	36.29
26/4/1996	05	38	59.30	−72.15067	−36.35217	56.39
26/4/1996	08	23	24.51	−70.50333	−33.47133	161.33
26/4/1996	08	35	58.83	−73.22617	−36.49183	26.21
26/4/1996	08	54	27.33	−71.41100	−35.64867	101.20
26/4/1996	09	16	27.69	−71.17667	−36.73050	136.81
26/4/1996	13	16	31.64	−71.83550	−37.25733	114.01
26/4/1996	19	06	43.61	−71.59683	−37.19583	119.79
26/4/1996	20	51	32.86	−72.65417	−36.38067	46.51
27/4/1996	00	52	25.24	−72.32467	−36.98633	58.22
27/4/1996	12	46	49.24	−71.65850	−35.93483	75.47
27/4/1996	14	44	42.07	−73.06117	−36.66967	34.72
27/4/1996	18	51	33.18	−71.37067	−35.84600	97.37
27/4/1996	21	46	54.74	−71.54967	−35.91767	82.77
28/4/1996	00	04	22.57	−70.96933	−36.29750	134.31
28/4/1996	02	39	6.15	−72.08917	−34.70167	69.63
28/4/1996	03	17	36.98	−72.25250	−35.28867	44.16
28/4/1996	10	55	45.40	−71.25550	−36.14533	111.35
28/4/1996	11	44	19.91	−71.81417	−36.14100	68.30
28/4/1996	16	45	27.37	−72.75500	−36.04783	36.18
28/4/1996	18	47	34.81	−71.42950	−36.87883	2.90
28/4/1996	20	58	23.35	−71.50333	−35.45883	93.51
29/4/1996	00	02	5.88	−71.53733	−36.14000	95.39
29/4/1996	20	11	27.21	−72.28850	−32.41567	127.76
29/4/1996	21	38	58.30	−71.34783	−35.06733	81.41
30/4/1996	04	31	29.91	−72.44917	−35.51667	8.33
30/4/1996	06	41	25.64	−71.86450	−35.72267	61.22
30/4/1996	10	21	34.65	−71.81367	−35.85450	65.85
30/4/1996	14	46	19.34	−70.33600	−31.62300	116.11
30/4/1996	16	17	23.91	−70.76617	−34.55350	144.32
30/4/1996	17	28	44.15	−73.02300	−36.40250	28.85
30/4/1996	20	18	38.00	−71.48700	−36.13050	102.49
30/4/1996	22	27	51.46	−71.37917	−35.87917	98.79
30/4/1996	23	47	48.34	−71.17650	−35.49500	110.72
1/5/1996	03	02	29.54	−72.46333	−35.57967	32.38
1/5/1996	04	31	29.69	−71.89100	−36.17317	66.09
1/5/1996	07	56	45.61	−73.71017	−34.93367	66.28
1/5/1996	11	41	7.55	−72.44033	−35.25250	18.70
1/5/1996	23	56	46.83	−71.52133	−37.39450	133.81
2/5/1996	01	51	27.85	−72.78717	−35.28500	12.51
2/5/1996	02	12	36.50	−71.13367	−34.97183	108.37
2/5/1996	03	42	18.49	−71.74183	−35.67550	80.84
2/5/1996	06	11	27.79	−72.76683	−36.17033	48.42
2/5/1996	08	20	16.47	−71.65683	−33.94683	94.06
2/5/1996	10	36	21.55	−71.38933	−35.51300	96.33
3/5/1996	00	55	43.12	−72.41650	−32.18033	99.91
3/5/1996	01	59	34.99	−72.12667	−37.42433	98.09
3/5/1996	02	03	4.36	−72.10817	−36.23417	55.07
3/5/1996	05	16	41.57	−71.22183	−37.49100	162.83
3/5/1996	08	01	46.99	−71.50883	−35.85233	90.40

Table 2 (*Continued*)

Date	Time			Latitude	Longitude	Depth
	Hour	Minutes	Seconds			
3/5/1996	17	50	20.15	−72.75100	−36.84800	50.68
3/5/1996	22	57	32.34	−71.53933	−36.10417	98.12
4/5/1996	04	42	55.31	−71.32683	−35.42183	93.12
4/5/1996	05	13	5.95	−72.02717	−36.12950	58.16
5/5/1996	01	04	22.79	−71.72000	−36.00100	69.58
5/5/1996	07	42	27.38	−72.97517	−36.25217	19.25
5/5/1996	10	00	13.49	−70.93650	−34.63200	126.01
5/5/1996	10	09	30.44	−72.94983	−36.25067	20.14
5/5/1996	18	21	51.89	−71.06217	−34.18800	134.72
6/5/1996	03	20	31.84	−70.99250	−35.09100	106.34
6/5/1996	06	28	13.84	−73.20517	−36.36633	20.51
6/5/1996	07	11	37.02	−71.35133	−35.60083	96.91
6/5/1996	09	15	53.13	−73.21667	−36.38567	27.52
6/5/1996	10	56	4.27	−73.23667	−36.35833	24.39
6/5/1996	16	40	37.52	−71.37900	−36.17750	99.86
6/5/1996	19	16	49.86	−70.21467	−33.22300	138.03
7/5/1996	00	58	54.24	−72.66917	−35.30633	15.82
7/5/1996	07	12	9.71	−71.78017	−35.44967	64.54
7/5/1996	13	17	12.90	−71.41317	−32.47667	129.50
7/5/1996	20	54	25.69	−71.34950	−35.34900	96.83
8/5/1996	10	23	47.98	−71.75917	−35.92367	70.76
8/5/1996	10	58	31.24	−71.41500	−35.50867	88.66
8/5/1996	14	27	33.34	−71.49617	−35.91217	98.55
8/5/1996	18	49	27.50	−72.82733	−36.32717	39.47
8/5/1996	23	50	34.58	−73.10067	−39.44583	146.87
9/5/1996	04	19	12.37	−73.03167	−36.30033	25.51
9/5/1996	04	59	42.63	−70.25067	−36.54550	1.32
9/5/1996	05	09	30.35	−70.27867	−36.54750	0.63
9/5/1996	05	37	36.05	−72.06100	−37.17483	89.45
9/5/1996	13	39	38.13	−70.95117	−35.33150	110.06
9/5/1996	22	50	1.12	−71.82250	−36.69883	88.30
10/5/1996	00	32	20.36	−71.52767	−35.87883	87.86
10/5/1996	01	27	34.09	−72.10300	−34.49833	38.69
10/5/1996	02	09	50.13	−72.50667	−35.18483	12.55
10/5/1996	04	45	26.84	−73.27833	−36.18367	16.27
10/5/1996	05	36	44.43	−72.05517	−31.99433	123.90
10/5/1996	06	11	22.17	−71.29733	−35.58233	97.43
10/5/1996	07	44	9.86	−71.51200	−35.46583	88.34
10/5/1996	08	03	20.95	−71.86867	−36.13533	78.09
10/5/1996	08	06	54.74	−73.74983	−38.21517	101.01
10/5/1996	14	58	8.69	−70.50850	−33.63050	184.48
10/5/1996	17	22	48.60	−70.74083	−33.39633	152.20
10/5/1996	17	48	6.41	−71.04517	−36.11850	130.11
11/5/1996	00	25	25.97	−73.62383	−36.62450	32.40
11/5/1996	00	29	52.08	−73.30083	−36.19467	31.38
11/5/1996	03	13	15.55	−71.31017	−36.84300	5.95
11/5/1996	17	23	50.76	−73.28567	−36.18750	13.22
11/5/1996	21	47	39.32	−70.29350	−34.44483	2.37
12/5/1996	02	51	58.36	−72.18600	−36.15883	56.76
12/5/1996	03	31	57.04	−70.15817	−37.27750	0.56
12/5/1996	05	01	3.99	−70.47683	−33.11817	160.42
12/5/1996	13	22	14.90	−71.09233	−35.01133	107.42

Table 2 (*Continued*)

Date	Time			Latitude	Longitude	Depth
	Hour	Minutes	Seconds			
12/5/1996	13	30	45.04	−73.51567	−33.75200	61.38
12/5/1996	18	15	16.59	−71.74233	−36.98117	8.92
12/5/1996	19	12	18.15	−71.91567	−36.00300	58.67
12/5/1996	19	47	35.07	−72.05017	−35.37767	47.82
12/5/1996	21	42	37.56	−73.26550	−36.20467	12.47
12/5/1996	22	15	46.69	−72.41833	−34.59367	2.01
13/5/1996	02	16	42.48	−71.63900	−36.15883	85.81
13/5/1996	07	49	22.91	−71.37950	−35.64650	99.30
13/5/1996	08	56	0.18	−70.97500	−34.95283	115.31
13/5/1996	10	17	11.72	−72.89033	−35.28683	0.59
13/5/1996	12	33	56.60	−71.24750	−35.48450	92.23
13/5/1996	20	53	31.23	−71.89650	−36.64883	75.21
13/5/1996	23	39	25.51	−71.52850	−36.17250	98.71
14/5/1996	03	57	43.14	−71.79267	−32.08700	114.37
14/5/1996	12	00	15.17	−73.48967	−36.97700	14.43
14/5/1996	16	34	46.37	−71.95800	−36.15617	62.13
14/5/1996	17	16	12.18	−72.08600	−35.77800	30.49
14/5/1996	17	19	6.32	−72.96967	−36.35800	23.65
14/5/1996	18	37	22.18	−71.53783	−35.21150	65.26
14/5/1996	23	34	34.95	−70.65317	−31.81800	121.24
15/5/1996	01	36	17.37	−71.46083	−35.59383	77.74
15/5/1996	01	54	15.29	−72.09733	−35.77533	29.90
15/5/1996	04	31	34.77	−71.28617	−35.73967	101.04
15/5/1996	04	42	6.70	−71.69333	−36.04200	66.91
15/5/1996	09	02	35.19	−71.68533	−36.08333	90.66
15/5/1996	11	40	0.82	−72.23683	−35.53533	12.51
15/5/1996	14	58	14.77	−75.45950	−39.31317	146.49
16/5/1996	14	23	20.35	−72.50500	−37.72017	82.51
17/5/1996	20	23	10.02	−71.71700	−36.03633	82.36
18/5/1996	02	45	35.34	−71.44500	−35.54667	88.0

The seismicity plotted in Figs. 6 and 7 is very similar to that of other parts of the Nazca plate subduction zone where subduction is so-called “normal”. The events define a narrow Wadati–Benioff zone of seismicity dipping with an angle of 35–40° that may be compared with that determined in northern Chile by Delouis et al. (1996), Comte et al. (1994), and Comte and Suárez (1995). We do not see in our vertical cross-sections of Fig. 7 any clear indication of a double seismic layer as reported by Comte and Suárez (1994) for a part of northern Chile. The double layer is well developed in northern Chile at depths greater than 150 km (Comte et al., 1999). Although the double seismic zone is not seen in our work, focal mechanism studies that will be discussed later, show some indications of its possible existence. In future work, relative location techniques will also be used to see whether there is any depth segregation.

Two other interesting features are observed in the seismicity plots of Figs. 6 and 7. White dots denoting shallow seismic events appear in two separate locations. First, shallow shocks align with the volcanic summit of the Andes. This is even more clear in the second vertical profile along line B–B′ of Fig. 7. In this profile, several small shocks appear isolated in the shallow crust very close to the volcanoes of the area. Earthquakes of this type are well known in central Chile near Santiago where an almost continuous activity affects a broad zone under the Andes mountains. Another interesting set of shallow earthquakes occurs near 35.5° S and 72° W. These events are very shallow and will be the subject of further discussion later in this study.

3. Earthquake mechanisms

We determined the source mechanisms for all the well located events. Unfortunately, it was not possible to obtain well-constrained fault plane solutions for all of them because in many cases the azimuthal distribution of stations was inadequate. This is generally true for many shallow focus events, except a few of them that we will discuss later.

For all the located events we computed take off angles using the velocity model of Fig. 5, and fault plane solutions were computed by hand. We could determine well constrained fault plane solutions for 32 events out of the 240 well located hypocenters (Fig. 8). These are events for which a minimum of eight reliable polarities were obtained and stations covered an azimuthal range of 180°. We distinguished three categories of mechanisms depending on the constraints on the fault planes. Category A comprises those events for which the two fault planes were constrained to better than 15°; category B if one plane was constrained to 15° and the horizontal plane was less accurate. This includes almost all the dip-slip events in our catalog. Finally, category C includes those events whose fault planes were not very well defined but such that the type of mechanism could be well determined. Only three events fall in this category and are in general agreement with the other events. In Fig. 8 we show the complete set of 32 fault plane solutions that we could determine together with the polarities that we read from vertical component stations.

The events for which we could determine well-constrained fault plane solutions (Fig. 9) are well distributed over the area of the experiment. The vast majority of these events belong to the main family of earthquakes located inside the Wadati–Benioff zone of the downgoing slab under Chile. This is better observed in the lateral view shown in Fig. 10 where we plot the mechanisms as they are observed from a viewer situated to the south of the profile. One of the most obvious features of this figure is the large number of dip-slip events, both thrust, slab-push or slab-pull events that occur in this area. The latter events are all inside the downgoing slab.

The most common type of mechanism in Fig. 9 is the slab-pull type of event. Events 5, 8, 10, 15, 19, 20, 22, 26, 28 and 32 have a sub-vertical fault plane, a compressional quadrant to the East and a horizontal fault plane so that their tensional axes are roughly aligned with the direction of subduction of the downgoing slab. These events are “slab-pull” earthquakes of the same type as inferred by Campos and Kausel (1990) and Beck et al. (1998) for the 1939 Chilean earthquake. Evidence for this type of event was found by Malgrange et al. (1981) and Malgrange and Madariaga (1983), and they seem to be ubiquitous along the whole Chilean subduction zone. Among our mechanisms there are couple of regular normal fault events with almost horizontal tension axes (12 and 13).

Five events (1, 3, 7, 9, 30) have also an almost vertical fault plane but they have a completely different polarity, with an extensional quadrant to the East. These events are typical “slab-push” earthquakes whose compressional axes are roughly aligned with the direction of slab subduction. These events have the same mechanism as the Punitaqui earthquake, about 300 km north of Santiago, of 15 October 1997 that was studied in detail by Lemoine et al. (2001). As observed in the lateral view of Fig. 10 events 1 and 3 are deeper than the main family of events. They may belong to a deeper part of the Benioff zone, hinting towards the presence of a double layered zone similar to that found by Comte and Suárez (1994) and Comte et al. (1999) in northern Chile.

A few other events (4, 6, 29, 17, 21 and 24) have reverse faulting mechanisms with compression axes that are roughly horizontal. Malgrange and Madariaga (1983) reported on a few of these events in northern Chile and they have been found lately in several other areas of northern Chile by Comte and Suárez (1994) and Comte et al. (1999).

Finally, a set of seven events (14, 16, 18, 23, 25, 27 and 31) of Fig. 8 form a conspicuous group of strike slip events. We may add event 2 at the bottom of the subduction zone but this event was category C, so that its mechanism is not very well determined. Of these the most unusual events for Chile are numbers 16 and 31, two rather shallow strike slip earthquakes. Since these events are quite unique and separate from the rest, they will be discussed in the next section. Of the other events the strike slip earthquakes 14, 18, 23,

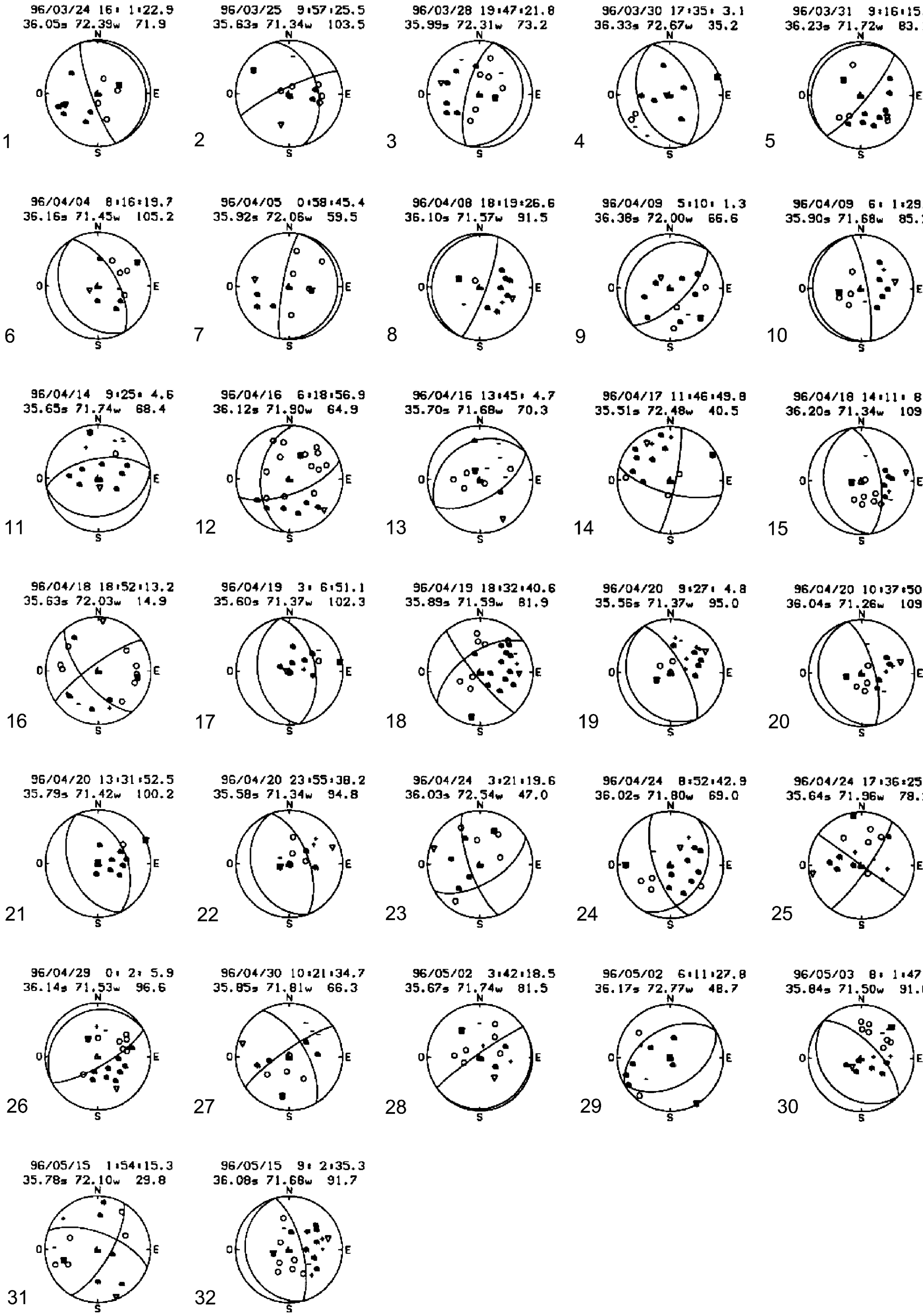

Fig. 8. Fault plane determination for the 32 events for which we could determine a fault plane solution. See Table 3 for parameters.

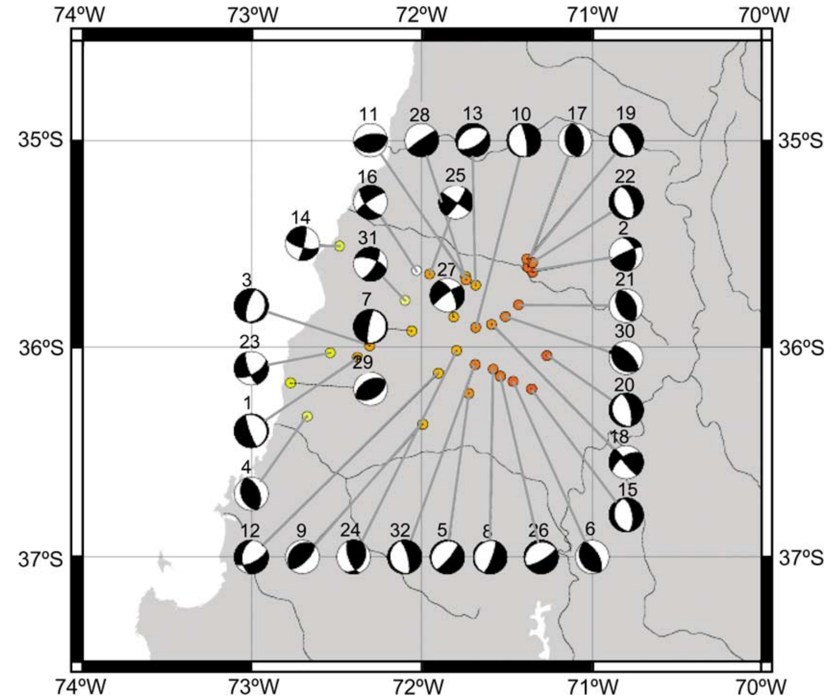

Fig. 9. The 32 fault plane solutions determined in the Concepción–Constitución from first motions of P waves. Normal and reverse dip-slip events are distributed quite uniformly in the area. A few interesting mechanisms dominated by strike slip motion occur near the coastal area. Identification numbers are from Table 3.

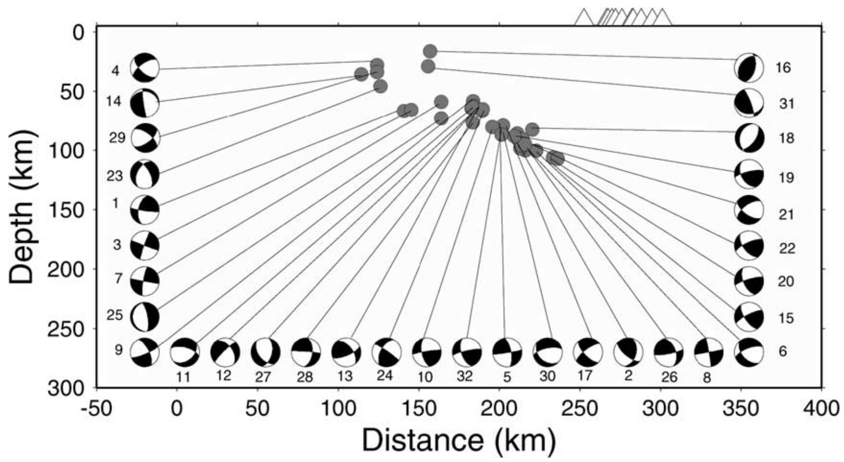

Fig. 10. Fault plane solutions plotted on a cross-section parallel to the direction of subduction of the Nazca plate. Most of the events, with a few conspicuous exceptions, occur along the inferred downgoing slab. See Table 3 for identification number. Cross-section of focal spheres are projected with wiever to the south.

25, and 27 are compatible with down-dip extension or slab-pull. Only event 2 is difficult to explain in this simple interpretation.

The pattern of seismicity and fault plane solutions revealed by our experiment as shown in Figs. 9 and 10 is fully compatible with the larger earthquakes as reported by the collection of centroid moment tensors (CMTs) from Harvard University shown previously in Fig. 4. In the CMT catalog all earthquakes under the central valley from 35 to 37° S are of the down-dip "slab-pull" just like the majority of ours. This agreement between the mechanism of large and small earthquakes is very interesting because it has frequently been said that small background seismicity does not give much information about large events. Here the small events recorded in our campaign, the CMT solutions for events of $M_W \geq 5.8$, as well as the very large Chilean earthquake all present the same "slab-pull" mechanism. Although longer-term observations are required, it seems to us that all available information tends to confirm the overwhelming domination of "slab-pull" as the dominating rupture mechanism in the Benioff zone of the Concepción–Constitución gap.

4. Study of two shallow crustal events

One of the most interesting and puzzling observations we made is the presence of two relatively shallow

Table 3
Fault plane solutions for 32 selected events

Event	Date	Time	Latitude	Longitude	Depth	az1	pl1	az2	pl2	Q
1	24/3/1996	16:01	−36.05	−72.38	71.0	160	80	340	10	B
2	25/3/1996	9:57	−35.64	−71.35	102.3	345	45	245	80	C
3	28/3/1996	19:47	−35.99	−72.30	72.4	195	70	15	20	B
4	30/3/1996	17:35	−36.33	−72.67	35.4	160	40	340	50	B
5	31/3/1996	9:16	−36.22	−71.72	82.0	40	80	220	10	B
6	4/4/1996	8:16	−36.16	−71.46	103.6	330	60	150	30	B
7	5/4/1996	0:58	−35.92	−72.06	59.3	190	80	10	10	B
8	8/4/1996	18:19	−36.10	−71.58	90.3	20	80	200	10	B
9	9/4/1996	5:10	−36.38	−72.00	66.2	45	65	225	25	C
10	9/4/1996	6:01	−35.90	−71.68	84.0	350	80	170	10	B
11	14/4/1996	9:25	−35.66	−71.74	68.3	80	30	260	60	B
12	16/4/1996	6:18	−36.12	−71.90	64.8	185	45	70	67	A
13	16/4/1996	13:45	−35.70	−71.68	69.8	60	60	240	30	A
14	17/4/1996	11:46	−35.51	−72.48	40.5	105	70	12	81	A
15	18/4/1996	14:11	−36.20	−71.36	107.5	350	60	170	30	B
16	18/4/1996	18:52	−35.63	−72.03	15.2	140	65	235	79	A
17	19/4/1996	3:06	−35.61	−71.38	100.7	350	50	170	40	B
18	19/4/1996	18:32	−35.89	−71.59	81.9	235	60	140	81	A
19	20/4/1996	9:27	−35.58	−71.38	94.1	330	70	150	20	B
20	20/4/1996	10:37	−36.04	−71.27	108.6	345	70	165	20	B
21	20/4/1996	13:31	−35.80	−71.43	98.6	335	45	155	45	B
22	20/4/1996	23:55	−35.59	−71.35	93.7	340	60	160	30	C
23	24/4/1996	3:21	−36.03	−72.54	46.9	60	60	160	73	A
24	24/4/1996	8:52	−36.02	−71.80	68.0	30	35	160	65	A
25	24/4/1996	17:36	−35.65	−71.96	77.7	35	80	305	90	A
26	29/4/1996	0:02	−36.14	−71.54	95.4	60	75	240	15	B
27	30/4/1996	10:21	−35.85	−71.81	65.8	235	80	330	63	A
28	2/5/1996	3:42	−35.68	−71.74	80.8	235	85	55	5	B
29	2/5/1996	6:11	−36.17	−72.77	48.7	60	45	240	45	A
30	3/5/1996	8:01	−35.85	−71.51	90.4	315	65	135	25	B
31	15/5/1996	1:54	−35.78	−72.10	29.9	30	70	290	64	A
32	15/5/1996	9:02	−36.08	−71.69	90.7	345	70	165	20	B

earthquakes, numbers 16 and 31 in Table 3, which were located at shallow crustal depths near the northern end of the study area. These events are located in the contact zone between the coastal cordillera and the central valley. Events of this type are very rare in other parts of Chile. Even in the Santiago area where a network has been in operation for nearly 30 years few events of this type are ever recorded. Most of the shallow activity near Santiago is similar to our "volcanic chain" events: It occurs along faults that run almost north–south at the limit of the piedmont of the Andes in front of Santiago. This is not the same as here, where our two events took place much closer to the coastal line as shown in Fig. 9. We studied these events very closely and we are confident that they are shallow. The shallow depth of these events was confirmed by a comparison of the recordings of event 16 with those of event 25. These two events have epicenters that are less than 4 km apart but have very different depths: event 16 had a depth of 15.24 km while event 25 had a depth of 77.7 km. The traces recorded for these two events are completely different: at station PICH situated about 15 km from the epicenter the S-P time is of a couple of seconds for event 16, but is about 9 s for event 25. A similar observation can be made at the SJV station that is almost at the same distance from the epicenter as PICH.

With the new depths and the locations determined from HYPO71 we recomputed the take off angles of P waves for the shallow events 16 and 31. Although most readings are for refracted phases (Pn) they are very consistent and clearly define two mechanisms that are dominated by right lateral strike slip components along faults oriented N20E or N30E. The mechanism is compatible with motion where the coastal range slips northwards with respect to the central valley. Several other shallow events were located near the bottom of the crust of our model at 45 km depth, although it may be that the depth computed for these events is biased by the particular crustal model used to locate them.

5. Conclusions

A seismic experiment was carried out in the south-central Chile subduction zone between the coastal cities of Concepción and Constitución. All the information we have gathered indicates that the last subduction zone event in this area took place almost 165 years ago in 1835. A very large and destructive event took place in January 1939 but recent studies of this earthquake by Campos and Kausel (1990) and Beck et al. (1998) indicate that it occurred inside the Wadati–Benioff zone at intermediate depth ca. 80 km. A good number of the intermediate depth events have large magnitudes and have produced significant damage. Some examples are the intraplate events of December 1950, Antofagasta ($M_W = 7.9$) in northern Chile with tensional focal mechanism at 100 km depth (Kausel and Campos, 1992); and the 28 March 1965 earthquake near Valparaí so studied by Malgrange et al. (1981). Recently, in October 1997, a magnitude 7.1 earthquake occurred in Punitaqui, north-central Chile, about 300 km north of Santiago. Results by Lemoine et al. (2001) show that this earthquake is also an intermediate depth intraplate event, but it had a very rare slab-push mechanism. Previous risk studies in Chile assume that all large earthquakes are of thrust type and are located along the coast. Some large intermediate depth intraplate earthquakes have erroneously been attributed to this category. A re-evaluation of seismic hazard in Chile, and probably other subduction zones, must be carried out in view of this new information.

The main result from our field experiment was that more than 90% of the earthquakes in the Concepción–Constitución gap during the two months of our experiment correspond to intraplate events that take place inside the subducted Nazca plate as it plunges under central Chile. Relatively few interplate events were detected in the main thrust zone between the Nazca and South American plate. The other subset of earthquakes occur at shallow depth near the volcanic zone of central Chile. These events are somewhat eccentric with respect to our network so that they were poorly determined and we could not compute source plane solutions for them. A very interesting result is the existence of shallow earthquakes occurring inside the crust under the central valley near the coastal ranges. This kind of event is very rare in Chile. More than 15 years of careful observations in northern Chile reported by Delouis et al. (1996) shows practically no events of this type that could be associated with the Atacama fault. In central Chile, near Santiago, where a permanent network monitors the seismic activity, shallow earthquakes west of Santiago are almost nonexistent. In the Concepción–Constitución area no major active fault is known to exist near the contact between the central valley and the coastal ranges so that the shallow events with strike slip mechanisms that occurred there during our experiment are candidates for further study, once a permanent network of stations starts working in Chile. Finally, this study confirms the 1835 seismic gap recently suggested by Campos and Kausel (1990) and Beck et al. (1998).

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