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Final Report

THE SEISMIC CYCLE IN CHILE: EVOLUTION AND MONITORING

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Abstract

We present a general description of the Concepción Constitución seismic gap and the problem posed by the seismicity of the area, in particular the nature of the $M = 8.3$ earthquake of January 1939. Then we summarize the work carried out in the framework of a contract between the European Union, represented by researchers from France (IPG in Paris and University Joseph Fourier in Grenoble) and Italy (University Federico II of Naples) and Chile, represented by CONYCIT and the Department of Geophysics of University of Chile.

From March 1 to May 31, 1976 a field experiment was carried out in the Concepción Constitución region during which we deployed a seismic network of 26 short period instruments provided by the French participants (mostly Grenoble). Data processing carried out by young Chilean researchers has been extremely successful: we could locate a group of 262 high precision hypocenters with location errors estimated at less than 50 m and rms travel time residuals of less than 0.20 s. A study of residuals for all earthquakes at each of the stations shows rms residuals that are everywhere less than 0.20 s for the events retained in the final set. For a subset of 31 events we could determine very well constrained source plane solutions. The large majority of earthquakes occurred along the so-called Wadati-Benioff zone, 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 that occur further North near Santiago in the Las Melozas seismic nest. Another very small group that took place at the boundary between the Coastal Ranges and the Central Valley will be discussed below.

Accurate fault plane solutions could be computed for 31 of the 262 well located events. Most of the earthquakes located on the Wadati-Benioff zone have the so-called "slab-pull" fault mechanism. Fracture in these events appears to be due to *tensional* stresses sub-parallel to the downgoing slab whose origin may be found in the the excess weight of the cold oceanic slab as it descends under Chile. This "slab-pull" mechanism is the same as that of 8 earthquakes of magnitude around 6 for the period 1980-1998 that are listed in the CMT catalog of Harvard University in the region under study. This is also the mechanism inferred by Beck and coworkers of the large 1939 Chillán earthquake. A few events of the Benioff zone had "slab-push" mechanisms in which the *pressure* axis of the fault plane solution was aligned with slab. These events are found in double layered Benioff-zones like in the North of Chile or Japan. Unfortunately our spatial resolution is not enough to detect the presence of a double layer, but we suspect there may be one. Another type of much rarer events were detected during our experiment: these are shallow events shallow strike slip events near the contact zone between the coastal ranges and the Central Valley. These events are very rare indeed and require further study because of the seismic risk that they may represent.

A first step in the set up of a GPS network for the measurement of displacements and strains in the Concepción Constitución was carried out in December 1996. The network will be measured again in March 1999. Soon later we will have the first information about deformation in the gap.

1 Introduction

Chile is one of the most seismically active countries of the World. On average a destructive earthquake of Magnitude larger than 8 has occurred every 10 years in the historical period that extends from the beginning of the 18th century. Many of these earthquakes produce extensive economical damage and life losses that have counted several times into the thousands. Figure 1 shows a synopsis of the very largest events that have occurred along Chile in the last 130 years. The ellipses represent rough estimates of the rupture zones of the largest earthquakes that occurred in this period of time. Although several of these earthquakes require a careful reevaluation, the most impressive result is that every single segment of the country has been the site of at least an event of magnitude 8 in this period of time. Since the early seventies, several sites along the coast were pin pointed by seismologists (see Nishenko, 1985 for a recent statistical evaluation) as probable sites of future large events. Among them at least one of these sites was successfully identified by several authors, including Lomnitz (1970,) Kelleher (1972), Kelleher et al (1973), McCann et al (1979), as well as Nishenko (1985). Although no actual time prediction was made by these researchers, Central Chile near Valparaíso suffered a large magnitude $M_w = 8$ earthquake on March 5, 1985. This event has been widely presented as a success of the so-called gap-method. We shall discuss the seismicity associated with this region later in this report. Another earthquake of magnitude $M_w = 8.1$ occurred South of Antofagasta on July 31, 1995. This event took place on a zone that had been considered either aseismic (Lomnitz, 1970; Compte et al 1994a, 1994b, 1998, Dorbath et al, 1996 and Delouis et al, 1996), or lacking adequate historical information; the reason being that most of northern Chile was uninhabited until the middle of the 19th century and, therefore, there is little information on past earthquakes.

Thus, although Figure 1 encapsulates most the current knowledge of large earthquakes in Chile, it is terribly deficient in many respects. Foremost of them is that, since Chile lacks a complete seismic network, the current seismicity of several of these "seismic gaps" (places where an earthquake is likely to occur) is unknown. Without an accurate knowledge of this seismicity there is little chance that once a seismic gap has been identified, a useful time prediction may be issued or that elementary precautions be taken in anticipation to a very large event. In order to improve this state of affairs, European seismologists from several institutions in France, Germany and Italy decided to contribute to the study of Chilean seismicity. Among these groups, geophysicists from Strasbourg, Paris, Berlin and Potsdam have actively participated in the study of the two northernmost seismic gaps, those where the last large earthquakes occurred in 1968 and 1977, respectively.

Our proposal, that obtained the support of the European Community, was to study the seismicity of another obvious seismic gap, that of South Central Chile which had the last subduction earthquake of magnitude 8.5 on February 20, 1835. This gap had been overlooked in some previous studies because a major shock, the Chillán earthquake occurred there on January 25, 1939. This is probably the most damaging seismic event in Chile's seismic history. Recent work by Kausel and Campos (1950), Barrientos (1992), Ponce et al (1994), Beck et al (1998) has shown that this earthquake was not a subduction event but an extensional shock in the interior of the Nazca plate as it subducts bellow Chile. It is remarkable that Gutenberg and Richter (1941) had already determined that the depth of this event was larger than 70 Km and that it occurred under the central Valley of Chile, not under the accretionary prism in the contact zone between the Nazca and South American plates. It is clear that if our hypothesis withstands the test of observations, the Concepción-Chillán area with a population of the order of a million people and the second largest industrial, agricultural economic pole in Chile is in serious danger of suffering a future destructive event of Magnitude greater than 8.

The purpose of our work, based on a cooperative effort between the department of Geophysics of University of Chile and the Seismology Departments of IPG in Paris, the University Joseph Fourier of Grenoble and the University Federico II of Naples, is to study in some detail the current seismicity of what we will call the *Concepción Constitución gap*, that is the area from 35°-37°S along the Chilean coast that, at least in our interpretation, has not experienced a large subduction earthquake since 1835. This final contract report covers our work of the last three years, several of the studies we initiated will continue under Chilean, French, German and European support. This is specially the case for the GPS survey and the installation of local seismic stations. It is very likely also that a group of American researchers headed by T. Wallace from the University of Arizona will also work on the seismicity of the Concepción Constitución gap in the years to come.

2 Seismicity of the Concepción Constitución area

Due to its curious geographical situation (Chile extends for more than 4000 km with only 150 km width on the average), the Chilean population is very unevenly distributed. Thus, the Northern deserts are sparsely populated although some industrial development in the last few years has attracted a burgeoning population to the coastal cities of Arica, Iquique and Antofagasta. On the other hand Central Chile from Valparaíso to Puerto Montt is home to most of Chile's 14 million inhabitants. Thus from the point of view of seismic risk, there is obvious urgency to study in detail the seismicity and seismic risk of the most densely populated area of Chile: the 1000 km from Santiago to Puerto Montt. This southern part of Central Chile was the site of the largest earthquake ever recorded: that of May 13, 1960 of a magnitude larger than 9.75 (see Figure 1 and the studies by Plafker and Savage, 1970; Cifuentes, 1989; Astiz and Kanamori, 1986; Barrientos and Ward, 1990; and Barrientos et al 1992). This earthquake produced a tsunami that destroyed practically all the coastal towns south of Concepción until the island of Chiloé. The port of Puerto Montt was also heavily destroyed although it is situated far from the open Oceans. In spite of its huge size many questions remain open about this event that require investigation because of the increasing seismic risk in a country that is rapidly developing and resettling its population around several urban centers in the south central regions of Chile. As seen from Figure 1 the 1960 bounds from the South the Concepción Constitución gap. Two other important magnitude 8 earthquakes immediately to the North of the Concepción

Constitución area are those of 1985 south of Valparaíso (Korrat and Madariaga, 1986; Compte et al, 1986); and that of Talca of December 1, 1928 (see Greve, 1964; Lomnitz, 1971; Beck et al, 1998), this event is less well-known although it destroyed most of the coastal areas north of 35.5°S. This event bounds the Concepción Constitución gap from the North; so that our study area is a well defined by major events to the North and South of it. It remains to elucidate the origin of the January 24, 1939 earthquake.

The Chillán Earthquake of January 24, 1939

In the gap between 1928 and 1960 took place the January 25, 1939 Chillán earthquake, the most deadly of all modern Chilean earthquakes. This very large and destructive earthquake event occurred at a time when Chile had practically no seismic instruments. This sad state of affairs was recognized by the committee that studied the damage produced by the earthquake. According to newspapers and historical data studied by Urrutia and Lanza (1993), the number of deaths due to the earthquake is close to 15000, although some journalists put the toll at 30000. The main damage was concentrated around the cities of Chillán (Intensity X), Parral (IX) and Cauquenes (IX). In Concepción, on the coast, the earthquake had an intensity of only VII, much less than in the central valley. A map of isoseismals drafted by Greve (1964) is shown in Figure 2. Intensity in this map is unfortunately measured in the old Chilean scale, in which intensity VI corresponds roughly to XI in the more common Modified Mercalli scale. It clearly shows that most of the damage was concentrated far from the coastal cities. Campos and Kausel (Personal Communication) collected some seismograms from this earthquakes and arrived at the same conclusion as almost every other author that has looked at this event: the 1939 earthquake was probably of the same type as that of March 28, 1985 at La Ligua, about 50 km North of Valparaíso and of the recent October 17, 1997 earthquake near Ovalle, about 200 km North of Valparaíso. Malgrange et al (1981, 1983) demonstrated that there are two types of large destructive earthquakes in Chile: the most common ones are the large events that occur at the frictional contact between the Nazca plate as it descends under the South American plate under Chile. The other type of destructive events are those of tensional type that take place *inside* the downgoing slab (the Nazca plate) at intermediate depths under the Coastal ranges and Central Valley of Chile. The location and mechanisms of these two types of events are shown in Figure 3, as well as that of those that occur beyond the trench. Malgrange et al identified a number of these kind of earthquakes, a result that was later confirmed by Kausel and Campos (1992), Compte and Suárez (1994) and, recently, by Beck (1998).

Thus our initial hypothesis, based on scarce seismic data, was that this event was not a subduction zone earthquake, but a rather deep event that took place in the oceanic plate being subducted under Chile. Two lines of evidence have recently come to confirm our initial hypotheses: First, in a little known note to their famous paper on the seismicity of the earth, Gutenberg and Richter (1941) determined the depth of this earthquake as 70 km from depth phases recorded at Pasadena. Second, recently Beck et al (1998) have studied records of the 1939 this earthquake from Europe and North America and determined its depths as 80-100 km and an almost vertical normal fault. If this is actually the case the 1939 did not break on the plate interface zone between the 1928 and 1960 earthquakes. In that case, as we believed when we started this project, the Concepción Constitución area is the oldest seismic gap in Chile, with its last large earthquake dating back to 1835. This was an event of Magnitude grater than 8.5 that almost completely destroyed Concepción and that was carefully studied by Darwin (1851).

Depth of the 1939 earthquake

The depth of the 1939 Chillán earthquake was determined by Gutenberg and Richter (1941) in a note to their famous paper on the seismicity of the earth. Reference to their depth determination somehow escape the attention of several authors that assumed that the 1939 earthquake was a typical interplate thrust earthquake like most other events of $M_w > 8$ in Chile. The depth of the of the January 24, 1939 Chillán earthquake was recently redetermined from body waveform modeling by Beck et al (1998). They concluded that the earthquake occurred between 80 and 100 km of depth and that it took place under the central valley. They not only determined depth but got a very reasonable source plane solution as shown in Figure 4 from the modeling of several North American stations. This mechanism, as well as a study of surface waves by the same authors, confirms that the 1939 event took place on an almost vertical fault plane with a very steep dip towards the West. This mechanism is almost the same as that of the 1985 earthquake near La Ligua that was studied by Malgrange et al (1981, 1983). This tends to confirm our hypothesis the 1939 event belongs to the intraplate family of earthquakes due to extension along the downgoing slab as shown on Figure 3.

Where did the 1960 earthquake stop?

The second important issue for a complete evaluation of the seismic risk in the Concepción area is to define the northern extension of the rupture zone of the huge $M > 9.3$ event of May 1960. Although many scientist studied in detail the rupture zone of this event, including Plafker and Savage (1970), Cifuentes (1989), Barrientos and Ward (1990), Barrientos et al (1992), Vita Finzi and Mann (1994) and many others, they concentrated their efforts mostly on the central part of the fault area, where large permanent coastal upheaval of up to 12 m was observed. The Northern end of the earthquake is much poorly known because it is situated in a very sparsely populated area of the former province of Arauco South of Concepción. Most authors agree however that rupture did not extend North of the Mocha Island near the Arauco Peninsula. A very clear indication that the 1960 earthquake stopped well South of Concepción is that several large events of $M \simeq 7.0$ took place near the Arauco Península in 1974-1975. Those events were clearly of thrust type.

The extent of the 1928 earthquake

The Talca earthquake of December 1, 1928 destroyed the coastal towns from Constitución in the South to Pichilemu in the North and produced heavy damage in the central valley cities of Talca, Curicó and San Fernando. This event was the object of careful study by Bobillier (unpublished manuscript from University of Chile, 1930). The isoseismals drafted by Greve are shown in Figure 5. It is clear from this Figure that the Talca earthquake did rupture along the plate interface from about 34°S down to at least 35.5°S, somewhat South of the city of Constitución. This is confirmed by the description of the damage reported by Urrutia and Lanza (1993), who claim that most of the city of Constitución was destroyed by the earthquake producing the emigration of almost half its population. In their recent reevaluation of large Chilean earthquakes, Beck et al (1998) recovered three seismograms at stations KEW, DBN and TNT and used them to determine the depth and mechanism of this event. From their bodywave modeling they determined an M_W magnitude of about 7.9, less that that usually quoted in the literature. According to these authors, the 1928 event was a shallow dipping thrust event with a centroid depth less than 20 km. From an analysis of intensities and the duration of the P-wave train they concluded that the 1928 Talca event had a rupture area of about 50 to 90 km. Thus, from every point of view this events looks like a twin of the 1985 Valparaíso earthquake that ruptured an area extending from Valparaíso on the North to Pichilemu in the South. This pair of $M = 8$ events plus the $M = 7.6$ event of July 8, 1971 cover the complete rupture zone of the much larger Valparaíso earthquake of August 20, 1906. (See Korrat and Madariaga, 1986; Compte et al., 1986, etc).

Historical seismicity of the Concepción Constitución gap

The historical seismicity of central Chile has been studied by numerous authors including Darwin (1851), Perrey (1854), Montessus de Ballore (1912-24), Greve (1964), Lomnitz (1971), Compte et al (1986) and Beck (1998), among many other authors. From their painstaking analysis of local reports, geological information, levelling changes, seismic data, etc, we have reconstructed the seismic history of the Chilean subduction zone from 30°S to 37°S in Figure 8. The horizontal lines indicate, for each earthquake, the length of the respective rupture zone as inferred by these authors from all sort of data including local damage, perturbation of rivers, lakes, elevation of coastal sites, tsunami magnitudes, etc. Although most of this data is not quantitative enough, the rupture extents are agreed upon by most recent authors (see, e.g., Compte et al, 1986, Madariaga, 1998 and Beck, 1998). The area of study, from 35-37°S, has suffered at least 3 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 has had no major subduction earthquake since 1835. The 1939 earthquake as discussed previously did not take place in the interface. Knowing that subduction occurs at a rate of about 8 cm/yr in this zone, a total deficit of slip of close to 11 m has accumulated in the area surrounding the city of Concepción since 1835. This is worrisome enough to warrant further detailed surveillance of the area. A continuous monitoring of the seismicity is obviously necessary in addition to the limited duration analysis as presented here. All the information gathered by many authors thus points in the same direction: the Concepción Constitución area is an ancient seismic gap with a great potential for a large earthquake in the future. The problem is how to estimate how close are we from this future rupture. Without any local seismic, geological or geodetic data this analysis is difficult to carry out. We hope that our experiment will attract further work in the area.

Recent seismicity of the Concepción Constitución gap

The South-central Chile seismic zone has been relatively quiet from the seismic point of view since the great earthquake of May 23, 1960. As our field experiment shows this relative calm is probably only apparent; we believe that it is most likely due to lack of local station coverage of the area. Only earthquakes well recorded by world wide seismic stations appear in the catalogs; this puts a lower bound for the completeness of the catalog at Magnitudes greater than 5. However, if the seismicity in the gap was confirmed to be low, then the Concepción Constitución gap would also be a quiescence zone. As Mogi and Fedotov showed, many areas in the world go through periods of seismic quiescence before large earthquakes. Thus the question arises whether the Concepción Constitución gap is quiet because it is expecting a large earthquake soon; or is it quiet because we are in the aftermath of a large earthquake and therefore the Concepción Constitución area will be quiet for a long time? This is of course not a simple question to answer when the seismic station coverage is as poor as that of southern Chile. Some elements of response may be found in the observation of Astiz, Lay and Kanamori (1988) and Kausel and Campos (1992) that the seismicity of regions with seismic gaps migrates down the slab in the interseismic period when the subduction interface is locked. This was clearly the case in Central Chile near Valparaíso where several large intraplate earthquake occurred inside the down-going slab before the 1971 inter-plate earthquake. The event of March 28, 1965 that occurred inside the down-going slab was very destructive and is considered as one of the worst events of the Valparaíso area of Central Chile.

The seismicity of the Concepción Constitución area is currently monitored by the Chilean stations in the central Valley near Santiago, a few isolated stations in South Central Chile and Argentinian stations in Mendoza province. This is clearly inadequate for such a seismically active country. One probable reason for this sparse coverage is the lack of seismic activity felt by the population. Discussing with authorities, inhabitants of the area before our experiment we reached the conclusion that earthquakes have not occurred at all in the area since 1939 or 1960. Yet, a seismic activity is clearly detected by world wide network of seismic instruments and a clear, yet not critical, increase in seismicity has been detected in the area. Just before the installation of the network two events of $M = 4 - 5$ occurred near the town of San Javier at the Northern edge of the study area. These events as well as others that occur everywhere in Chile are described by the earthquake information sheets issued after every felt earthquake by the Chilean Seismological Service based at the Department of Geophysics of the University of Chile. During the experiment itself 3 medium sized events felt by the population took place on the area of the experiment. As an example, the corresponding information sheets are included in Figures 6 and 7.

The recent level of seismicity of earthquakes of Magnitude greater than 4.5 located by the Seismological Service of the University of Chile is shown in Figure 9. Notice the obvious concentration of activity near the northern end of the area. Most of these events are aftershocks of the earthquake of 3 March 1985 that took place near Valparaíso. The locations are also biased by the denser seismic network that monitors the seismicity of the central valley from 32°S to 34.5°S. The seismic activity seems to pick up again south of Concepción (37°S), this are most likely aftershocks of a series of events of $M_W > 7$ that occurred south of the Arauco península (the large bay near 37.3°S) between 1975 and 1984. Thus the Constitución-Concepción area appears to have a lower seismicity than the surrounding areas to the North and South. These locations have to be evaluated carefully because their poor quality is obvious from this picture where events are scattered from 70°W to 75°W. Our results will show that activity is much more concentrated above the Central Valley; this lack of longitudinal control is due to the concentration of seismic stations to the North of the area. These stations control distance relatively well but lack azimuthal resolution so that the actual location of most of these events is very large. Also, because depth phases like pP and sP are rarely used in these locations there is a very poor depth control on the locations. However, in spite of these biases it is quite clear from Figure 9 that although the activity of the Concepción Constitución is weak it is by no means negligeable.

A better estimate of the seismicity of the zone can be obtained from the recent homogeneous catalog of relocated earthquakes computed by Engdahl et al (1996). These authors retained in their catalog only well located earthquakes with location errors of less than a few hundred meters and determined depth from readings of depth phases (pP and sP). The seismicity for the area from 30°S to 40°S contained in their catalog is shown on Figure 10. The seismicity of the Andes is strong enough that a clear picture of variations of activity along the coast of Chile are clearly observed. Compared to the seismicity determined from local data shown in Figure 9, the seismicity appears to be much more homogeneous with a smooth transition from North to South. An obvious effect of using well controlled locations is that seismicity tends to concentrate in a narrow band along the coast and the Central Valley of Chile. The increase of depth of the seismicity as the subducted plate descends bellow Chile is also clearly evidenced by the gray scale that describes depth. Shallow events (white) only occur near the trench but are very rare, and in the vicinity of the volcanic axis of the Andes. All other shallow events occur in Argentina in the Northern part of the province of Mendoza. Events in the Concepción Constitución area are mostly concentrated on a narrow band of intermediate depth (deep gray) events. Coastal earthquakes are rare specially between 34.5 and 36°S where the December 1, 1928 earthquake occurred. The same clustering of aftershocks of the 1985 earthquake North of 34.5°S as well as that around the Arauco península is observed as in the seismicity determined by the University of Chile shown in Figure 9.

Thus the much better data of Engdahl et al (1996) shows the same features as the local earthquake locations: it is clear that *the region between 35.5°S and 37°S is a place of relative quiescence of shallow seismicity.* This is even more spectacularly shown in Figure 11 where the seismic moment tensors of all available earthquakes since 1980 are shown. Clearly 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 extremely conspicuous since this is the only area of Chile where such a quiescence can be observed. On the other hand, a frequent activity is observed at depth in the CMT catalog as shown by the 8 mechanisms for intermediate depth events shown along the Central Valley. This alignment of events correspond very precisely with the same North South line of activity clearly observed in Figure 10.

All these observations clearly indicate that the source area of the 1835 earthquake between Concepción and Constitución is a place where a large event has been missing for a long time, almost 164 years, and where current seismicity is relatively weak at least since the early 70s. These features are typical of potential seismic gaps, regions where an earthquake is missing and where seismic quiescence has been detected.

This is the reason we decided to propose this experiment to the European Community. The seismicity as shown in Figures10 and 11 may be very biased because it only represents relatively large well located events. We suspected that a weaker shallow seismicity was not being detected by the worldwide network of seismic stations and may be giving a false picture of the seismicity. This was the main purpose of our experiment: to determine the precise depth of this background seismic activity. It is quite important to understand whether these events are crustal, occurring inside the overriding South American plate or whether they occur near the interface of the down-going slab and the continental plate. In other areas of Chile the crustal activity is weak but significant, it appears that as we move towards the South of the central valley seismic province the crustal activity diminishes and all local earthquakes occur inside or on the boundary of the subducted plate. It is also very important to find out what is the nature of the mechanisms of the events shown in Figure 10. Without this knowledge it is impossible to tell whether the activity is located in the plate interface that would then be unlocked or inside the down-going slab as it slowly reaches its breaking point.

Figure captions

Figure 1: Source areas of the largest $M > 8$ Chilean earthquakes of the last 130 years. Each dark ellipsoidal patch defines the estimated source area for these events.The estimated source area of the 1939 earthquake is indicated by a white ellipse.

Figure 2: Isoseismals for the large Chillán earthquake of 24 January 1939 in South Central Chile dressed up by Greve (1964). The isoseismals are closed inside the central valley of Chile, suggesting that this event occurred somewhere under the valley and is not a typical subduction event like most of those shown in Figure 1. Intensity is measured in the old Chilean units in which intensity VI corresponds roughly to XI in the more common Modified Mercalli scale.

Figure 3: Vertical cross-section through the Chilean subduction zone showing the top of Nazca plate as it subducts under the South American plate. Couples of large $M > 7.5$ were identified by Malgrange and Madariaga (1984) at several sites along the Chilean coast. Some of these events are typical shallow thrust subduction earthquakes occurring at the interface between the two plates, for instance the 9 July 1971 earthquake in the bottom section. Others are almost vertical normal faults that take place inside the

down-going slab (subducted Nazca plate)

Figure 4: Mechanism of the January 25, 1939 earthquake in Chillán as determined by Beck et al (1998)

Figure 5: Isoseismals for the large Talca earthquake of 1 December 1928 in South Central Chile dressed up by Greve (1964). Except for Chilean Intensity V, isoseismals are open to the Ocean, suggesting that this event is a typical subduction event like most of those shown in Figure 1. Intensity is measured in the old Chilean units in which intensity V corresponds roughly to IX in the more common Modified Mercalli scale.

Figure 6: Earthquake Information Sheet issued by the Department of Geophysics after the small but felt event of 9 April 1996. This was the second of four large events that took place during our field experiment. All of them took place on what we believe is the source area of the 1939b Chillán earthquake.

Figure 7: Earthquake Information Sheet issued by the Department of Geophysics after the small but felt event of 26 April 1996. This was the third of four large events that took place during our field experiment. All of them took place on what we believe is the source area of the 1939b Chillán earthquake.

Figure 8: Time-space plot of the large earthquakes that took place along the Chilean subduction zone from 30°S to 37°S. The earthquake rupture zones, inferred from local damage data as well as field observations by numerous authors, are indicated by the horizontal lines. The whole area has ruptures repeatedly since 1647, the largest earthquake being that of 1730. The area of the Chillán 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 (see Figure 3).

Figure 9: Seismicity of $M > 5$ in the Concepción Constitución since 1970 as determined by the Geophysics Department of Universidad de Chile in Santiago. The large number of shocks to the North end of the area is due to the aftershock activity following the $M = 8.1$ Valparaíso earthquake of 3 March 1985. The region between 35.5°S and 37°S is identified as a potential seismic gap, i.e. a place where a large event is missing for a long time.

Figure 10: Seismicity of $M > 5$ in the Concepción Constitución since 1980 determined from the new seismic catalog of Engdahl et al (1996). The large number of shocks to the North end of the area seen in Fig 9 has now disappeared but the Concepción Constitución still looks less seismic than the rest of Central Chile.

Figure 11: Mechanism of all the earthquakes containing in the Centroid Moment Tensor catalog produced by Harvard covering the period from 1980-1998.

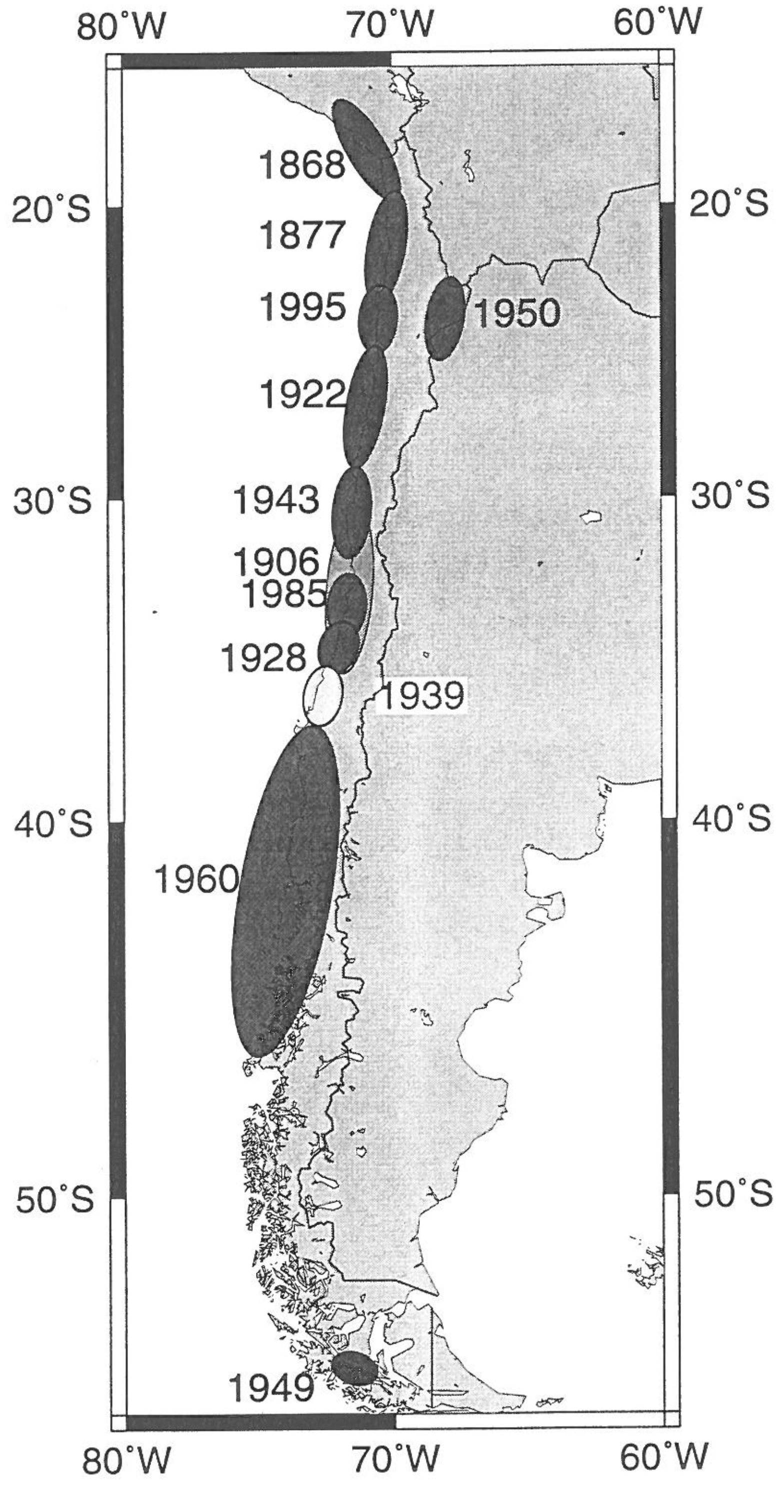
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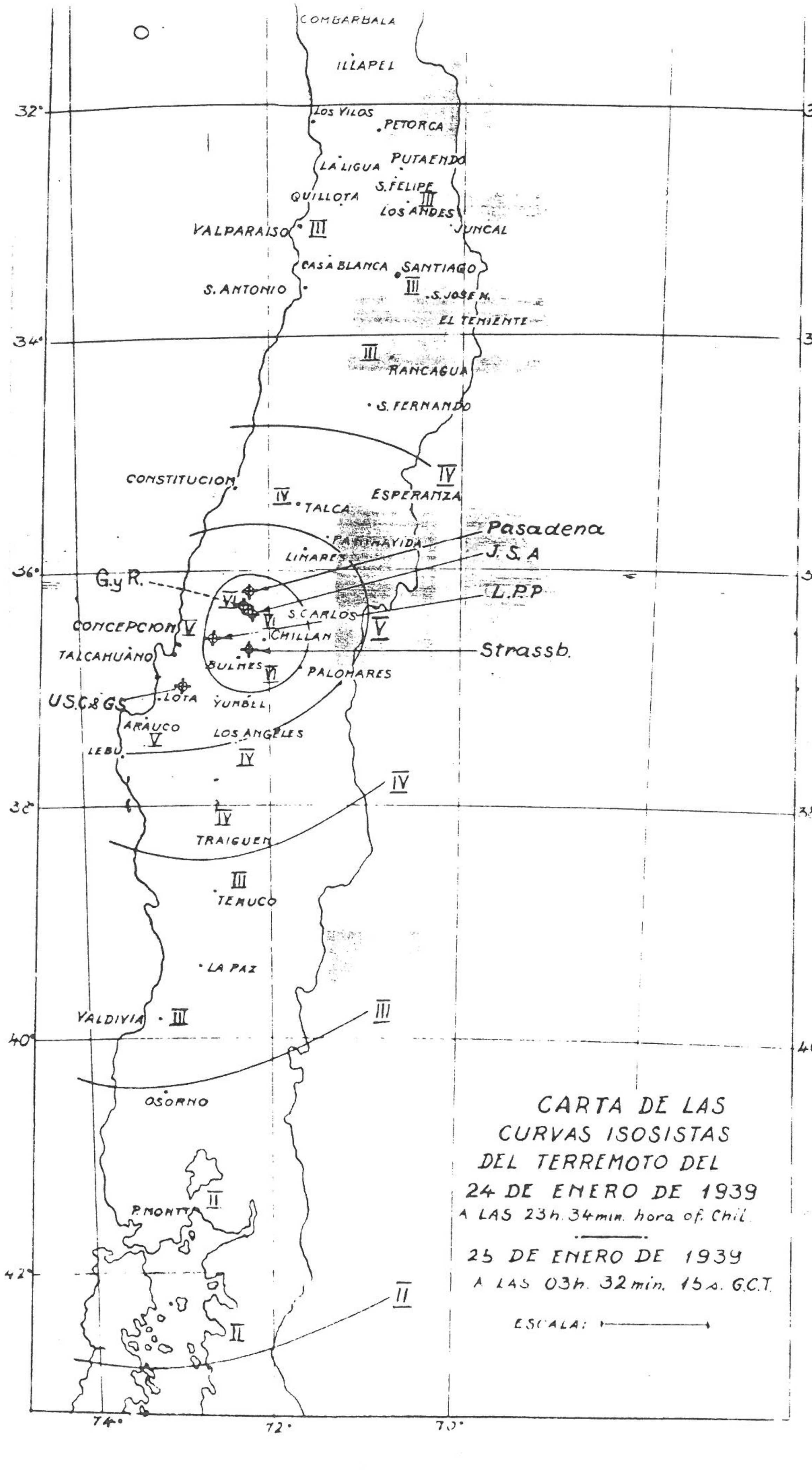
Fig 1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II
II
ESCALA:
74°
72°
70°

Fig 2

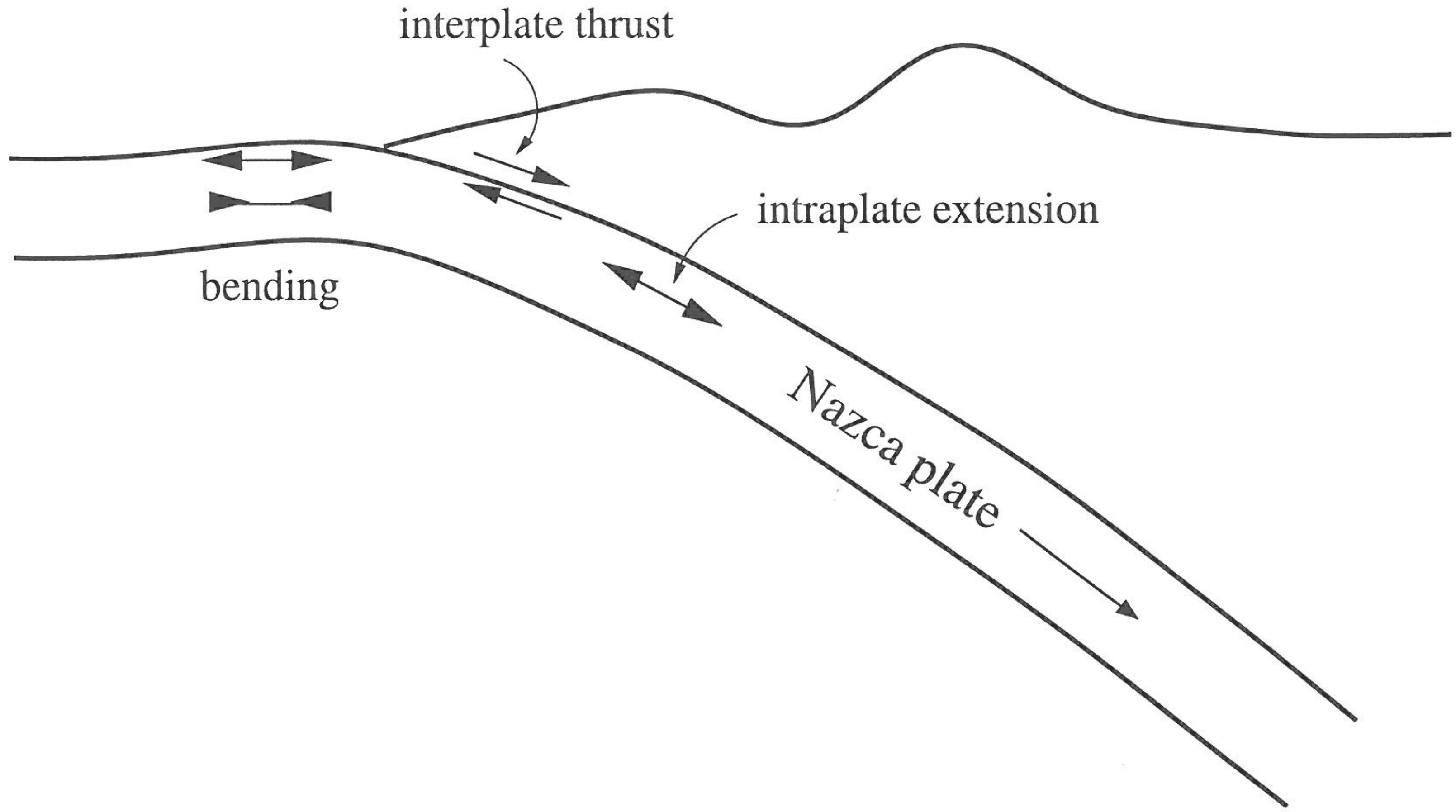
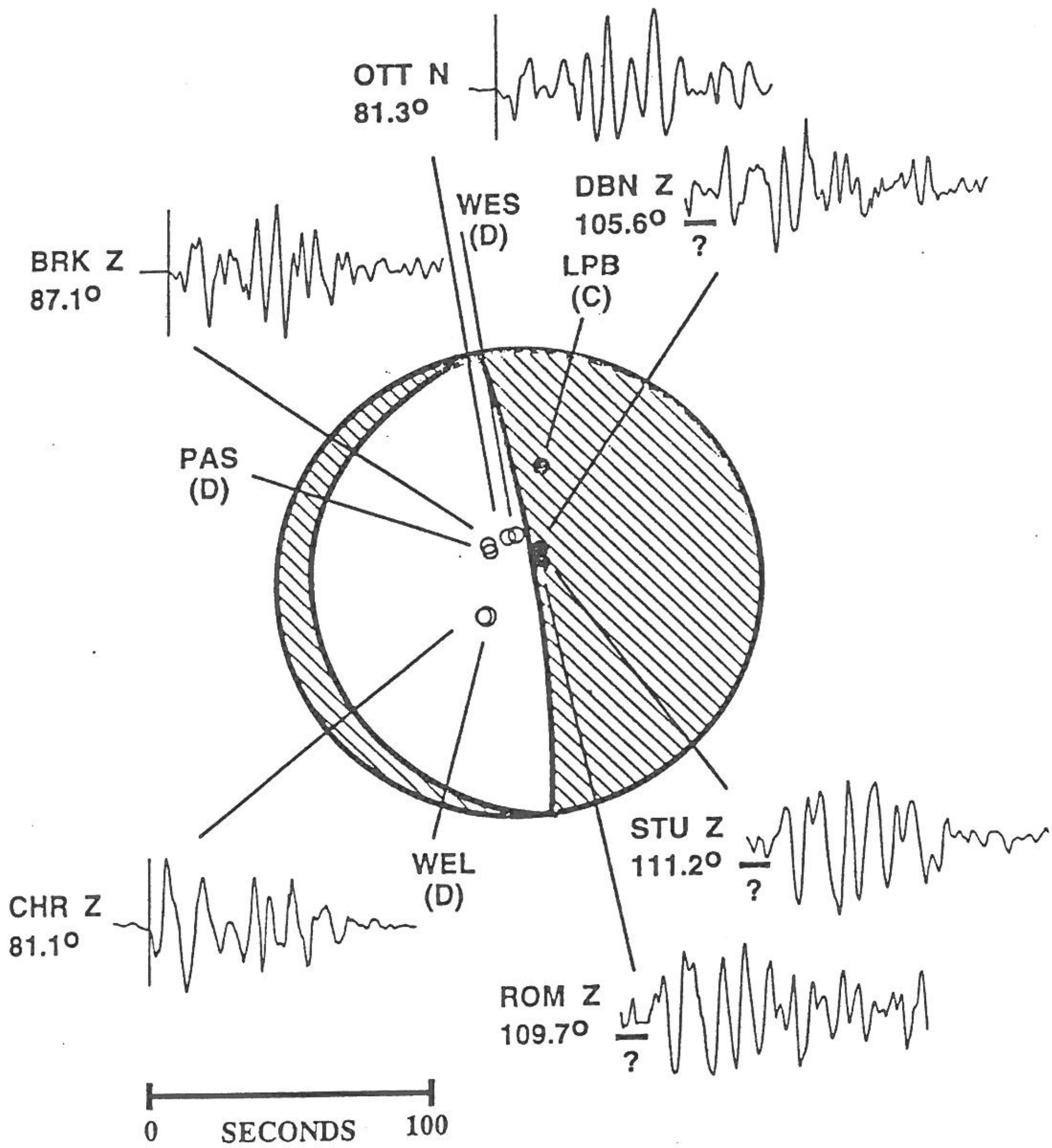

interplate thrust
intraplate extension
bending
Nazca plate

Fig 3

CHILE 1939 EARTHQUAKE



FROHM BECK ET AL (1998)

Fig 4

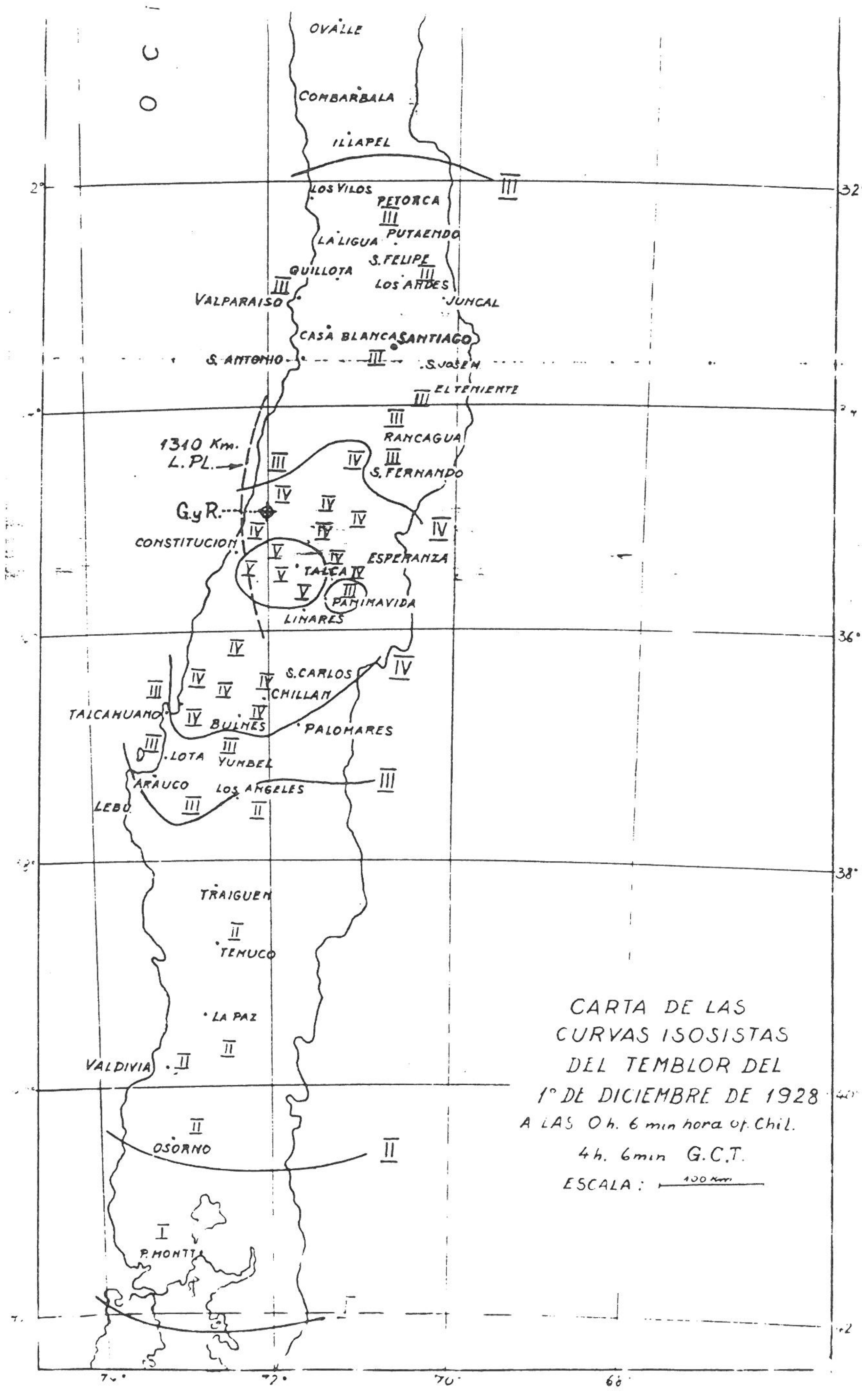

OVALLE
COMBARBALA
ILLAPEL
LOS VILOS
PETORCA
LA LIGUA
PUTAENDO
S. FELIPE
QUILLOTA
LOS ANDES
JUNCAL
VALPARAISO
CASA BLANCA
SANTIAGO
S. ANTONIO
S. JOSE
EL TENIENTE
RANCAGUA
1310 Km.
L. PL.
S. FERNANDO
G. y R.
CONSTITUCION
ESPERANZA
TALCA
PANIMAVIDA
LINARES
S. CARLOS
CHILLAN
TALCAHUANO
BULNES
PALOMARES
LOTA
YUMBEL
ARAUCO
LOS ANGELES
LEBU
TRAIGUEN
TEMUCO
LA PAZ
VALDIVIA
OSORNO
P. MONTT
32°
36°
38°
70°
CARTA DE LAS
CURVAS ISOSISTAS
DEL TEMBLOR DEL
1° DE DICIEMBRE DE 1928
A LAS 0 h. 6 min hora of. Chil.
4 h. 6 min G.C.T.
ESCALA: 100 Km.

Fig 5

DEPARTAMENTO DE GEOFISICA
UNIVERSIDAD DE CHILE
Blanco Encalada 2085 - Casilla 2777
Teléfonos: 6784298 - 6966563 - Fax 56-2-6968686
E-mail: sismoguc@dgf.uchile.cl
SANTIAGO - CHILE

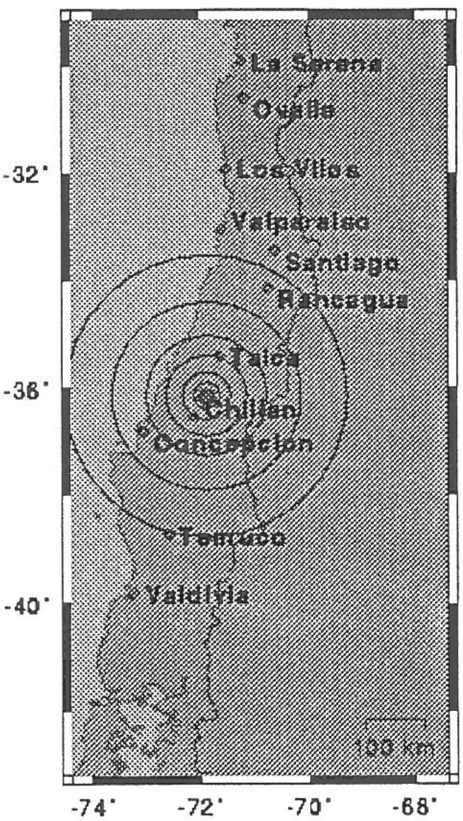
SERVICIO SISMOLOGICO
INFORME DE SISMO

Fecha: 09 de Abril de 1996
Hora Local: 15:17:44.4

HIPOCENTRO

- Hora UTC: 19:17:44.4 09/04/96
- Latitud: 36 ° 09.3 ' Sur
- Longitud: 71 ° 53.7 ' Oeste
- Profundidad: 137 km
- Magnitud (Richter): 4.6
- Fuente de Información: DGF

REFERENCIAS GEOGRAFICAS:
06 kilómetros al Oeste de PARRAL.



INTENSIDADES

Escala de Mercalli. Fuente: ONEMI

- Parral : IV
- Linares : III-IV
- Constitución : III
- Talca : III
- Cauquenes : II-III
- Chillán : II-III
- Concepción : II-III
- Curicó : II
- Chanco : II
- Los Angeles : II

Fig 6

DEPARTAMENTO DE GEOFISICA
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E-mail: sismoguc@dgf.uchile.cl
SANTIAGO - CHILE

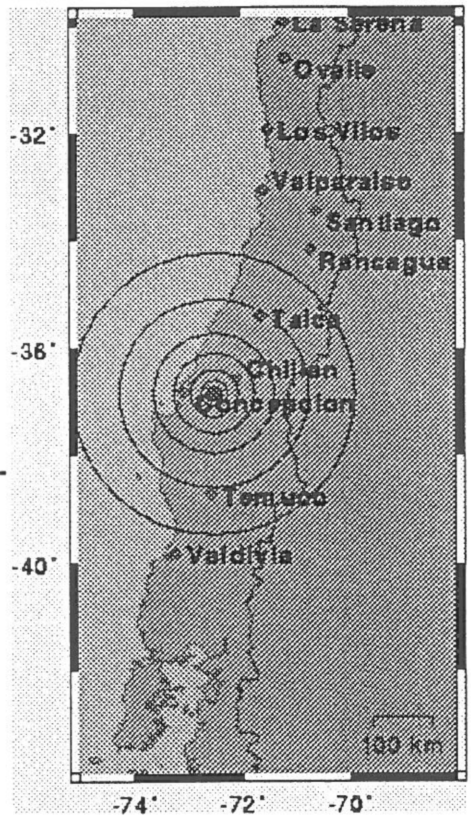
SERVICIO SISMOLOGICO
INFORME DE SISMO

Fecha: 26 de Abril de 1996
Hora Local: 09:16:33.4

HIPOCENTRO

- Hora UTC: 13:16:33.4 26/04/96
- Latitud: 36 ° 50.7 ' Sur
- Longitud: 72 ° 31.6 ' Oeste
- Profundidad: 40 km
- Magnitud (Richter): 4.5
- Fuente de Información: DGF

REFERENCIAS GEOGRAFICAS:
46 kilómetros al Este de CONCEPCION.



INTENSIDADES

Escala de Mercalli. Fuente: DIREMER 8a.Reg.

- Concepción : III
- Angol : II-III
- Ranaico : II-III
- Los Angeles : II

OBSERVACIONES:
No se reportan desgracias personales ni daños materiales.

Informe preparado por:
H. Massone(SAN)
Servicio Sismológico.

Fig 17

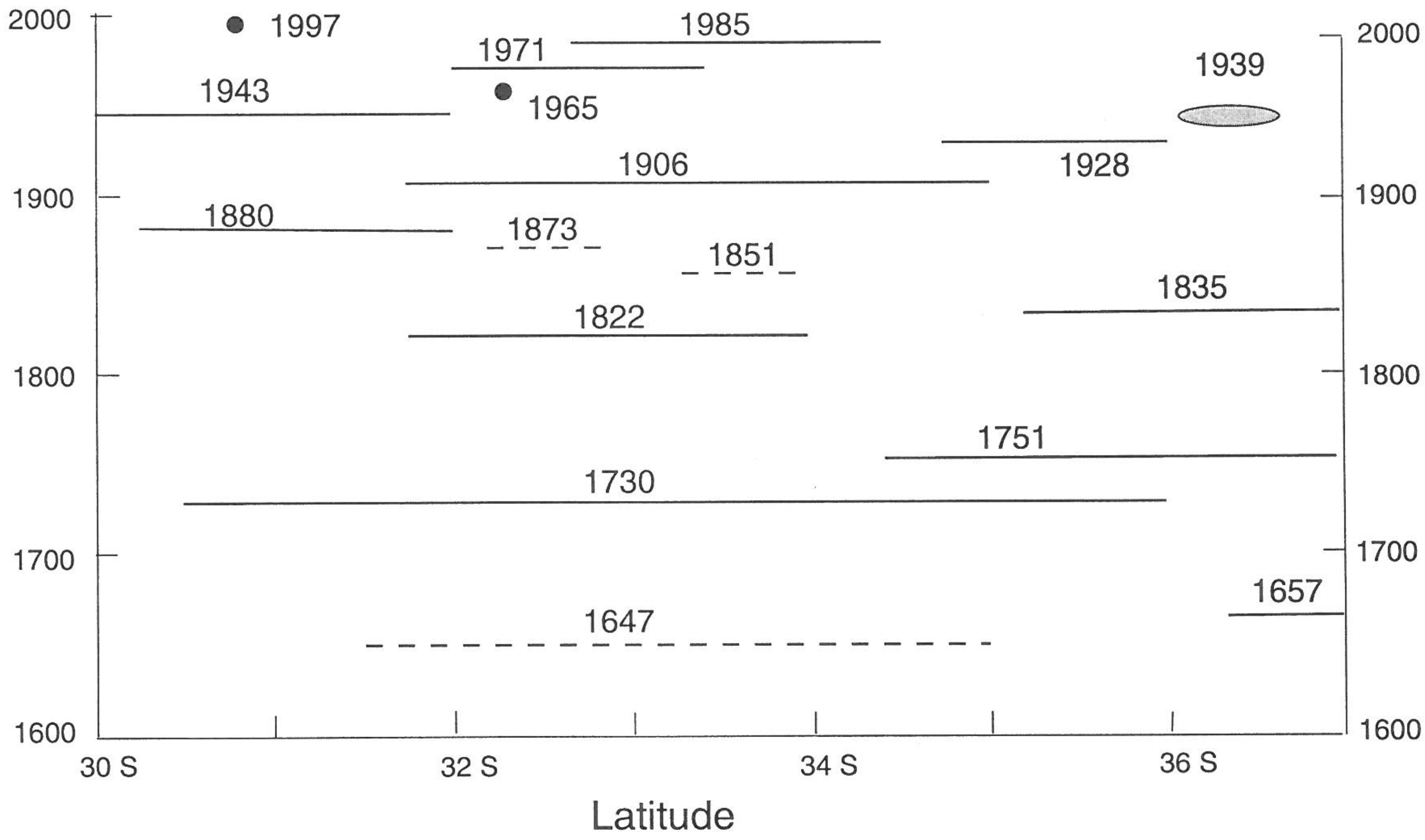

2000
1900
1800
1700
1600
1997
1943
1971
1965
1985
1906
1880
1873
1851
1822
1730
1647
1939
1928
1835
1751
1657
30 S
32 S
34 S
36 S
Latitude

Fig 8

Seismicity 1970-1995

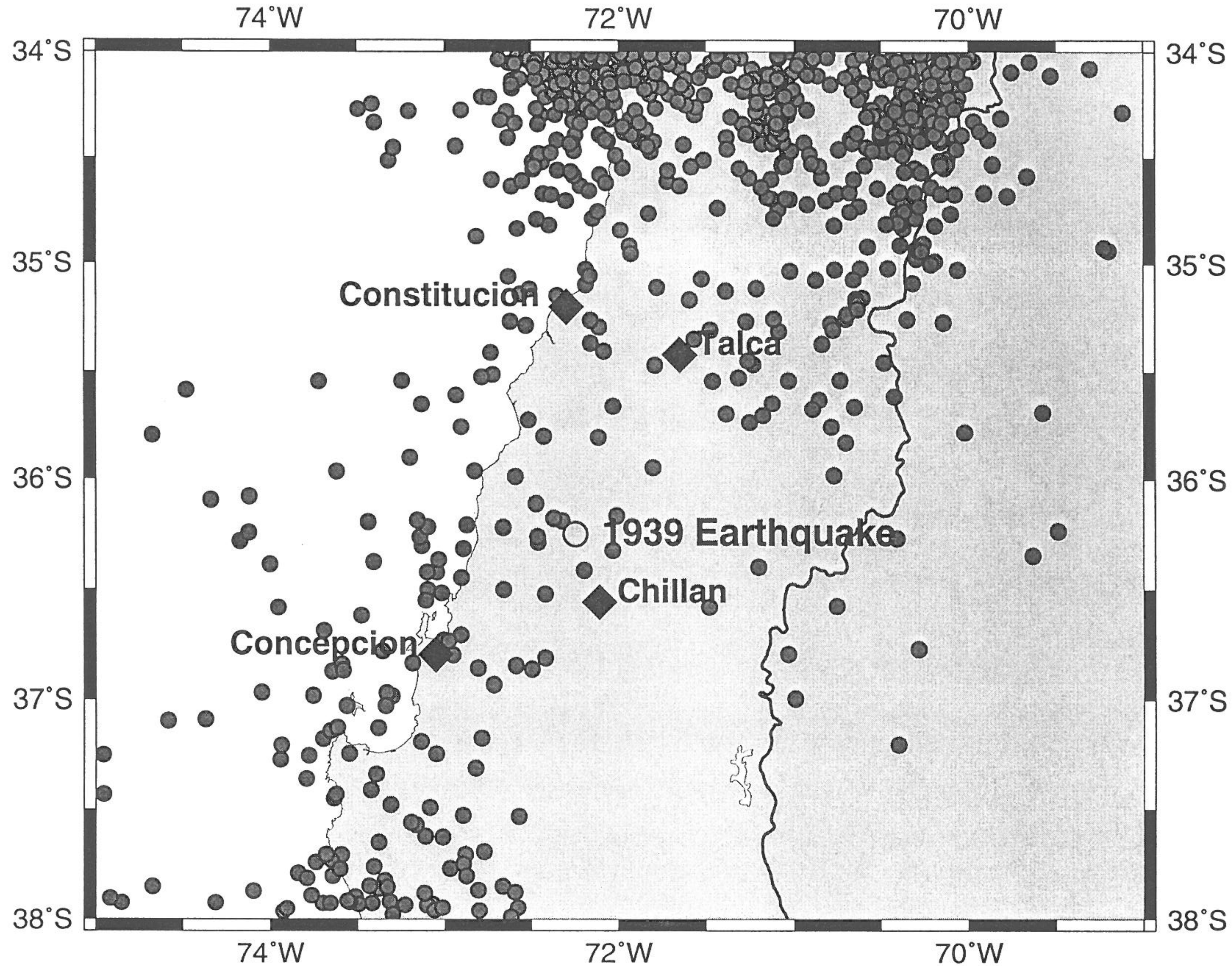


Fig 9

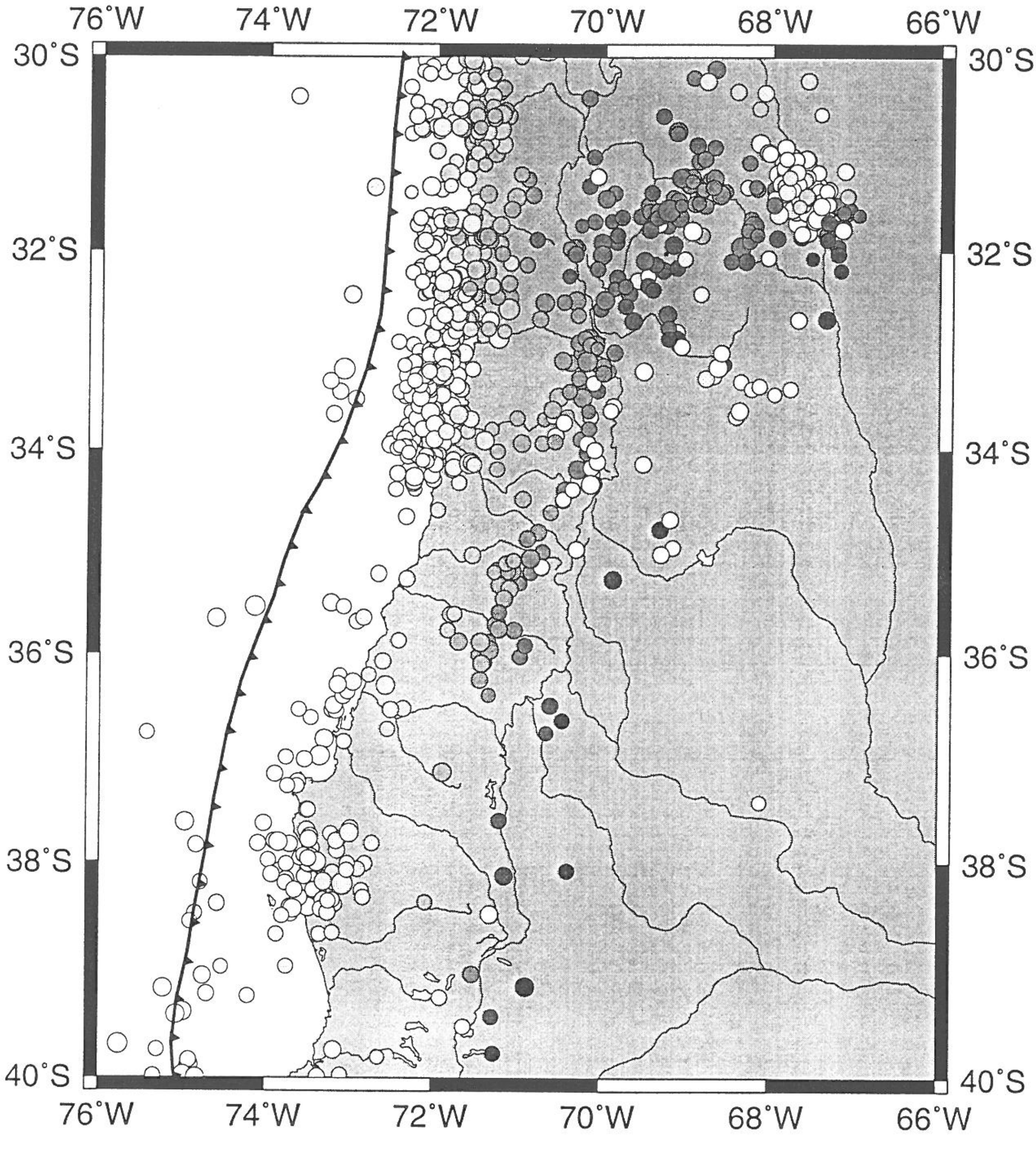


Fig 10

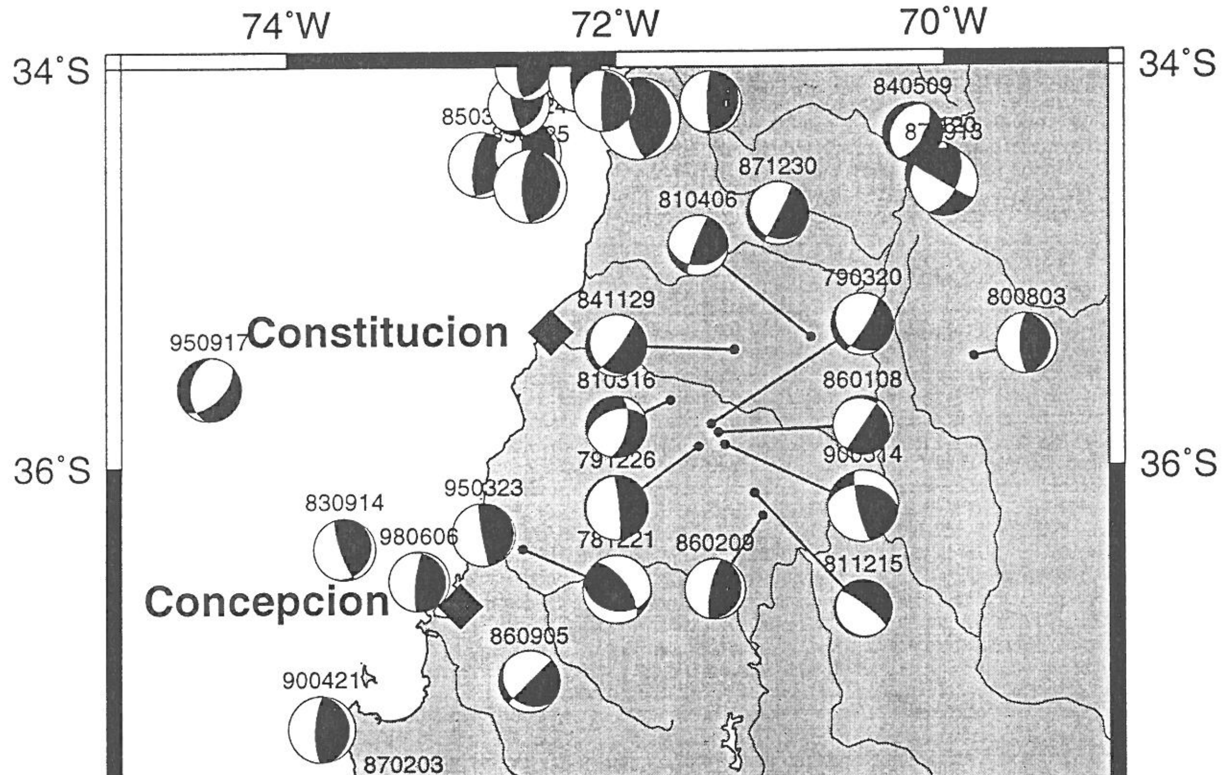

74°W
72°W
70°W
34°S
36°S
38°S
Constitucion
Concepcion
840509
871230
810406
790320
800803
841129
950917
810316
860108
791226
950323
830914
980606
781221
860209
811215
860905
900421
870203
850602
780102

Fig 1.1

3 The Seismic Field Experiment of the Fall 1996

From March 1st to June 1st, 1996 the seismic field experiment that was the main purpose of our proposal was carried out in the Concepción Constitución by researchers from all the participating institutions: This experiment followed a preliminary survey of the area made in July 1995 by Sergio Barrientos and Jaime Campos of the University of Chile and by Raúl Madariaga from IPG in Paris. Several sites were identified at that time and it was decided that the experiment would cover the area from the Maule river in the North to about 50 km South of the Itata river. Communications within this zone were quite good but it was necessary to avoid certain unpaved routes that could become difficult to use if it rained. It was also decided at that time to install the Operational Center in the city of Cauquenes, at the center of the study area. This city that has all the necessary logistic facilities, and is well served by a network of paved first class roads. From Cauquenes the entire area of the experiment could be visited by two or three groups of participants driving about 450 km per day. The participants from the different institutions are listed bellow

Participants at the Field Experiment

- Universidad de Chile
  Edgar Kausel
  Sergio Barrientos
  Jaime Campos
  about a dozen graduate students

- Institut de Physique du Globe de Paris
  Raúl Madariaga
  Hélène Lyon-Caen
  Geneviève Patau

- Laboratoire de Geophysique Interne et Tectonophysique (LGIT)
  Observatoire de Grenoble
  Denis Hatzfeld
  Robert
  Catherine Pequegnat
  1 Graduate Student

- Dipartamento de Geofisica Vulcanologia, Università di Napoli,
  Giovanni Iannaconne
  Aldo Zollo
  1 Graduate Student

Instruments

The initial research group that installed the seismic stations arrived in the field on March 16, 1996. The main site where seismic stations were prepared, and data was verified and processed was installed in the city of Cauquenes near the center of the experiment area. The city is connected both to the main Central Valley cities (Talca, Linares, Chillán) and to coastal villages by a good set of paved roads. The only difficulties were experimented on the road that connects San Javier in the North to Concepción in the South which was under construction at several places. A total of 25 seismic stations were deployed under the direction of Denis Hatzfeld from the LGIT at Grenoble. This work took about 10 days. After a period of essay following their installation some of the seismic stations that were located on noisy sites were relocated as well as those that were inaccessible in a single day tour from Cauquenes. The final distribution stations is listed in Table I and shown in Figure 12. The distribution of stations is quite 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, sediment cover is very thick at places, the best sites were found in isolated hills of the valley.

In this experiment we used two kind of instruments:

- 19 Tad portable recorders using 2 Hz single component vertical seismometers indicated by circles in Figure 12.
- 6 Reftek three component recorders using 2 Hz three component seismometers indicated by stars in Figure 12.

These instruments had an autonomy of about 4 days under the conditions of seismicity found in the area. In this way a complete tour of the network could be completed in four days, leaving enough time for data processing, coping magnetic tapes and doing minor repairs in Cauquenes.

To our surprise, and actually to many people of the area, our network recorded an almost continuous seismic activity located directly under the network. As we discussed in the previous chapter studies of locally located data (Fig. 9), world wide data (Fig. 10) as well as the Centroid Moment Tensor catalog of Harvard University (Fig. 11) indicated a lack of activity near the coast of the Concepción Constitución area. This was certainly not the case and as our results proved later a continuous layer of seismicity extends from the trench situated about 100 km off-shore all th way down to about 150 km under the Andes. This seismicity is associated with the downgoing slab, the Nazca plate as it subducts under Chile.

A few recordings

As we already mentioned briefly, during the period of the experiment four events of Magnitude greater than 4 took place inside the temporary network on March 7 (actually this one occurred while we were preparing material to move to the field), and on April 9, April 26 and May 2, 1996. As our network was designed to locate smaller events than these, most of the recordings of these earthquakes were saturated but could still be used to locate them. On Figure 13 we present plots of the traces recorded by all those stations that triggered during the 9 April 1996 event near the town of Parral, about 45 km E of the city of Cauquenes where our Operations Center was located. The corresponding information sheet distributed by Servicio Sismológico of the University of Chile in Santiago was shown on Figures 6. The timing in these records needs to be corrected for triggering time. The stations closest to the earthquake are DIGU, SNIC and THER; looking at the position of these stations we can locate the earthquake right bellow the Reftek station CACH. The event is deep because the two not completely saturated recordings at SNCL and THER show S-P times in the order of 12 and 15 sec, respectively. This is 120 and 150 km from these stations so that the event is deep as indicated also in the earthquake report sheet of Fig.6.

Another large event recorded by our network is that of April 26 at 13:16:31.6 GMT (9:16 local Chilean time) as indicated in the information sheet of Fig. 7. The record section is shown in Figure 14. The timing in these records needs to be corrected for triggering time. The earthquake signals arrive the earliest at THER then successively at NIPA, FLRD and SNIC. As these records are raw, they require time corrections in order to use them for location. Once this was done we could locate the event at 71.35°W, 37.25°W and 136 km depth. The event is thus situated at some depth bellow the southern boundary of the network. Location and depth determined using the local network in Santiago and shown on Figure 7 have errors of up to 60km, showing again the urgent need for a local network of stations in the area.

Just to give an idea of the type of recordings obtained for more common, less strong events that do not saturate the records, we show in Figure 15 a seismic section of the recording from event N°106. This is a very well recorded event for which an earthquake mechanism was computed as shown in table 4 and Figure 24. The section shows clearly recorded P and S waves. The S-P time is of the order of 10 s (100 km distance) at most stations indicating again a deep event. Our best location for this event listed in table 2 is 71.59°W, 35.83°S and 75.8 km depth. This event is actually a precursor of the larger event of April 9 at 19:17 GMT whose recordings are shown on Fig 13. The 19:17 GMT shock was preceded by several interesting foreshocks and by practically no aftershocks. This is quite curious and opposite to what is usually observed for subduction zone earthquake. A possible interpretation of this observation is that these events are taking place inside the down-going slab of the Nazca plate. Unfortunately we can not pursue a comparative study of the main shock and its foreshocks much further because of the saturation of record for the main shock.

Additional record sections will be discussed later in our presentation of the shallow seismic events near the border of the Coastal Ranges and the Central Valley.

Earthquake location

Once the network was returned to France data analysis was done by a young Chilean researcher, Ms. Gloria López, under the research supervision of Dr. Denis Hatzfeld of Grenoble. Lately, the data obtained by Lopez and Hatzfeld was reprocessed and studied carefully by Robert Fromm and Jaime Campos of University of Chile and Raul Madariaga, formerly from IPGP and now from Ecole Normale Supérieure in Paris. The data was extracted from magneto-optical disks, processed with the software developed by the SISMALP team in Grenoble that selects data, corrects for time corrections to the clocks that control the recordings. Sismalp programs can be used to pick the arrival times of P and S waves at the different stations of the network, and can prepare data for the HYPO71 program that computes earthquake location by a process of linearized inversion and regression. Other programs in the SISMALP software can be used to plot records and fault plane solutions, compute polarities and determine focal plane solutions. All along the data processing work, numerous test of the internal consistency of the data were carried out, plotting residuals, evaluation average rms residual per station, etc.

Once all the records had been read from the tapes, they were read individually in order to determine both P and S wave arrivals and polarities were determined from all those records that had clear onsets. 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 289 events was selected for hypocentral determination using the HYPO71 program. These are events that have a root mean square residual (RMS) less than 0.5 s, that have more than 10 readings of either P or S wave arrivals and whose depth error is less than 50 m.

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 abut the velocity structure of the crust and upper mantle is scarce. From experience gathered by the central Chile seismic network in Santiago and temporary networks deployed near Santiago as reported by Pardo et al (1998) we decided to use an extremely simple model of a crust over a uniform half space. Three different crust models extracted from previous experiments in Chile were designed as shown in Figure 16.

Model 1 used to locate earthquakes

P-wave speed	depth
6.200	.000
7.000	15.000
7.900	45.000

Model 2 used to locate earthquakes

P-wave speed	depth
6.600	.000
7.900	45.000

Model 3 used to locate earthquakes

P-wave speed	depth
5.500	.000
7.000	15.500
8.100	47.900

The models differ in the crustal structure and in the upper mantle velocity which varies from 7.9 for models 1 and 2 to 8.1 for model 3. Previous work in some areas of

Chile has shown that upper mantle P-wave speeds are rather low wo that we expected models 1 and 2 to be more realistic. Model 3 is used by the Seismological Service of the University of Chile in order to locate earthquakes in Central Chile. It is of course very likely that upper mantle structure be quite complex instead of the simple homogeneous medium assumed in these models. It is very likely however that this structure be three-dimensional because of the presence of a cold downgoing slab penetrating a rather low velocity upper mantle. Such improvements must wait for a complete tomographic analysis of the travel time data collected during our experiment. In order to locate the earthquakes recorded during the experiment we used both P and S wave arrivals. The S-wave velocity models needed for location were derived from the P-ave velocity dividing by a constant factor determined from a Wadati diagram. For the Concepción Constitución area we found that the optimum v_P/v_S ratio for earthquake location was 1.752. This value was determined from a Wadati diagram constructed from 3276 phases read for a selection 88 earthquakes. The rms error of the v_P/v_S ratio is estimated as ± 0.0031.

Locations were computed using the Hypo71 program using each of the three velocity models of Figure 16. The locations determined for each model are plotted in Figures 17, 18 and 19, respectively. The similarity of the distribution of seismicity obtained with the different structure models is clearly appreciated in the Figures 17, 18 and 19. Except for earthquakes located clearly outside the network, in the Ocean or in Argentina, most other events, specially those under the Central Valley do not move when we change the velocity model. This is a clear sign that earthquake location is robust and stable to changes in the velocity model.

Once the locations were computed we ran a series of tests in order to detect systematic errors and biases in the station distribution. Again, except for events situated well beyond the borders of the network, the locations are robust and well controlled. These are of course the location errors as detected by the Hypo71 programs. We are aware that the entire seismic distribution may be biased by the simple upper mantle structures adopted in our velocity models. This will require further work with a longer duration experiment in which both far field and local data could be recorded in order to do a proper tomographic determination of the distribution of seismic wave velocities in the upper mantle.

The simplest way to test the internal consistency of the locations is to compute rms residuals for each of the stations; We selected the set of the 379 best located events plotted in Figures 17 to 19 and computed for every one of them the rms residuals obtained at every station of the network. The rms residuals at the individual stations are all less 0.2s. We interpolated the rms residuals computed for every station in order to obtain the contour plot shown in Figure 20. In this plot the dark circles are the positions of the seismic stations of the network. This particular plot is for the residuals computed from locations made with model 1. Very similar result were obtained for the three other models both when Hypo71 computed weighted and unweighted locations. The weighting scheme for the stations does not affect the locations nor the residuals. This is a further indication that arrival data are internally consistent and that the average upper mantle model we used my not be far from the actual one. Residual topography in Figure 20 is very flat and averages 0.20 s both for P and S waves. This result is not unexpected since we rejected any hypocenter that had more than 0.5 s rms residual for all the readings used to locate it. Since most of the events we retained in the sample are located bellow the network, their rms residuals were well bellow the maximum of 0.5 s. In fact what we are observing is that most of the events had a very good azimuthal coverage; so that only events situated outside the network have large residuals. This may also mean that the models used to locate the events are not far from reality.

Earthquake distribution in the Concepción Constitución area

After running several tests of the data, we proceeded to exclude a few more events that were either far outside our network, and therefore we could not put much faith in their positions, or events that moved more than 100m when changing models, indicating probably a poor azimuthal distribution of stations in the location of these events. The final set of events retained to study the distribution of earthquakes determined during our experiment contained a set of 264 shocks. These are listed in table 1 for the record and plotted on plan view in Figure 21. The events plotted 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 further they are from the Peru-Chile trench. The trench is indicated by the ocean bottom topography plotted with light contour lines. This trend of the seismicity is better defined by looking at the three vertical cross-sections taken along the lines B1, B2 and B3 defined on Figure 21. These three cross-sections are taken along lines parallel to the direction of subduction as determined by the standard plate velocity models. The cross-sections are shown on Figure 22. All three clearly show that the great majority of the seismicity aligns along a more or less narrow Wadati-Benioff zone that plunges with a dip angle of roughly 38° bellow the Central Valley. This trend indicates that up to 90 % of the events belong to the downgoing slab, the part of the Nazca plate as it plunges into the upper mantle bellow Chile. Our results show that most earthquakes in the Concepción Constitución gap are due to activity on the Nazca plate bellow its coupling zone with the South American plate.

The seismicity plotted in Figures 21 and 22 is very similar to that of other parts of the Nazca plate subduction zone where subduction is so-called "normal". Barazangi and Isacks (1976) were the first to notice that the South American Nazca plate boundary is segmented with areas of "normal" subduction at nearly 30^0 dip and others where the Nazca plate seems to flatten bellow the South American plate. Our region of study was clearly identified as a "normal" subduction zone. The events define a very narrow down-going zone of seismicity that may be compared with that determined in Northern Chile by Delouis et al (1996) and Compte et al (1994, 1995). We do not see in our vertical cross-sections of Figure 22 any clear indication of a double seismic layer as reported by Compte and Suárez (1994) for part of Northern Chile and definitely confirmed in a recent preprint by Compte et al (1998). The existence of a double layered zone can not be ruled out however because our locations are probably not accurate enough to detect a narrow separation between the two layers. In order to properly detect a double layered zone we would nedd a longer period of observation in order to increase the number and distribution of events used to determine a better velocity model. Once the structure is better determined by tomography, it is possible to recompute the hypocenters in order to visualize small scale features in the seismic activity.

Two other important features are observed in the seismicity plots of Figures 21 and 22. 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 third vertical profile along line B3 of Figure 21. In this profile several small shocks appear isolated in the shallow crust very close to the volcanos of the area. Earthquakes of this type are well known in Central Chile near Santiago where an almost continuous activity affects a broad one between the Central Valley and the Andes. A large earthquake occurred in Las Melozas close to Santiago in 1958 and many such events are recorded by the central Chile network. In the Concepción Constitución area, in the 1930s and 40s a seismic station was sporadically in use near the town of Panimávida, close to station CACH of our network (see Fig. 12). Bobillier and Greve (1954) reported evidences of local events recorded in this station. Our result, obtained in a vry short recording period, confirms the existence of this shallow seismicity. The origin of these earthquakes is an interesting subject, since we do not know whether they are directly associated with volcanic activity (since most of these volcanos are currently active); or whether they are due to faults that extend along the Andean precordillera (Armijo, personal communication, 1998). Unfortunately, these shallow events are at the Eastern edge of the network so that it was not possible to determine fault plane solution for any of them.

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 study later in this report.

Study of Earthquake Mechanisms

Once earthquake locations were satisfactory determined we tried to determine source mechanisms for all the well located events. Unfortunately it was not possible to obtain well-constrained fault plane solutions for all of the events because in many cases the azimuthal distribution of stations was inadequate. This is generally true for many shallow focus events, except a couple of them that we will discuss presently.

For all the located events we computed take off angles using the preferred velocity model 1 (see figure 16). Then fault plane solutions were computed by hand plotting the polarities and then determining the optimum fault planes. We could determine well constrained fault plane solutions for 31 events out of the 264 well located hypocenters. These events are well distributed and are quite representative of the variety of mechanisms that have been observed elsewhere in Chile. In the 3 panels of figure 23 we show examples of the determination of fault plane solutions for typical events in the series. Clearly shallow events shown in the first panel are less well-determined than intermediate depth events shown in the other two sets of fault plane solutions. This is quite logical, most rays for intermediate depth events leave the focal sphere in the upward direction and are very little affected by refraction and multipathing in the crust and upper mantle. For shallower events the mechanisms are not as well determined because of the inclusion of readings from short period Pn waves which are well known to be relatively instable. Two more examples of fault plane solutions for shallow events are shown in Fig 30 which will be discussed separately later.

In Figure 24 we show the set of 31 fault plane solutions plotted on top of the epicenters of all the events that could be located in the course of our study. The events for which we could determine a well-constrained fault plane solution 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 Figure 22 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 Figure 23 is the large number of dip-slip events, both thrust and normal faults that occur in this area. These events are all inside the downgoing slab as can be appreciated from Figure 26 where only dip slip events are plotted. Among them only 6 (30, 73, 163, 176 and 203) 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 areas of Northern Chile by Compte et al (1994, 1998). By far the most common type of mechanism in Figure 23 is the "normal fault" type of event. These are events that have an almost vertical fault plane. Those bellow the Central Valley all have a sub-vertical fault plane and a compressional quadrant to the West. These events have mechanisms of the "slab-pull" type, the same kind of mechanism as inferred by Beck et al (1998) for the Chillán earthquake of 1939. As shown from the sketch of Figure 3 these events can be interpreted as due to pulling forces inside the downgoing slab. Evidence for this type of events since the first works by Malgrange and they seem to be ubiquitous along the whole Chilean subduction zone. Three "normal fault" events (N° 10, 24, 105 and 106) near 36°S by 72.°W have a sub-vertical fault plane gain but the compression Al quadrant is situated to the East of this plane. If the vertical plane is the fault, these events correspond to slab compression rather slab-pull as all the previous ones. As observed in the lateral view of figure 22 events 10 and 24 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 Compte et al (1994, 1998) in Northern Chile. However slab pull events 105 and 106 are not deeper than surrounding events so that it is not possible to conclude to the existence of a double layered zone. Our data is not abundant enough to confirm this preliminary observation. Let us hope that future permanent networks will let us clarify the presence of such a double layer.

Finally, a set of 8 events (78, 120, 151, 162, 201, 204, 242 and 364) form a conspicuous group of mainly strike slip events. To these we may add event 14 at the bottom of the subduction zone. Of these the most unusual events for Chile are N° 162 and 364; two rather shallow strike slip earthquakes as seen in the profile 22. These events are quite unique and separate from the rest, they will be the subject of next section. Of the rest of the strike slip events, 242, 204, 120 and 201 are compatible with down-dip extension or slab-pull. Only event 14 is difficult to explain in this simple interpretation.

The pattern of seismicity and fault plane solutions revealed by our experiment as shown in Figure 24 is is fully compatible with the larger earthquakes as reported by the collection of Centroid Moment Tensors (CMT) from Harvard University shown previously in Figure 11. In the CMT catalog all earthquakes under the Central Valley from 35°S 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 been frequently been said that small background seismicity does not give much information about large events. While this may be true in California where the San Andreas is currently almost completely silent, it is clearly not the case in Chile. Other observations on the similarity of small and large event mechanisms have been reported elsewhere in Chile, so that it may be possible that Californian seismicity be the exception rather than the rule. 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 Chillán earthquake all present the same "slab-pull" mechanism. This requires of course longer term recordings but 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.

Study of two shallow crustal events

One of the most interesting and puzzling observations we made are two relatively shallow earthquakes, number 162 and 364 in Table 2 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 the run almost North South at the limit of the piedmont of the Andes in front of Santiago. This is not the same as here, our two events took place much closer to the coastal line and as shown in Figure 24. We studied these events very closely and we have little doubts that they are very shallow. The depths were computed using velocity model 1 for a set of predetermined depths. As shown on Fig 31 in which we plot the rms residual of observed minus computed travel times, the depths are very well determined, for both events 162 and 364 a sharp deep rms minimum determine their respective depths as 15 and 30 km. This shows that these two events occurred in the crust of Central Chile in a very unusual location.

The shallow depth of event can be also inferred from a comparison of the recordings of event 162 with those of event 204; as seen from figure 24 these two events share almost the same epicenter but are located at very different depths: event 162 of April 18, 1996 at 18:52 had a depth of 15.24 km while event 204 of April 24, 1996 at 17:36 had a depth of 77.7 km. The two events have epicenters that are less than 4 km apart. We show on Figures 28 and 29 the traces recorded by our network for these two events. They are completely different: For instance at station PICH situated about 15 km from the epicenter the S-P time is of a couple of sec for event 162, but is about 9 sec for event 204. Similar observation is made at the SJV station that is almost at the same distance from the epicenter as PICH.

With the new depth and the locations determined by Hypo71 we recomputed the take off angles of P waves for both shallow events 162 and 364. The corresponding fault plane solutions are presented in Figure 30. 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 slip 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. It may be that the depth computed for these events is biased by the particular crustal model used to locate them. Thus, although we would have liked to do more detailed analyses of this shallow depth seismicity, with only two well recorded events it is difficult to do more. Hopefully future networks installed in the area will help in studying these events in more detail.

Future work

Although we have not yet attempted to do this, our data clearly contains information about lateral velocity fluctuations in the upper mantle under the network. These fluctuations can be inverted using a tomographic method although as we showed the variations are very weak with rms less than .25 s. Many other temporary networks have been used to invert for lateral variations of structure with this kind of residuals in Chile (see, in the case of Chile, work by Pardo et al ,1998, Compte et al, 1996, etc) so that we will also try to do a tomographic study in the next year. We do not expect however very accurate results because of the very particular distribution of seismicity in the Concepción Constitución gap. Almost all event are located on the Wadati-Benioff zone so that ray paths are limited. We will have to limit the volume inverted to a small zone bellow the Central Valley.

In addition to recordings of local earthquakes our network was successfully triggered by several regional and distant events that occurred during our operation. Thus, we obtained a very complete section of recordings for the events that occurred at the end of March in Ecuador. These data will be used to obtain local station residuals and with some luck to do some prototype tomography. But the latter is difficult because of the poor distribution of seismic activity around Chile.

Figure captions

Figure 12: Seismic stations deployed during the field experiment of March-May 1996 in the Concepción Constitución . Station indicated with a circle are the TAD type, while the 6 three component REFTEK stations aligned EW are indicated by stars.

Figure 13: Seismic section of selected available recordings for the $M = 4.6$ event of April 9, 1996 at 19:16 GMT near the city of Parral. The information sheet for this event is presented in Figure 6.

Figure 14: Seismic section of selected available recordings for the $M = 4.6$ event of April 26, 1996 at 13:16 GMT near the southern end of the network. The information

sheet for this event is presented in Figure 7.

Figure 15: Seismic section of selected available recordings for a small precursor of the $M = 4.6$ event of 9 April 1996 near the city of Parral in the middle of our network. S-P times of 10 s indicates that the event is about 100 km deep. This foreshock preceded the main event shown in Figure 13 by several hours. It was followed by a large number of small events that could not all be located due to difficulties in triggering the more distant stations in the network.

Figure 16: Three simple velocity models used to locate earthquakes recorded by our temporary seismic network.

Figure 17: Location of well determined events that satisfy several quality criteria. These events were located using model 1 for the velocity structure (see Fig 16).

Figure 18: Location of well determined events that satisfy several quality criteria. These events were located using model 2 for the velocity structure (see Fig 16).

Figure 19: Location of well determined events that satisfy several quality criteria. These events were located using model 3 for the velocity structure (see Fig 16).

Figure 20: Distribution of root mean square residuals (rms) at different stations of the network that for the location of earthquakes in the Concepción Constitución gap. Stations are indicated by black dots. (a) P-waves, (b)S-waves

Figure 21: Distribution of the final selection of earthquakes located during our experiment in the Concepción Constitución area. These events were very well located according to a set of different criteria. The three lines marked B1, B2 and B3 are the orientation of the crossections plotted on Figure 22. These events were located using model 1 for the velocity structure (see Fig 16).

Figure 22: Distribution of the final selection of earthquakes located during our experiment in the Concepción Constitución area plotted along three profiles indicated on Fig 21. These events were located using model 1 for the velocity structure (see Fig 16).

Figure 23: Examples of fault plane solutions computed for selected earthquakes. Figure a shows mainly shallow coastal events, Figure b shows events near the center of the downgoing slab bellow the Central Valley and Figure c shows events situated to the East, under the Andes.

Figure 24: The 31 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.

Figure 25: The 31 fault plane solutions determined in the Concepción Constitución from first motions of P waves plotted on a cross section parallel to the direction of subduction of the Nazca plate. Most of the events with a few conspicuous exceptions

occurs along the inferred downgoing slab.

Figure 26: Well determined dip slip events, both reverse and normal plotted on the area of the experiment. At several places almost vertical dip-slip earthquakes of opposite polarity occur at almost the same place. This may indicate the presence of a double seismic layer as reported by Compte et al for Northern Chile.

Figure 27: Well determined strike slip events, most of these events occur at shallower depths both inside the downgoing slab and in the crustal layer (earthquakes 162 and 364).

Figure 28: Seismic section of selected available recordings for the very shallow focus event of April 18, 1996 at 18:52 GMT near the town of Sna Javier at the Northern edge of our network.

Figure 29: Seismic section of selected available recordings for the intermediate depth (77.7 km) event of April 24, 1996 at 17:36 GMT near the town of San Javier at the northern edge of the network.

Figure 30: Mechanism for the 2 shallow focus earthquakes located near San Javier in the limit between the Central Valley and the Coastal Cordillera. Both mechanisms are of strike slip type, but are dominated by Pn readings, so that they may not be too accurate.

Figure 31: Depth determination the 2 shallow focus earthquakes located near Sna Javier in the limit between the Central Valley and the Coastal Cordillera. The Figures show the rms residual between observed and computed travel times to the stations in the network. Very deep minima are observed for both events.

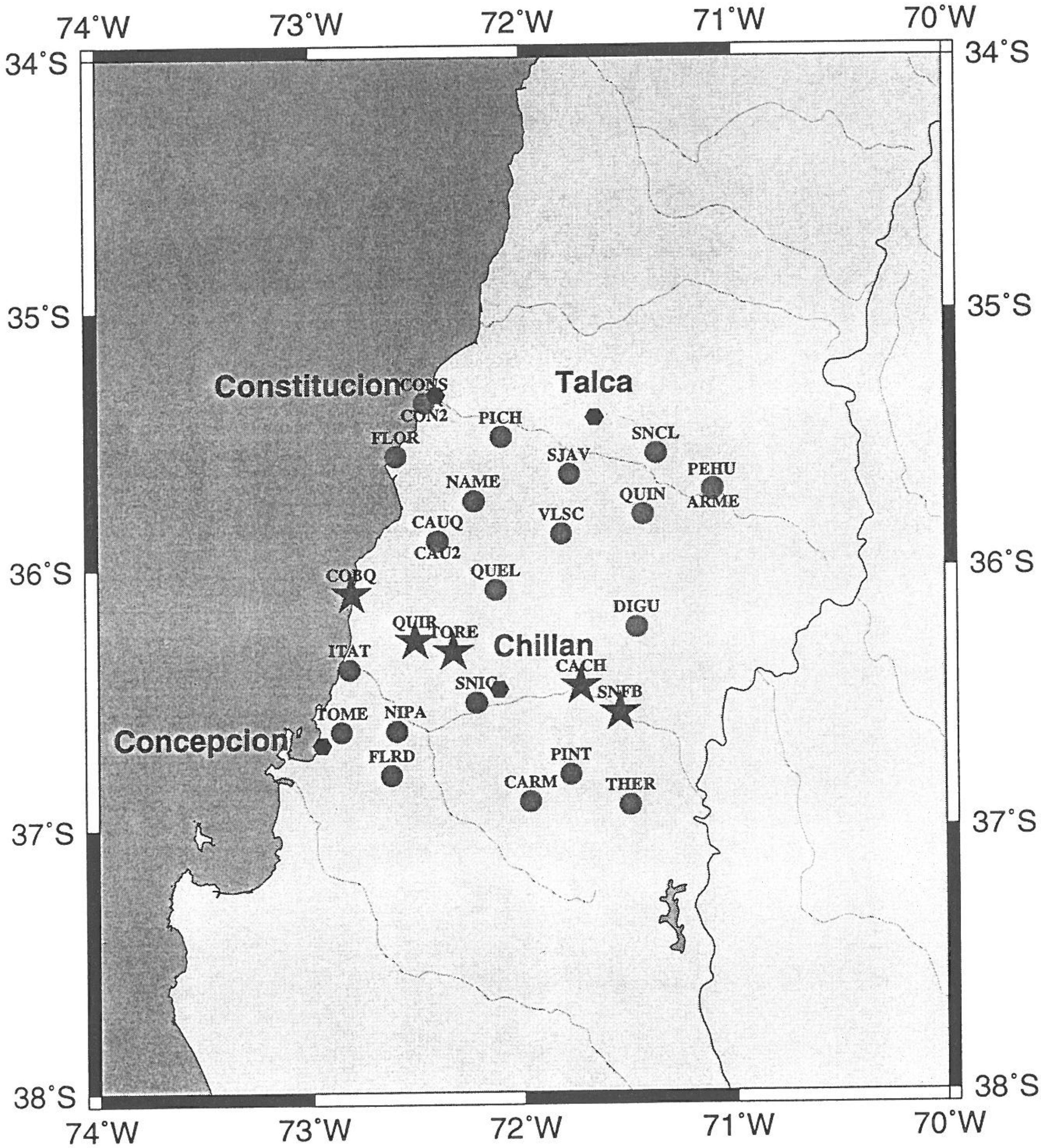

74°W
73°W
72°W
71°W
70°W
34°S
35°S
36°S
37°S
38°S
Constitucion
CONS
CON2
Talca
PICH
FLOR
SNCL
SJAV
PEHU
NAME
QUIN
ARME
CAUQ
VLSC
CAU2
COBQ
QUEL
DIGU
QUIR
TORE
Chillan
ITAT
CACH
SNIC
SNFB
TOME
NIPA
Concepcion
FLRD
PINT
CARM
THER

Fig. 12

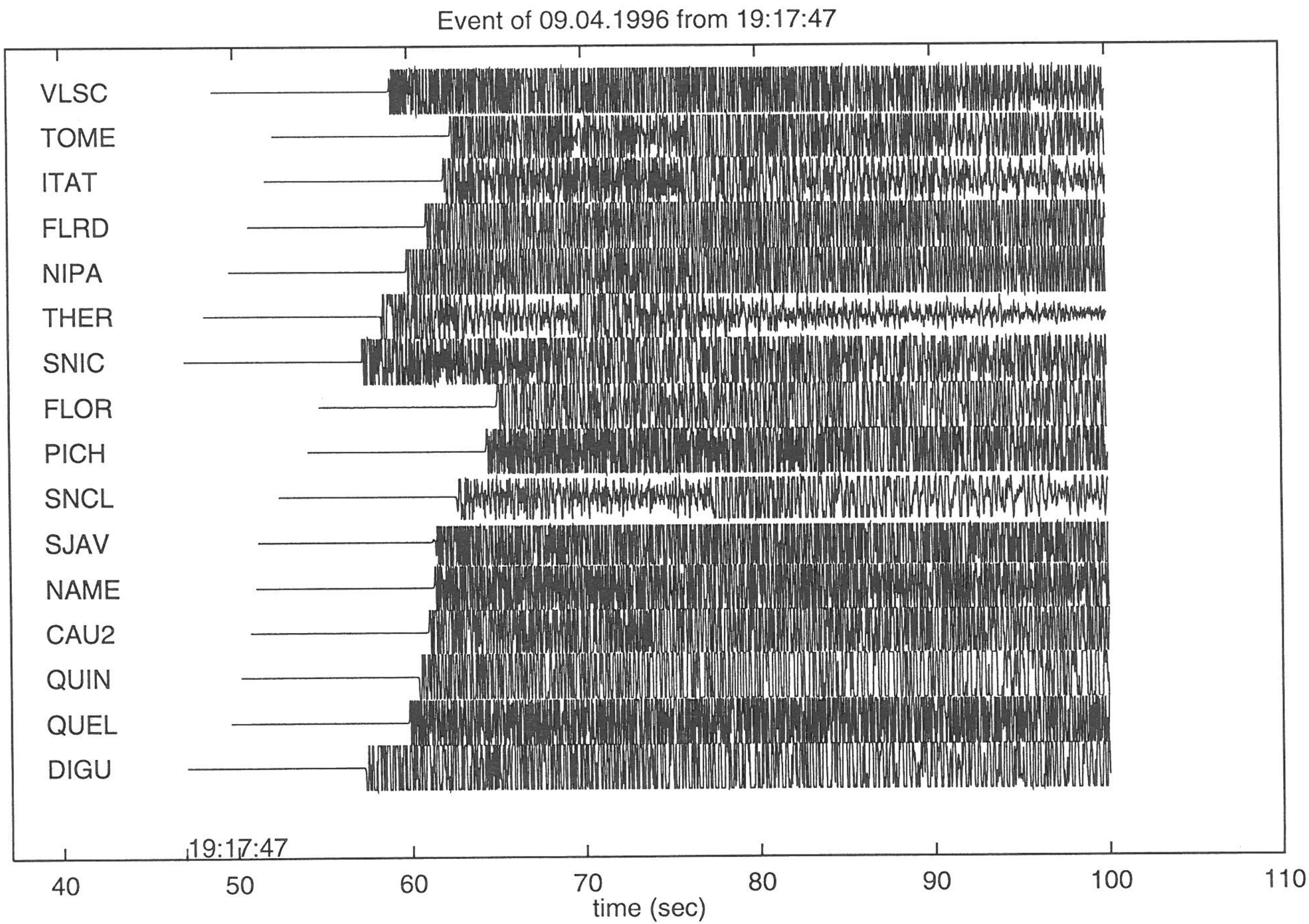

Event of 09.04.1996 from 19:17:47
VLSC
TOME
ITAT
FLRD
NIPA
THER
SNIC
FLOR
PICH
SNCL
SJAV
NAME
CAU2
QUIN
QUEL
DIGU
19:17:47
40
50
60
70
80
90
100
110
time (sec)

Fig 13

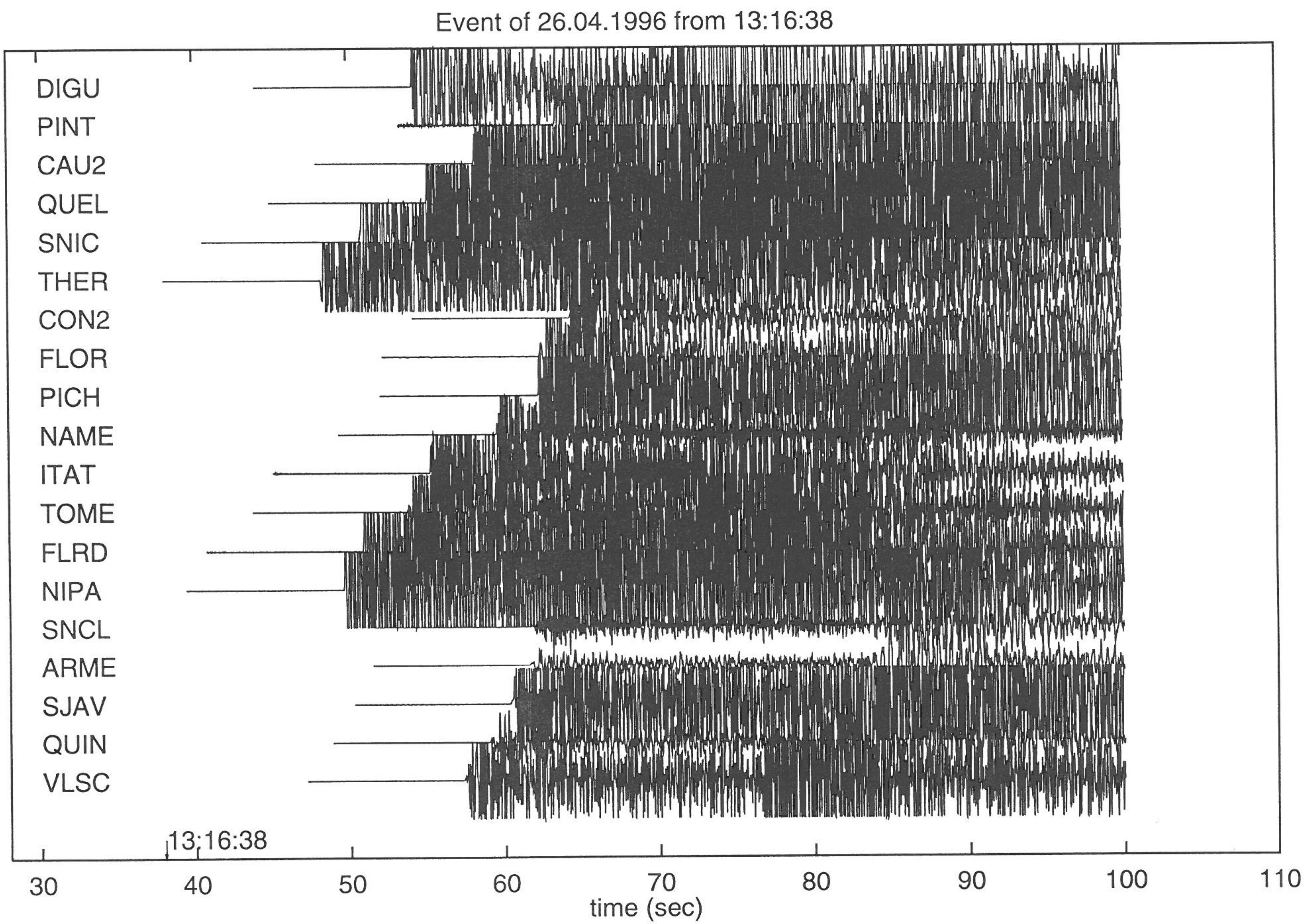
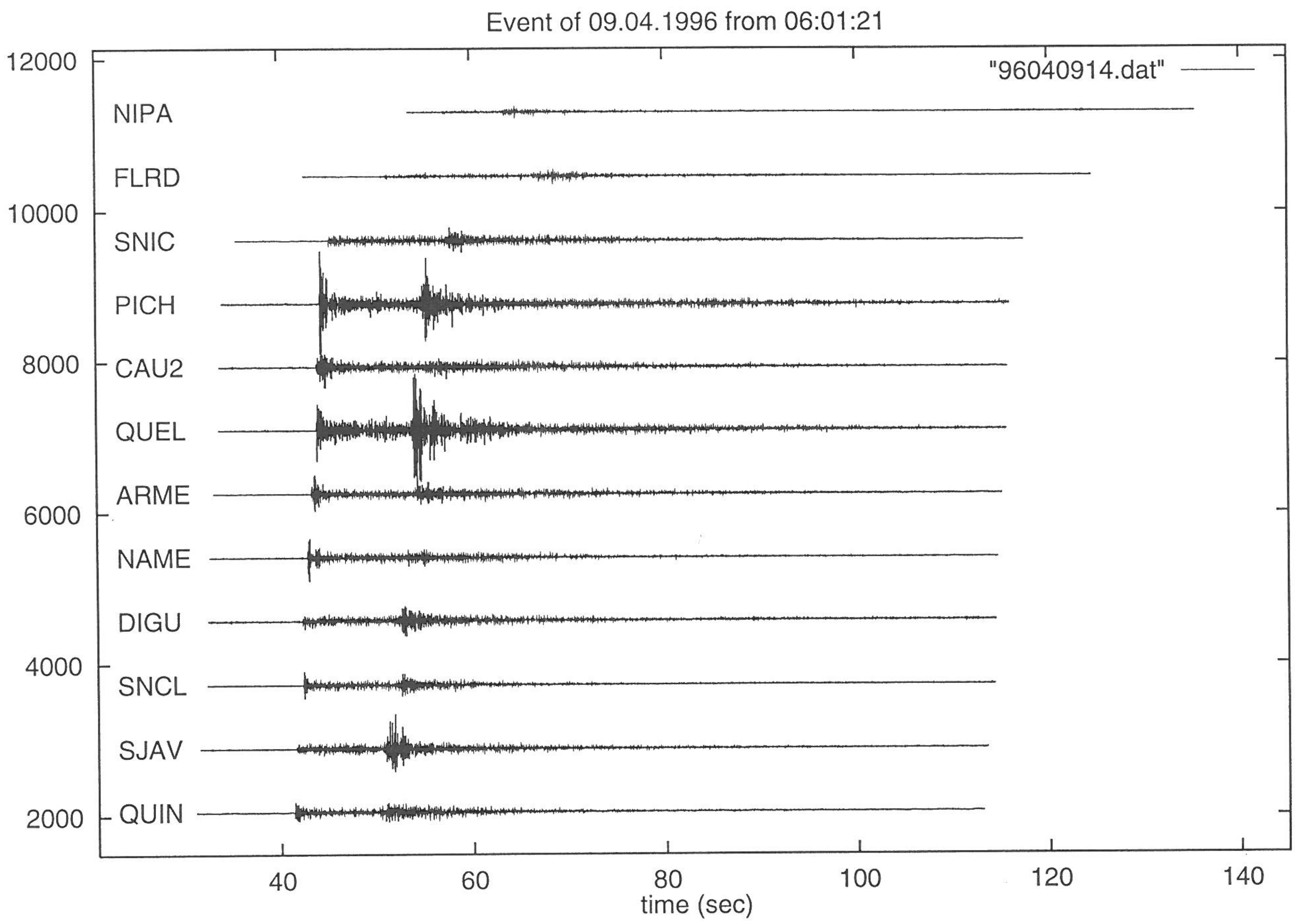

Event of 26.04.1996 from 13:16:38
DIGU
PINT
CAU2
QUEL
SNIC
THER
CON2
FLOR
PICH
NAME
ITAT
TOME
FLRD
NIPA
SNCL
ARME
SJAV
QUIN
VLSC
13:16:38
30
40
50
60
70
80
90
100
110
time (sec)

Fig 14



Event of 09.04.1996 from 06:01:21
"96040914.dat"
NIPA
FLRD
SNIC
PICH
CAU2
QUEL
ARME
NAME
DIGU
SNCL
SJAV
QUIN
12000
10000
8000
6000
4000
2000
40
60
80
100
120
140
time (sec)

Fig. 15

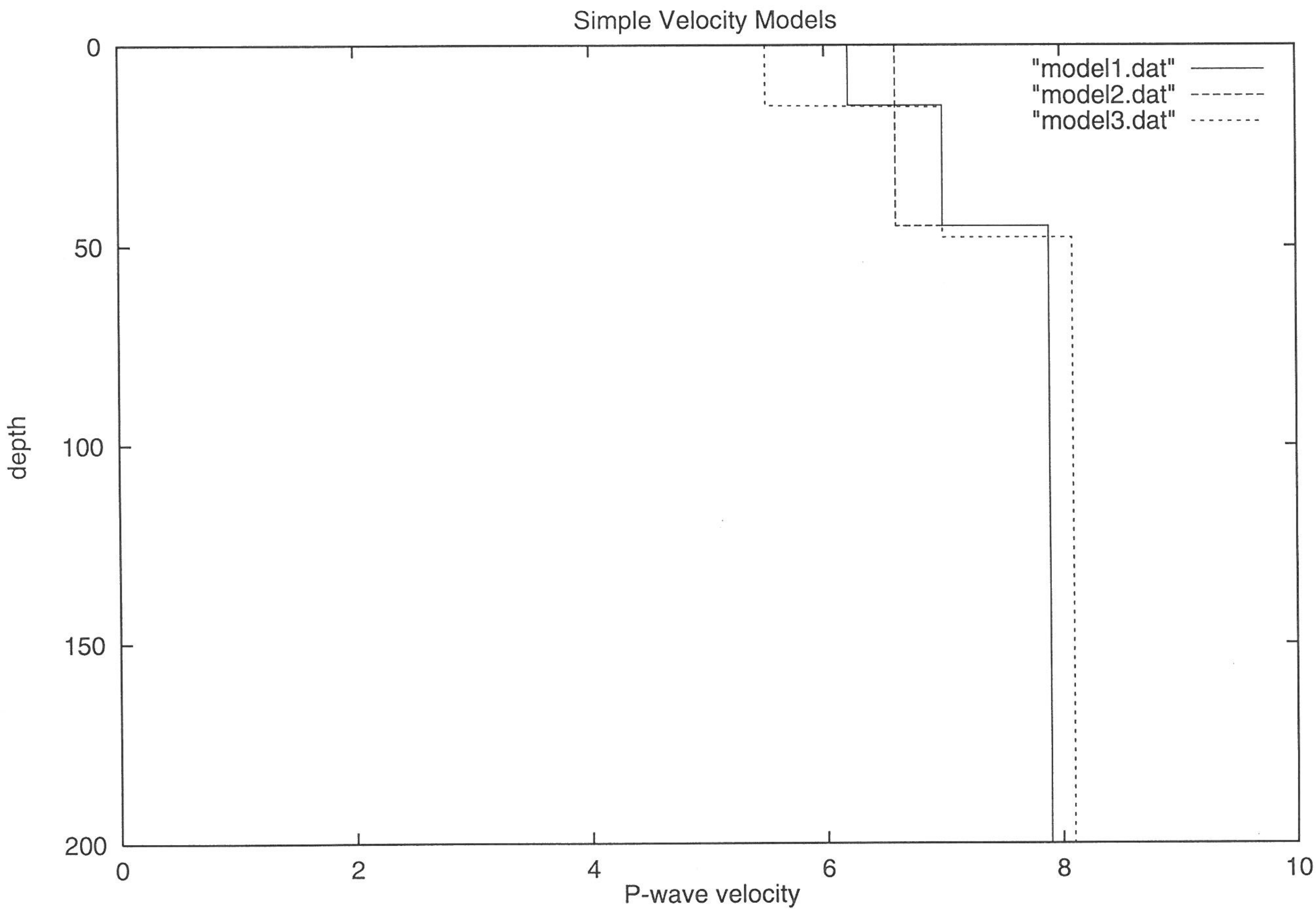

Simple Velocity Models
"model1.dat"
"model2.dat"
"model3.dat"
depth
0
50
100
150
200
0
2
4
6
8
10
P-wave velocity

Fig 16

SELECTED EARTHQUAKES

chile.cal.sum

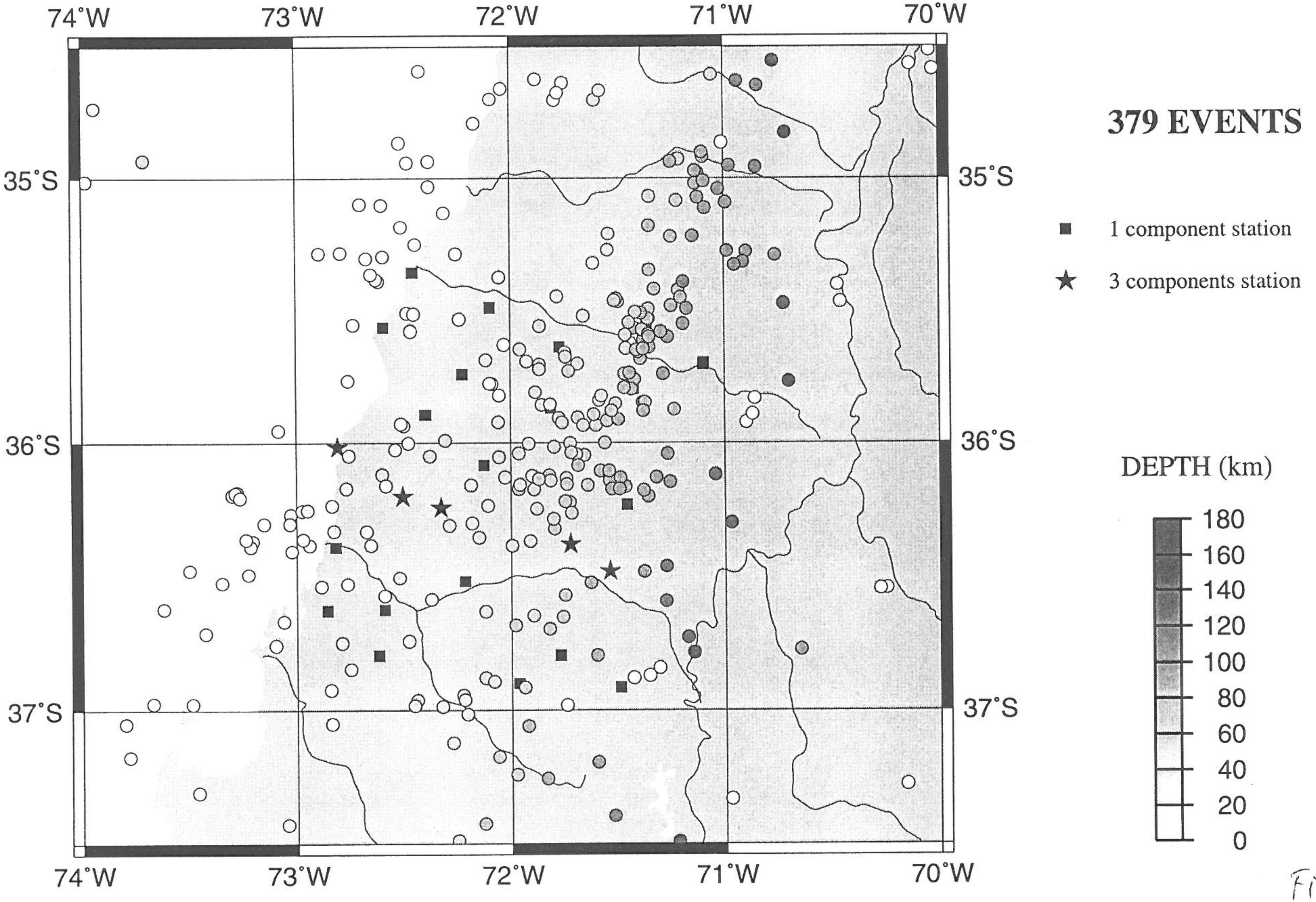


Fig 17

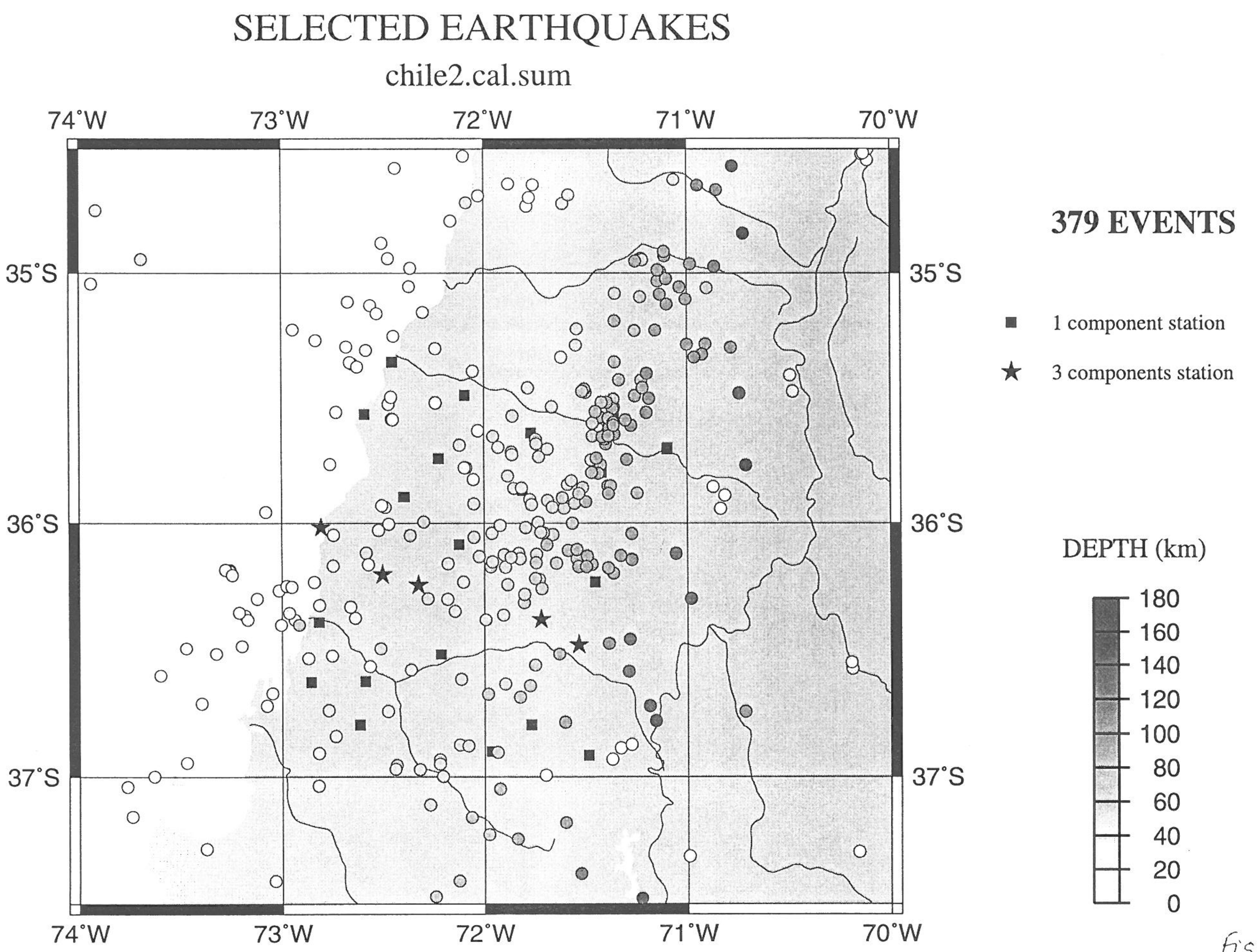

SELECTED EARTHQUAKES
chile2.cal.sum
74˚W
73˚W
72˚W
71˚W
70˚W
35˚S
36˚S
37˚S
379 EVENTS
1 component station
3 components station
DEPTH (km)
180
160
140
120
100
80
60
40
20
0

Fig 18

SELECTED EARTHQUAKES

chilec.cal.sum

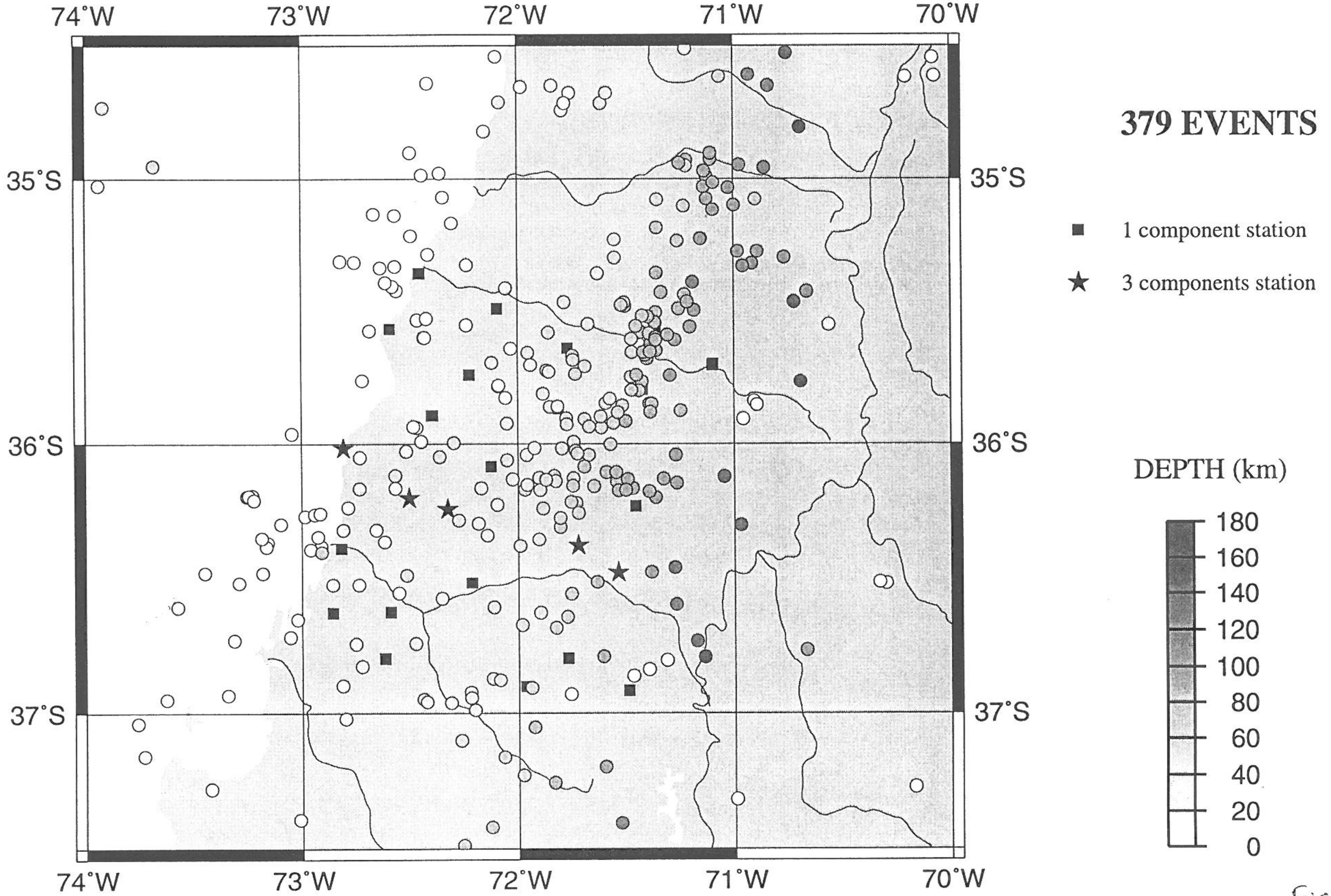


Fig 19

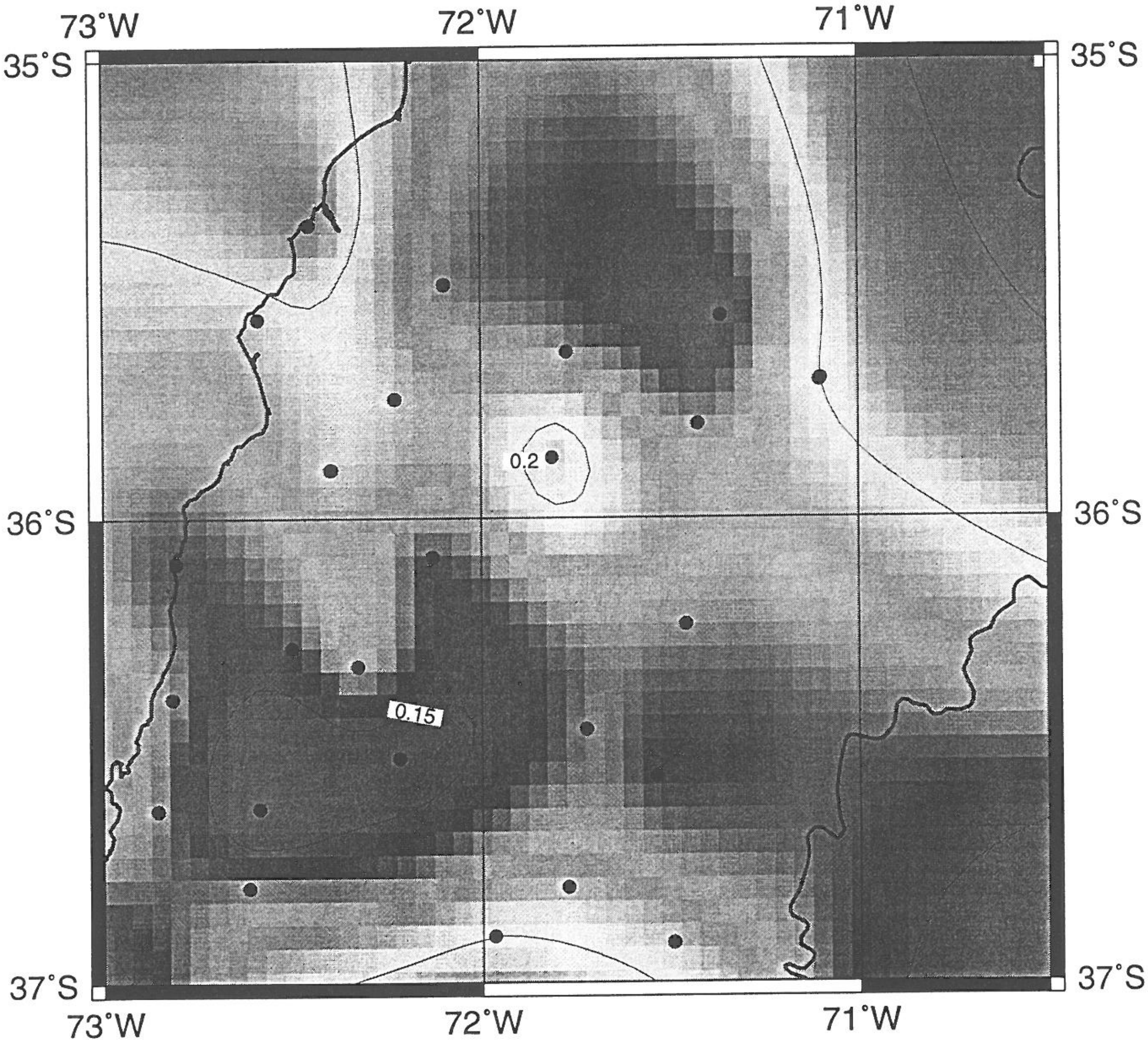


Fig 20a

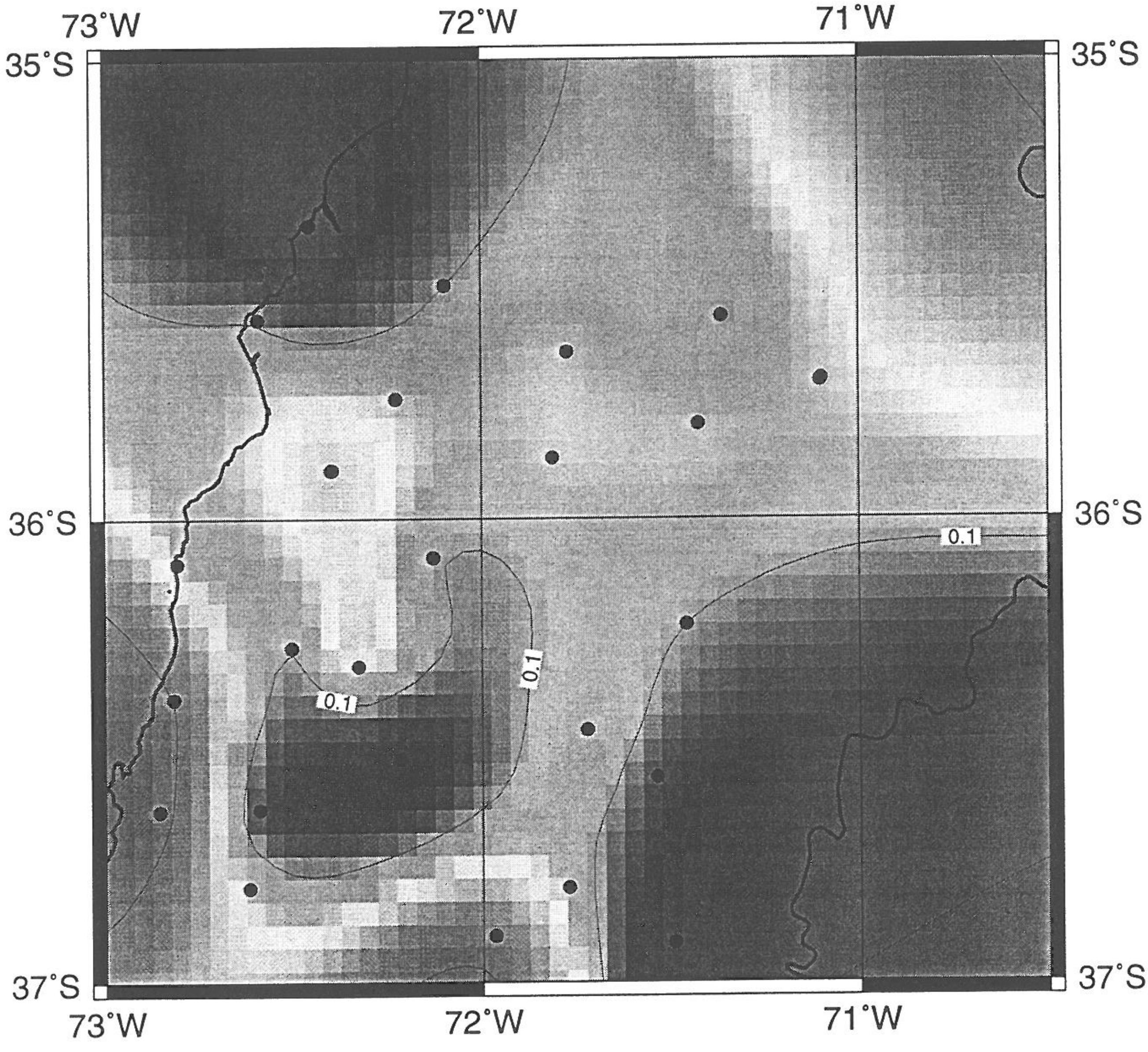


Fig 205

CROSS SECTIONS PARALLEL TO THE DIRECTION OF CONVERGENCE

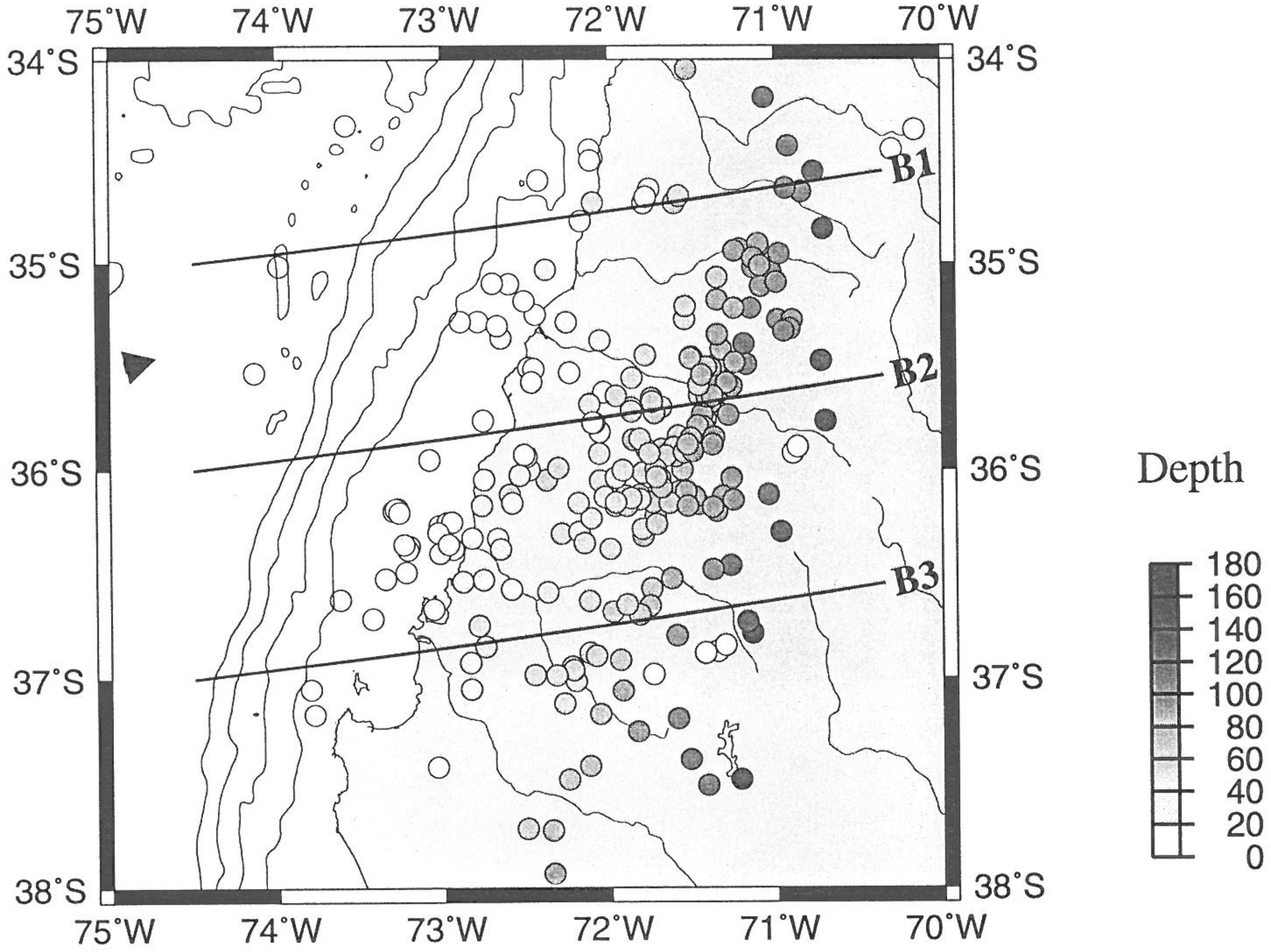


Fig 21

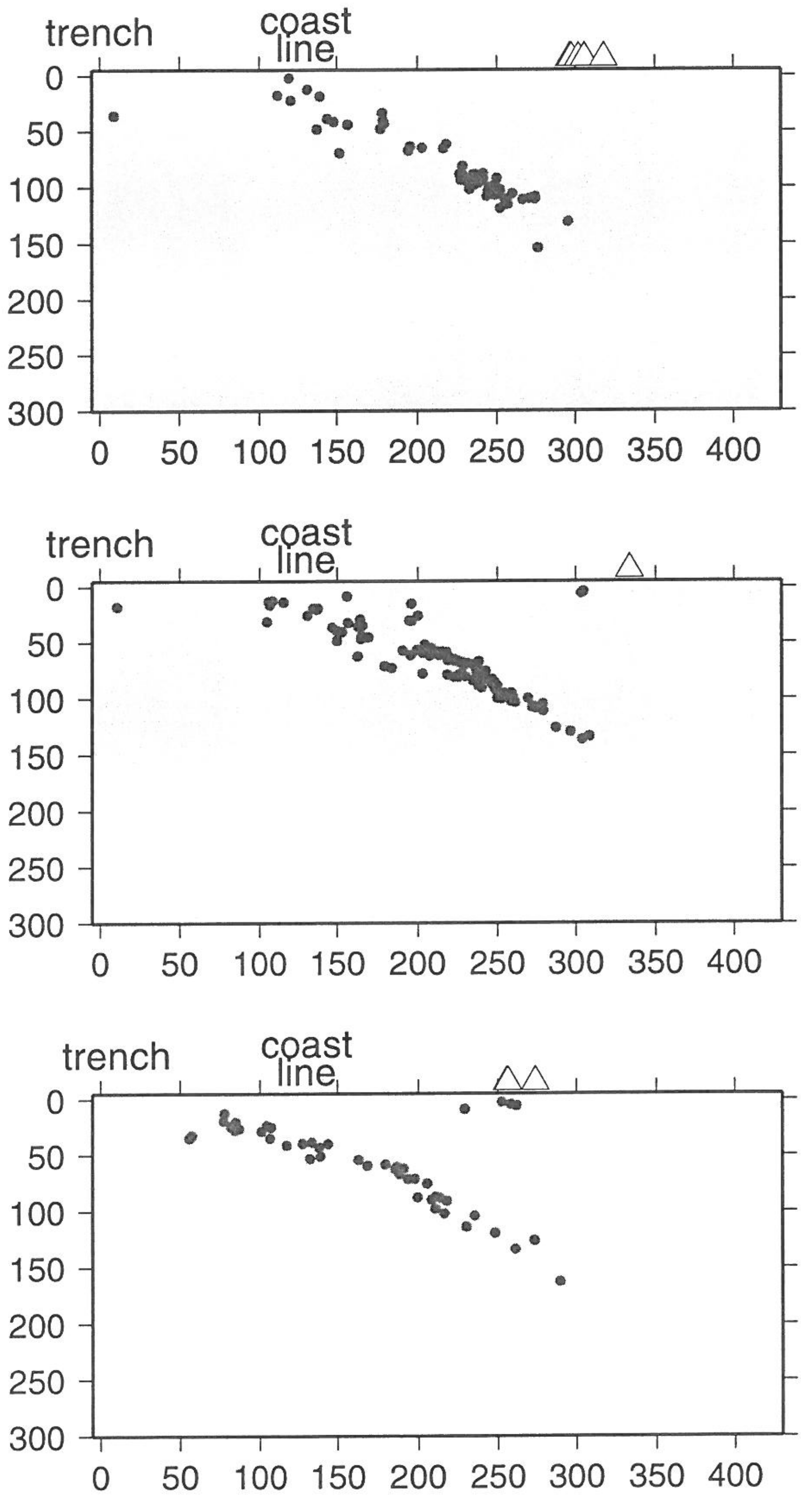

trench
coast line
0
50
100
150
200
250
300
0 50 100 150 200 250 300 350 400
trench
coast line
0
50
100
150
200
250
300
0 50 100 150 200 250 300 350 400
trench
coast line
0
50
100
150
200
250
300
0 50 100 150 200 250 300 350 400

Fig 22

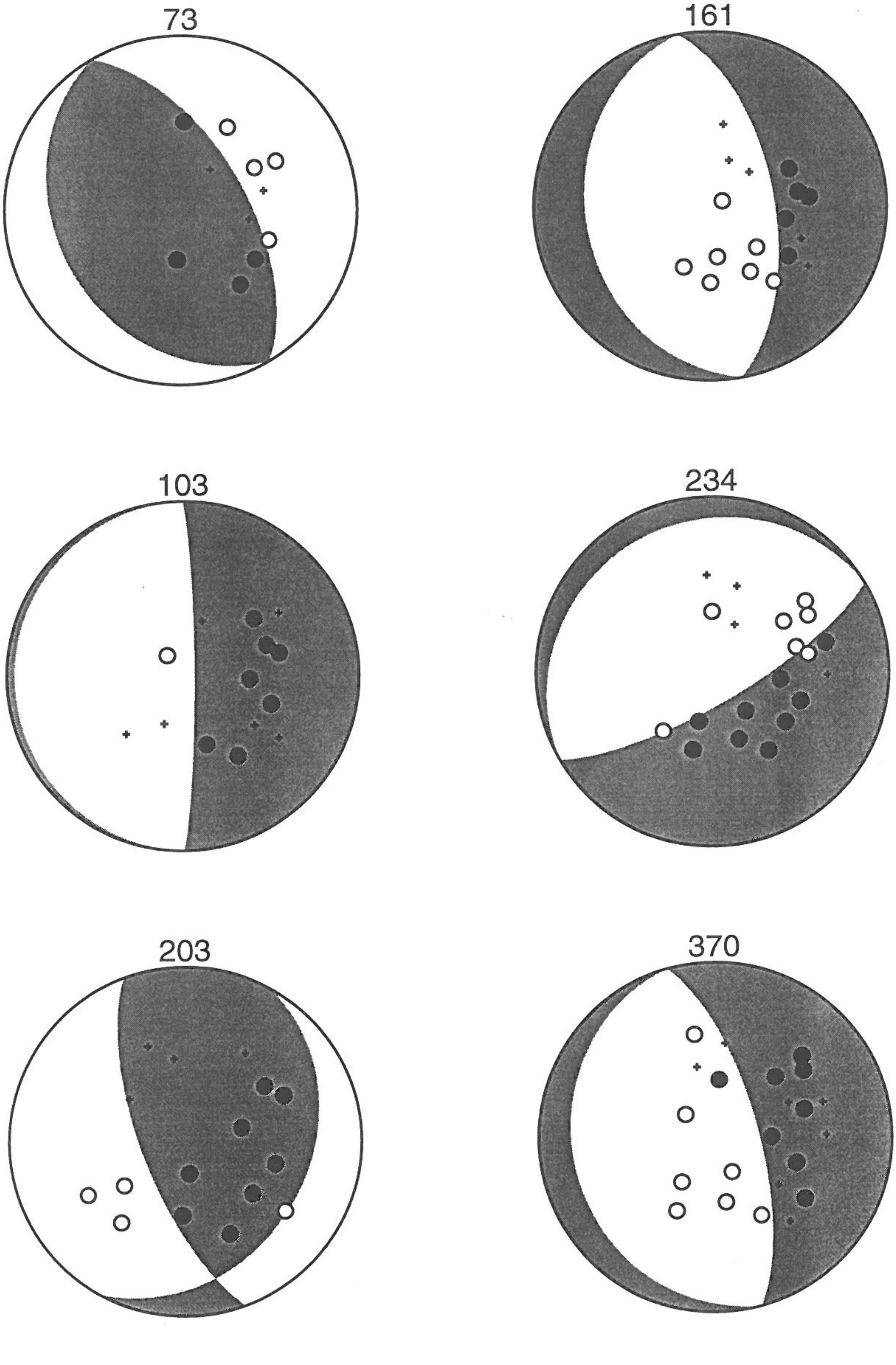


Fig 23a

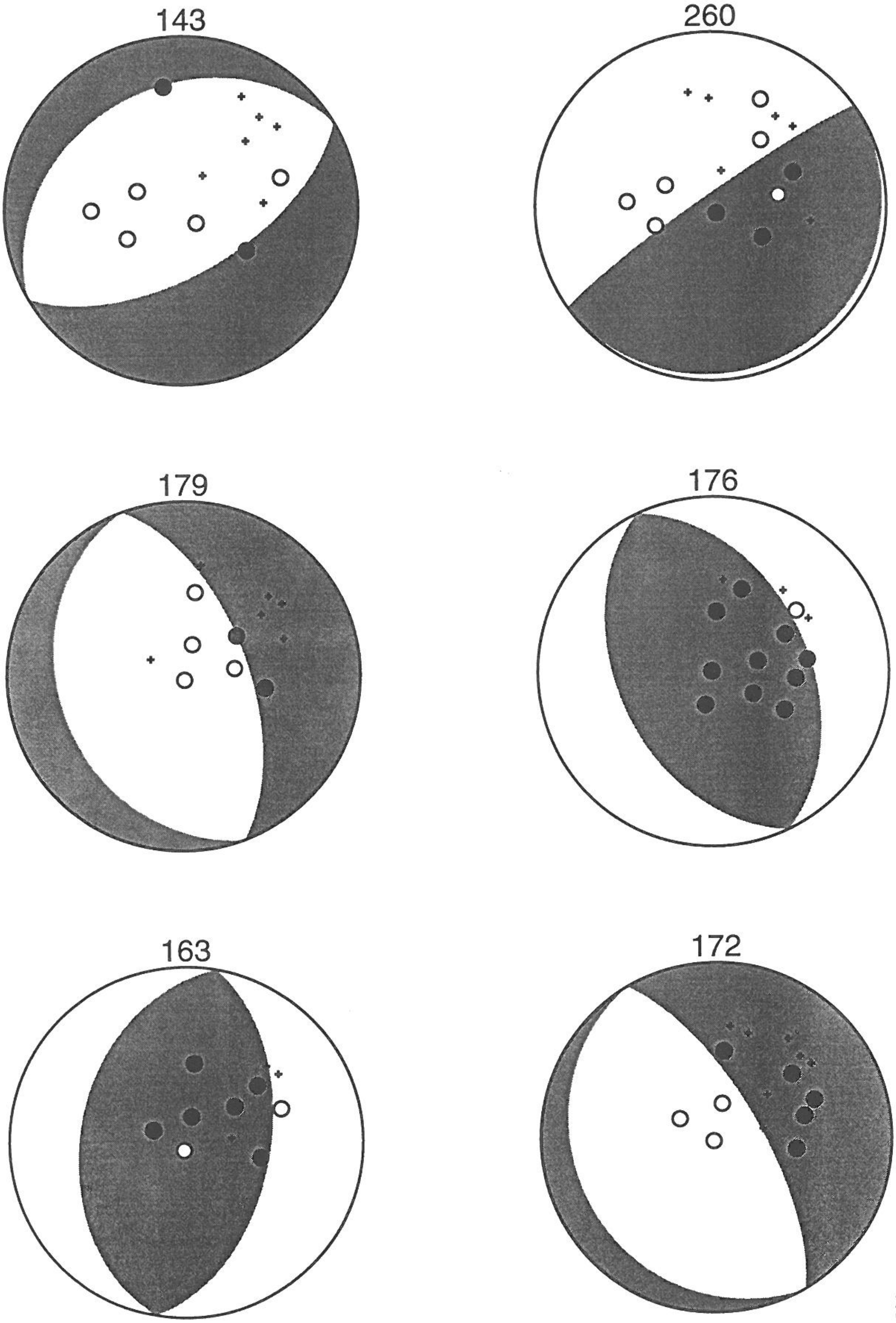


Fig 235

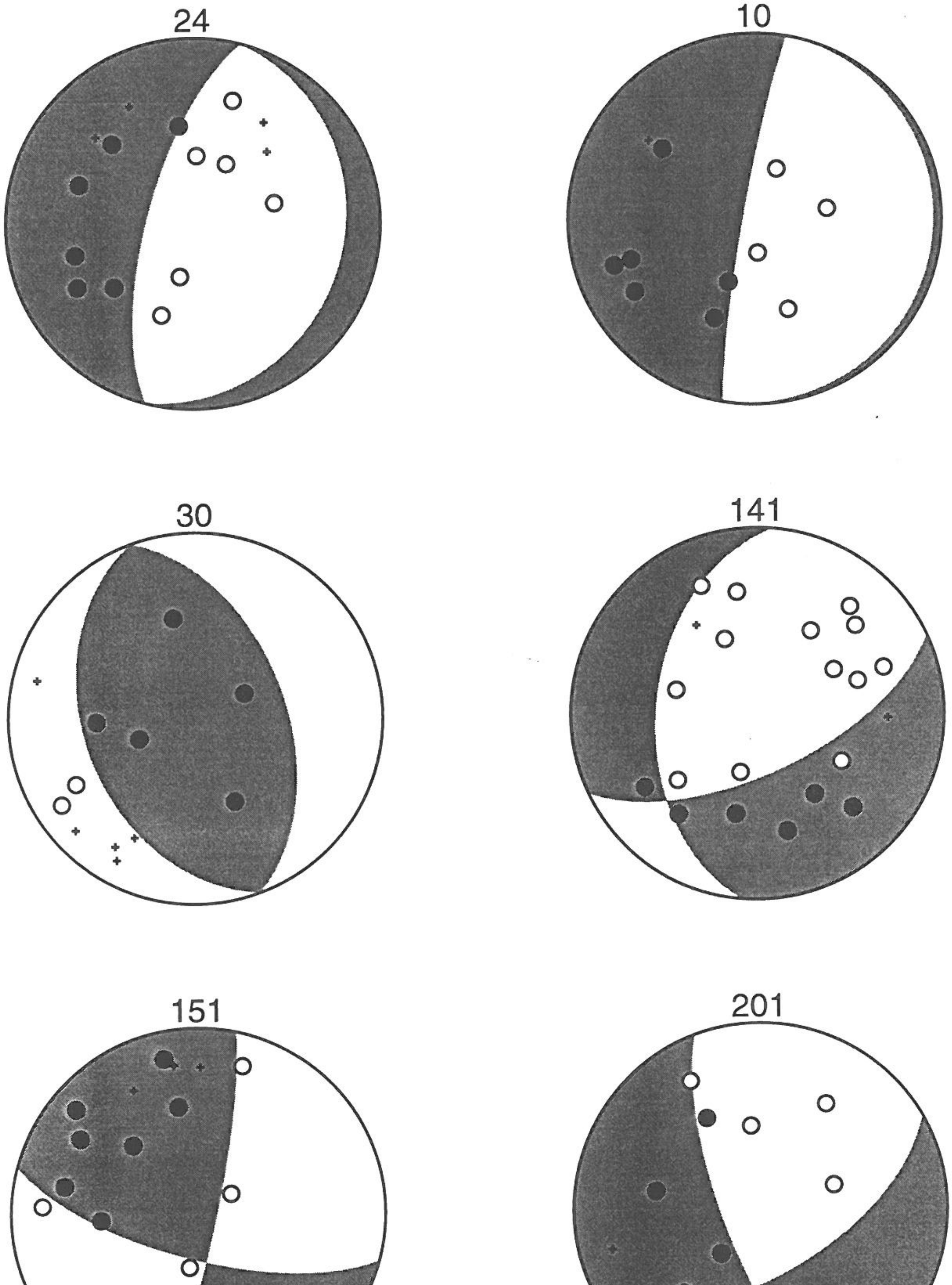


Fig 23c

WELL DETERMINED EARTHQUAKE MECHANISMS

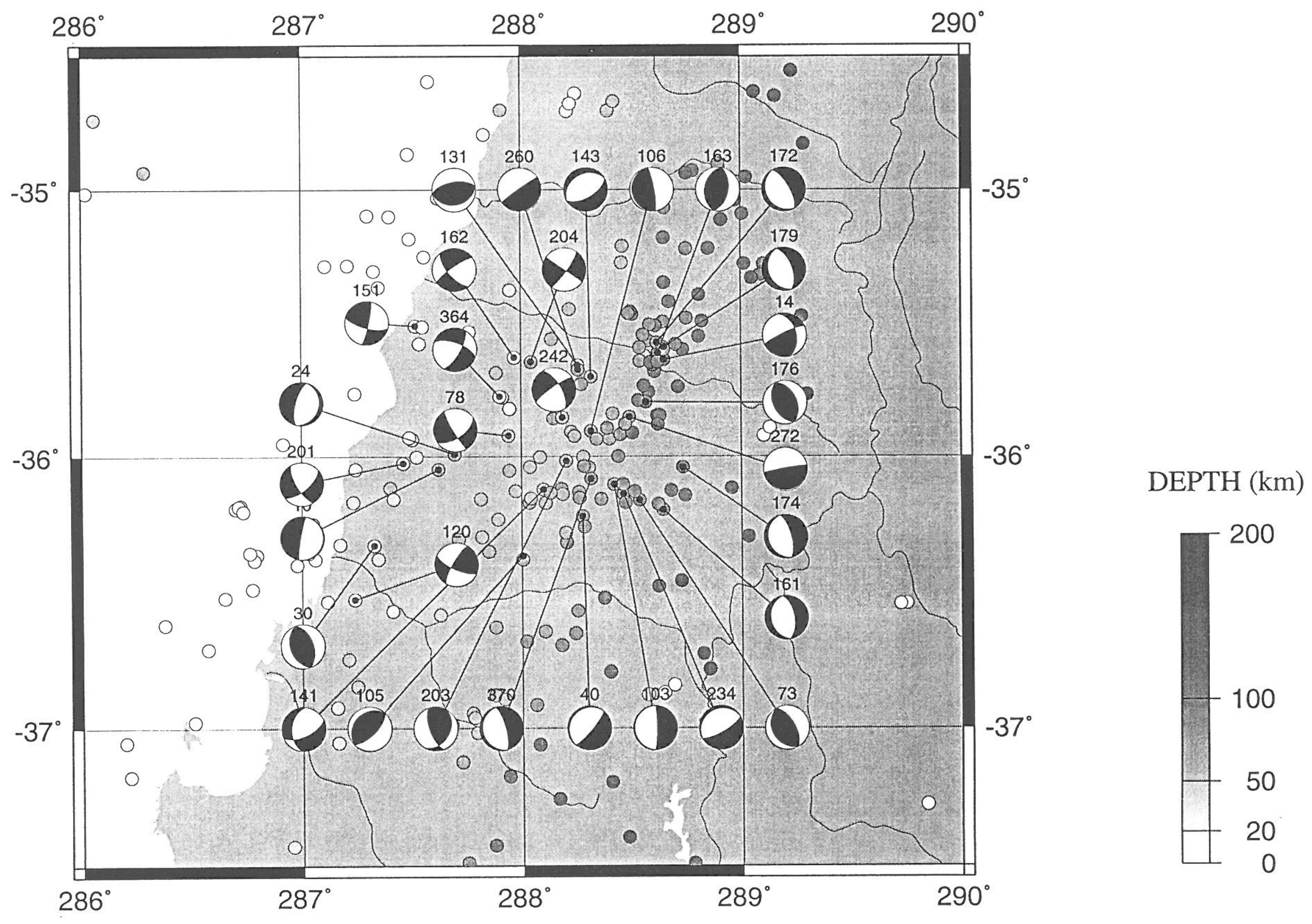


Fig 24

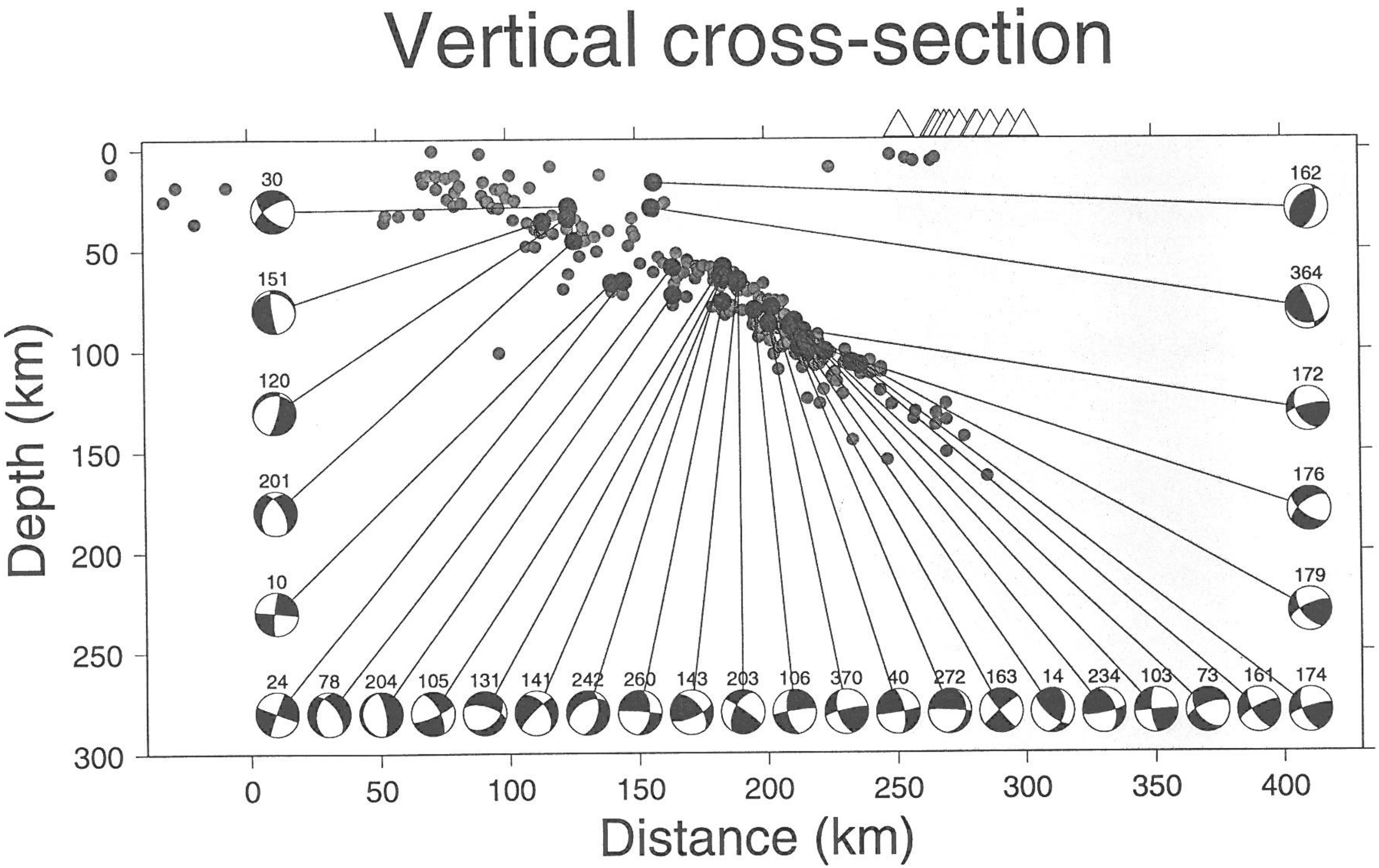

Vertical cross-section
Depth (km)
0
50
100
150
200
250
300
Distance (km)
0
50
100
150
200
250
300
350
400
30
151
120
201
10
24
78
204
105
131
141
242
260
143
203
106
370
40
272
163
14
234
103
73
161
174
162
364
172
176
179

Fig 25

DIP SLIP EVENTS

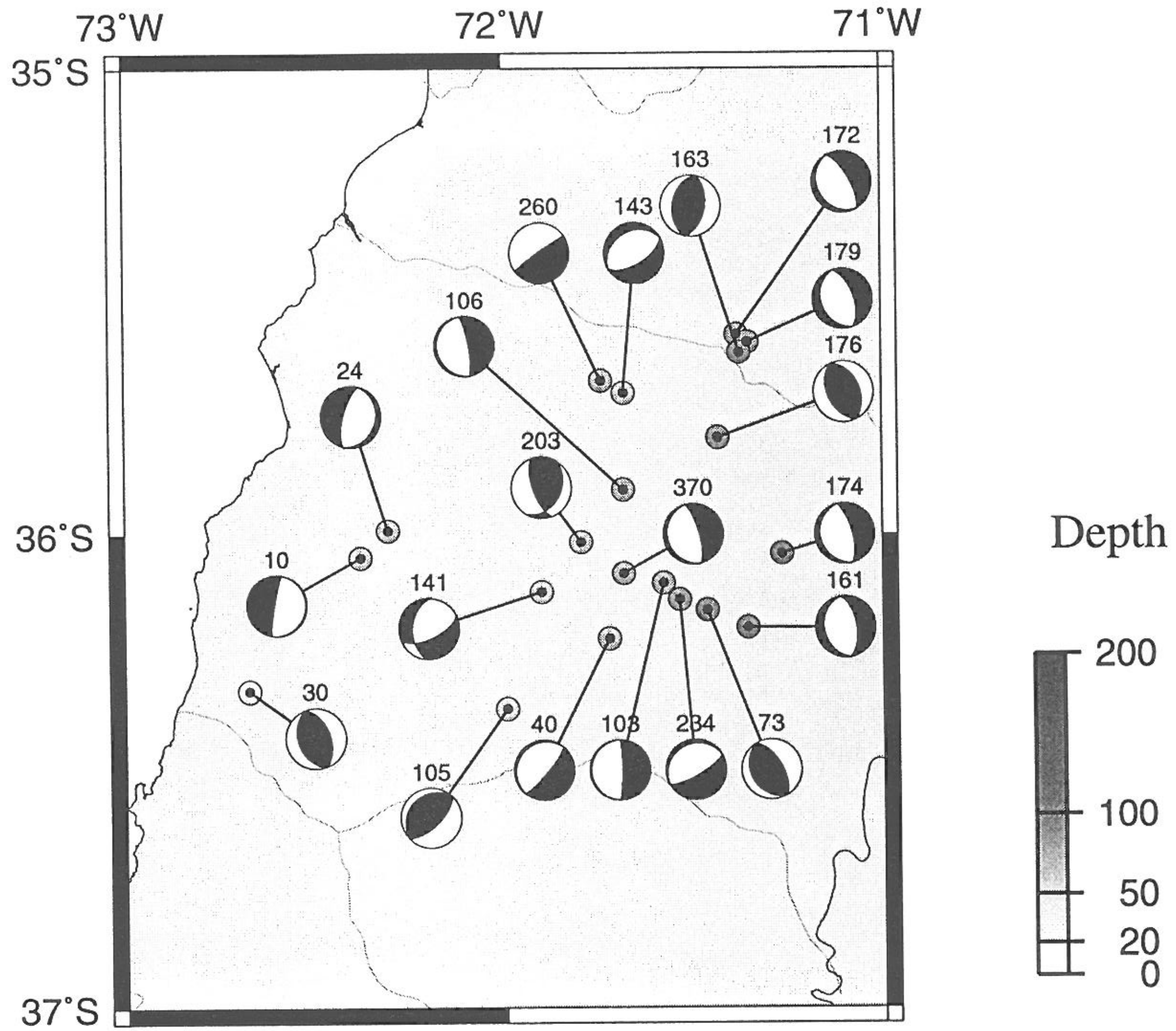


Fig 26

STRIKE SLIP EVENTS

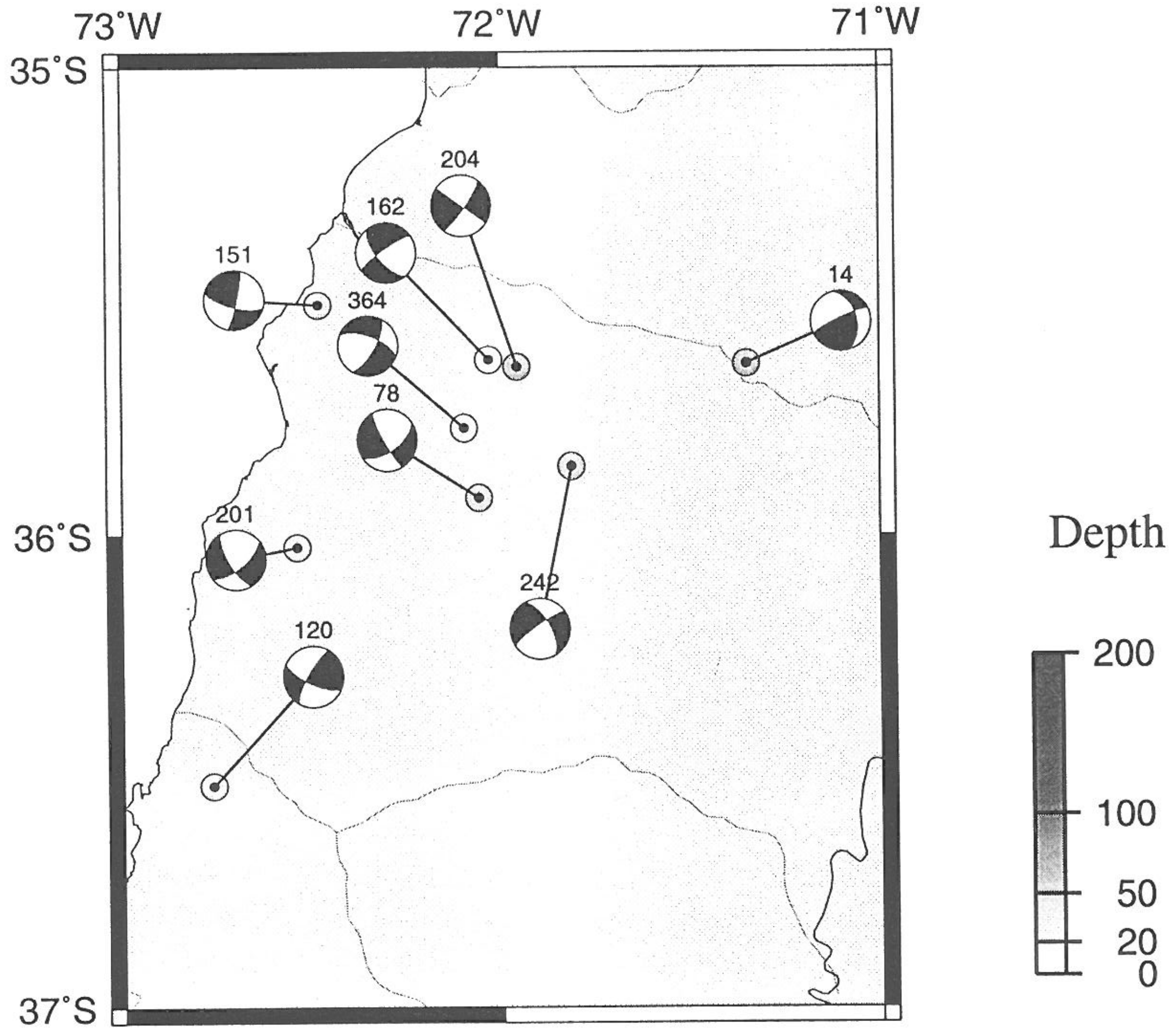


Fig 27

162

Event of 18.04.1996 from 18:52:6

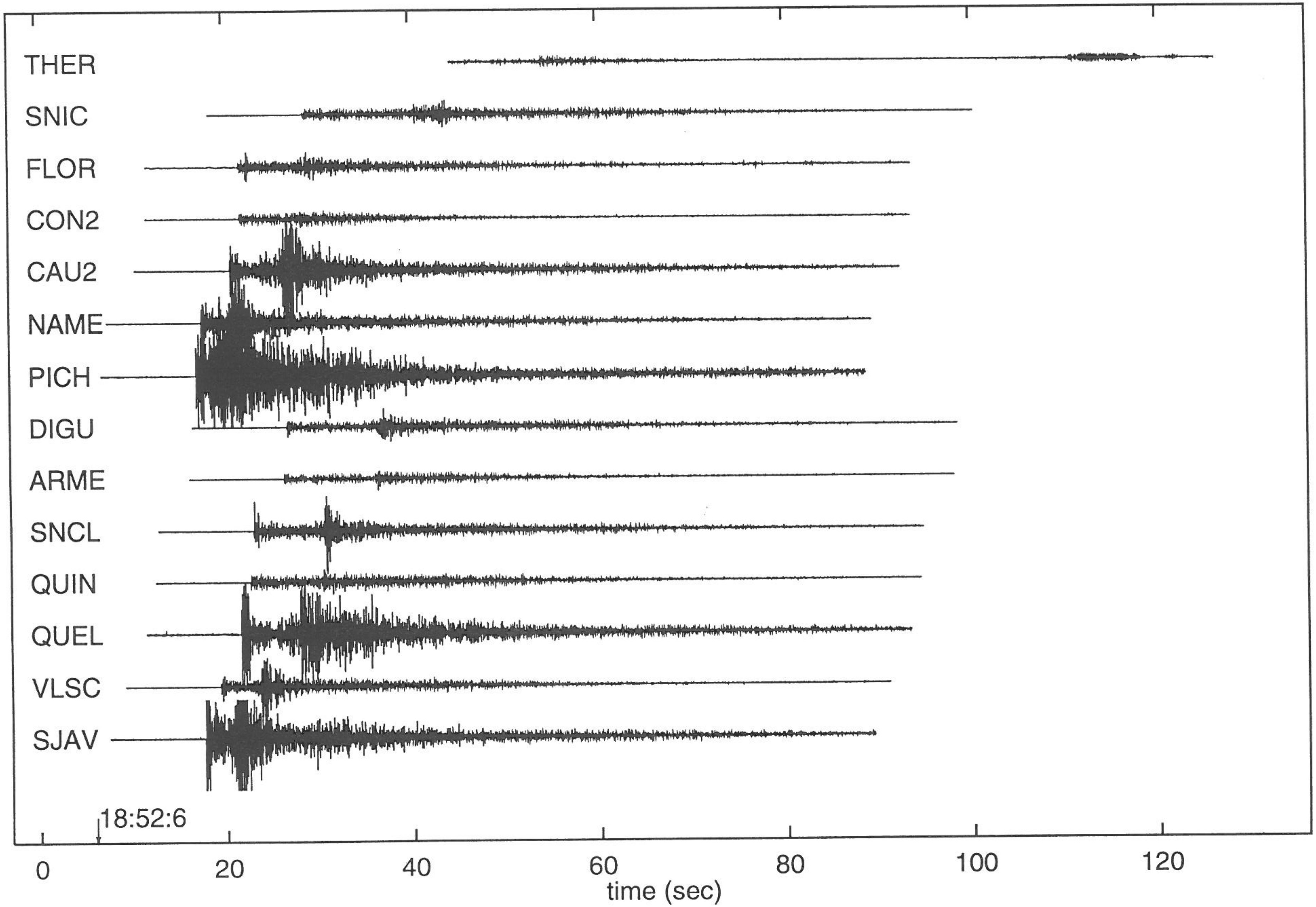


Fig 28

204

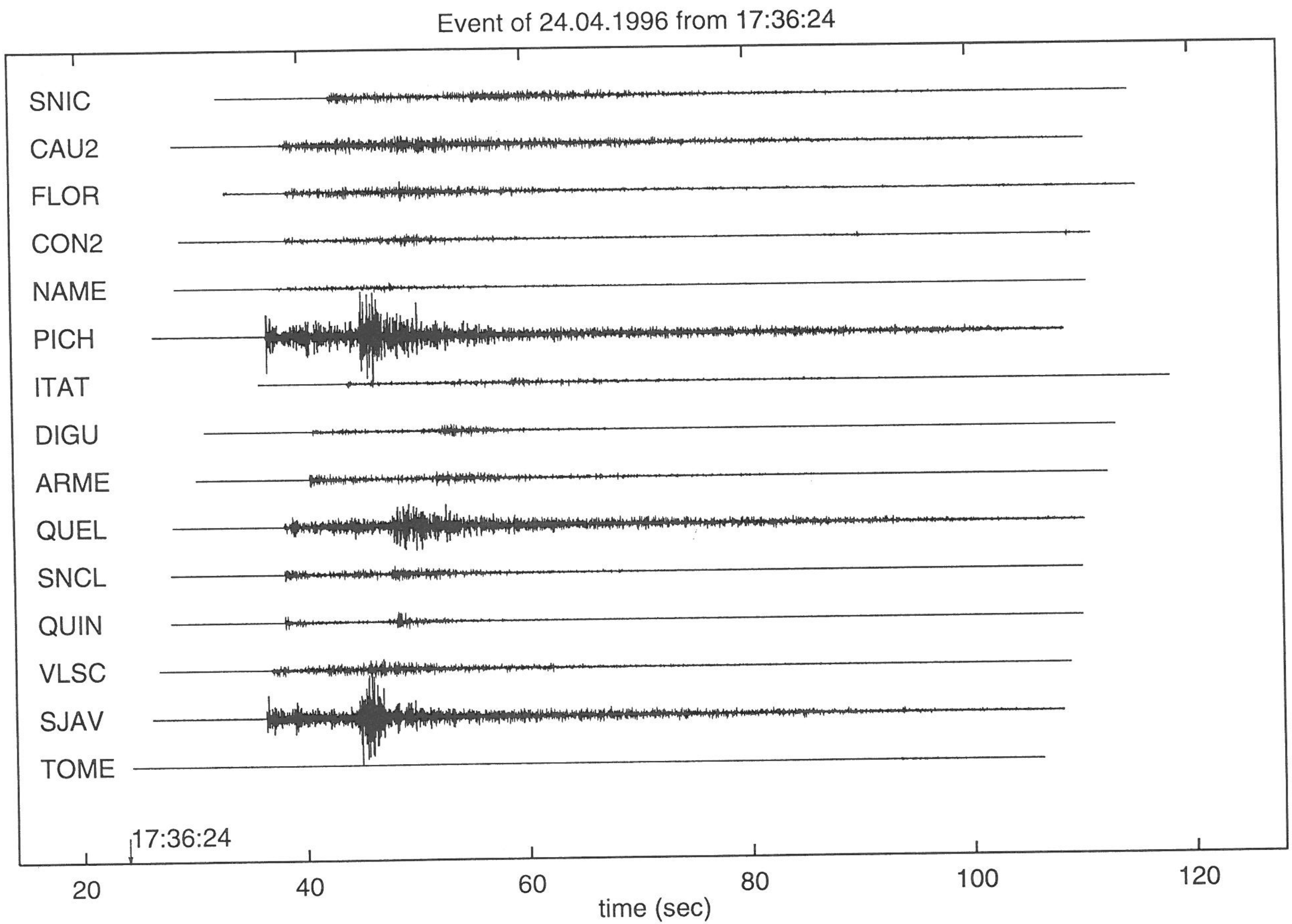
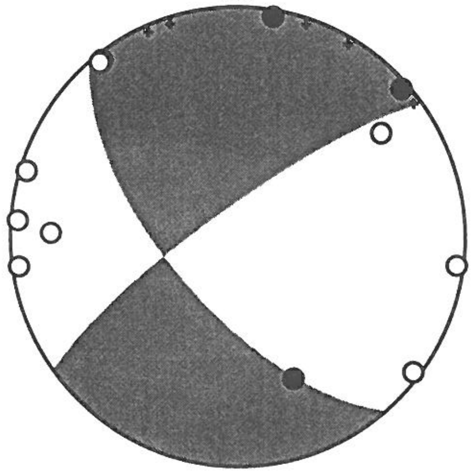
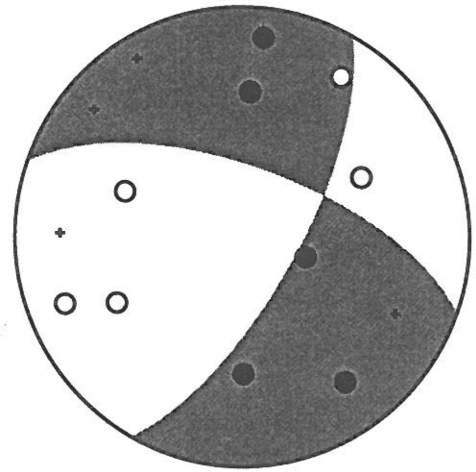

Event of 24.04.1996 from 17:36:24
SNIC
CAU2
FLOR
CON2
NAME
PICH
ITAT
DIGU
ARME
QUEL
SNCL
QUIN
VLSC
SJAV
TOME
17:36:24
20
40
60
80
100
120
time (sec)

Fig 29

Mechanisms of two shallow strike-slip earthquakes in the Central Valley



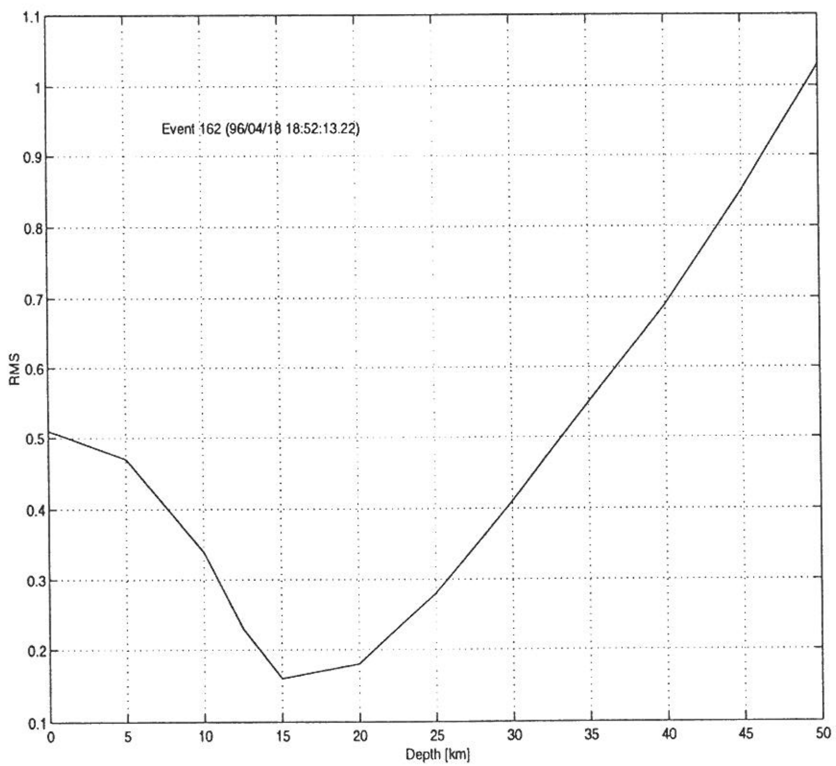
Event No 162



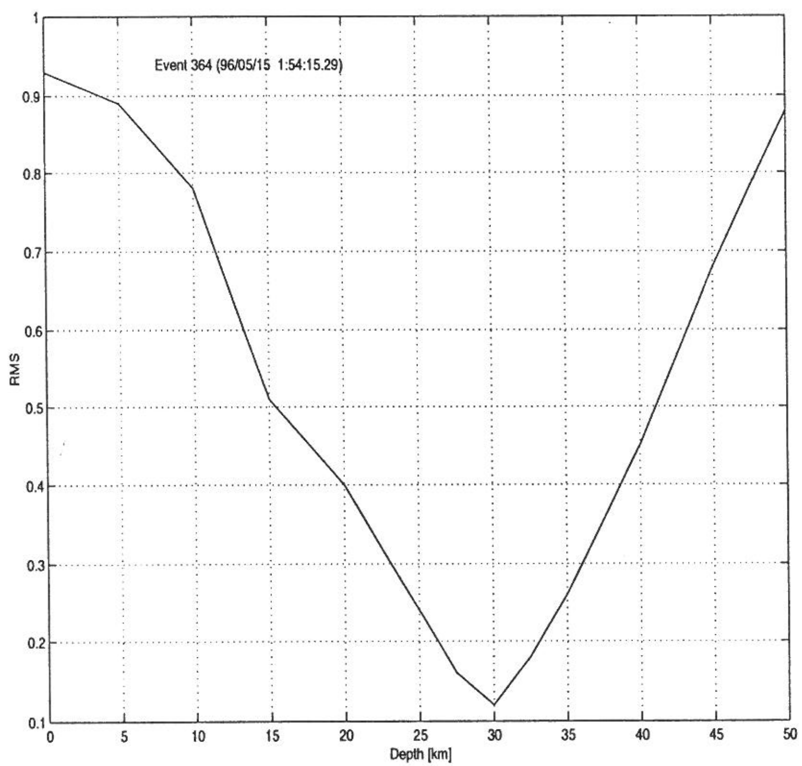
Event No 364

Fig 30

Depth of shallow Central Valley earthquakes



event 162



event 364

Fig 3.1

4 GPS Monitoring of Concepción-Constitución

An essential part of our study is to establish conditions for the long term monitoring of the Concepción Constitución with the goal of detecting long range changes in seismic activity and strain. For this reason we installed a network of GPS sites covering the entire area of the experiment. The goal of this network was to establish an accurate set of geodetic points with the goal of measuring the deformation of the the Concepción Constitución . The network of GPS sites and a first measure of it were carried out from 6 to 14 December 1996.

The network consisted in a set of 33 geodetic sites installed and measured during the campaign of December 1996. Each point was installed and accurately located from observations of GPS signals from two satellites during two sessions of at least 6 hours each. In addition to these points the sites COLB (Colbun), CO60 (Pelluhue) and QLA(Quella) worked continuously during 5 to 6 consecutive day with respect to the IGS network of South America defined byb stations SANT (Santiago), AREQ (Arequipa, Peru), FORT (Fortaleza, Brazil), KOUR (Kourou, French Guyane), BRAZ (Brazilia), EISL (Eastern Island, Chile) and LPGS (La Plata, Argentina).

The GPS network contains three main profiles:

- A NS profile along the Pacific coast between the Maule river (PTU0) and a point south of Concepción PTU, CO1 to CO9, CBQ, CLM, MLA, UCO.
- A WE profile at the Northern edge of the gap extending from Constitución and the Chile-Argentina boundary CO10, CT2, CT3, CT4, COLB, CT6, CT7.
- Another WE profile at the Southern end of the study region from the Arauco peninsula and the Laja lake RMN, LTA, MER, MIR, CLP, LLA
- Some additional GPS points in the Central Valley BAT, PUN, QLA, CHL, NIN.

The participants at this measurement campaign were

1. S. Barrientos DGF Universidad de Chile
2. J. Campos DGF Universidad de Chile
3. T. Monfret DGF Universidad de Chile and Orstom, France
4. J.B. De Chabalier IPG Paris
5. J.C. Ruegg IPG Paris
6. D. Dimitrov, ABS Bulgarie
7. 3 students of the Universidad de Chile.

The instruments consisted of 9 GPS receivers of Ashtech type Z-12 belonging to the French instrument pool of CNRS-INSU. 3 receivers of Trimble SSE type that belong to GFZ Postdam and that were lent to Prof. S. Barrientos of the University of Chile for the duration of this campaign.

Data processing

Daily GPS positions of the network with respect to the IGS network were computed using the GAMIT version 9.72 software. The coordinates of the measuring points were determined by the fit of all daily solutions with respect to the IGS station located in Peldehue near Santiago, Chile. This station was in turn located with respect to the ITRF96 system for day 330 of 1996. The estimated accuracy of these coordinates is estimated to be of the order of 1 cm. On table 4 we present a list of the GPS points established in our field experiment.

Future GPS experiment of March 1999

This field experiment that was originally planned for the end of November 1998 was postponed until March 1999 because of personal problems of one of the main participants. In this campaign all the original GPS points will be reoccupied and a new profile will be developed in the Southern part: this Southern profile was not part of the initial project but it was decided to install it after discussion with the Chilean participants who think that it is necessary to identify the Northern extent of the very big Chilean earthquake of May 1960. As previously discussed the Northern edge of the 1960 rupture zone is generally considered to be the Arauco peninsula, while the southern edge of the previous large earthquake in the Concepción Constitución , that of 1835, is also considered to have stopped near the Arauco peninsula following from Darwin's description of the event. The Arauco peninsula is thus at the edge of the two rupture zones and it has reportedly been raising recently. Its interest in the study of the Concepción Constitución gap is then quite obvious. Unfortunately due to time limitations it was not possible to complete this profile in December 1996. Recently, in December 1997, the central part of the profile was studied by Dr. Jean-Claude Ruegg from IPG in Paris. The following points will be installed in the next campaign due for March 1999:

latitude	longitude	Code	location
-72.3853	-37.215	SLTs	Salto Laja
-72.2292	-37.393	SGDs	San Gerardo
-72.335	-37.345	GUAs	Guanaco
-72.6955	-37.256	LAJs	La Laja
-72.942	-37.285	PULs	Purgatorio
-73.5751	-37.193	LLIa	LLico
-73.4354	-37.246	TUBa	Tubul
-73.2727	-37.245	ARUa	Arauco
-72.467	-37.297	PERs	Perales

Figure caption

Figure 32: GPS network for the monitoring of preseismic deformation in the Concepción Constitución of South Central Chile. In circles the stations deployed and

measured during the first field experiment of December 1996. With triangles we denote the new GPS sites to be installed and measured during the next field experiment due in March 1999.

Conclusions

With the financial support of the European Community a very interesting seismic experiment was carried out in the South Central Chile subduction zone between the coastal cities of Concepción and Constitución in the heart of Chile's prosperous forest industry. All the information we have gathered indicates that the last subduction zone event in this area took place almost 164 years ago in 1835. A very large and destructive event took place in January 1939 but recent studied of this earthquake by Beck et al (1998) indicate that it occurred inside the Wadati-Benioff zone. The most interesting result of our experiment is that the seismicity in the Concepción Constitución gap is very simple indeed. In the two months of our experiment more than 95 % of the events were directly associated to subduction. These are earthquakes that take place inside the subducted Nazca plate as it plunges under Central Chile. Relatively few events were detected in the contact 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. The main surprise 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 (1997) shows practically no event 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 inexistent. In the Concepción Constitución area no major active fault is known to exist near the contact between the Central Valley and the coastal ranges subduction 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, when we planned our experiment we were doubtful that the Concepción Constitución was an active seismic gap. We were the first to be surprised the sheer size of the seismicity recorded during the experiment. This plus all the other observations made during the experiment and the recent work by Beck et al (1998) confirm that our choice of experimental site was judicious. As to Chile, the 1835 gap is probably the most dangerous place in Chile, even more so than the Northern Chile gap between Arica and Antofagasta. Considering the damage produced by the 1939 in Chillán, the monitoring of the Concepción Constitución gap should be a major priority for Chile. The city of Concepción and its neighborhood should be the site of a major effort to reduce seismic hazards.

Acknowledgments

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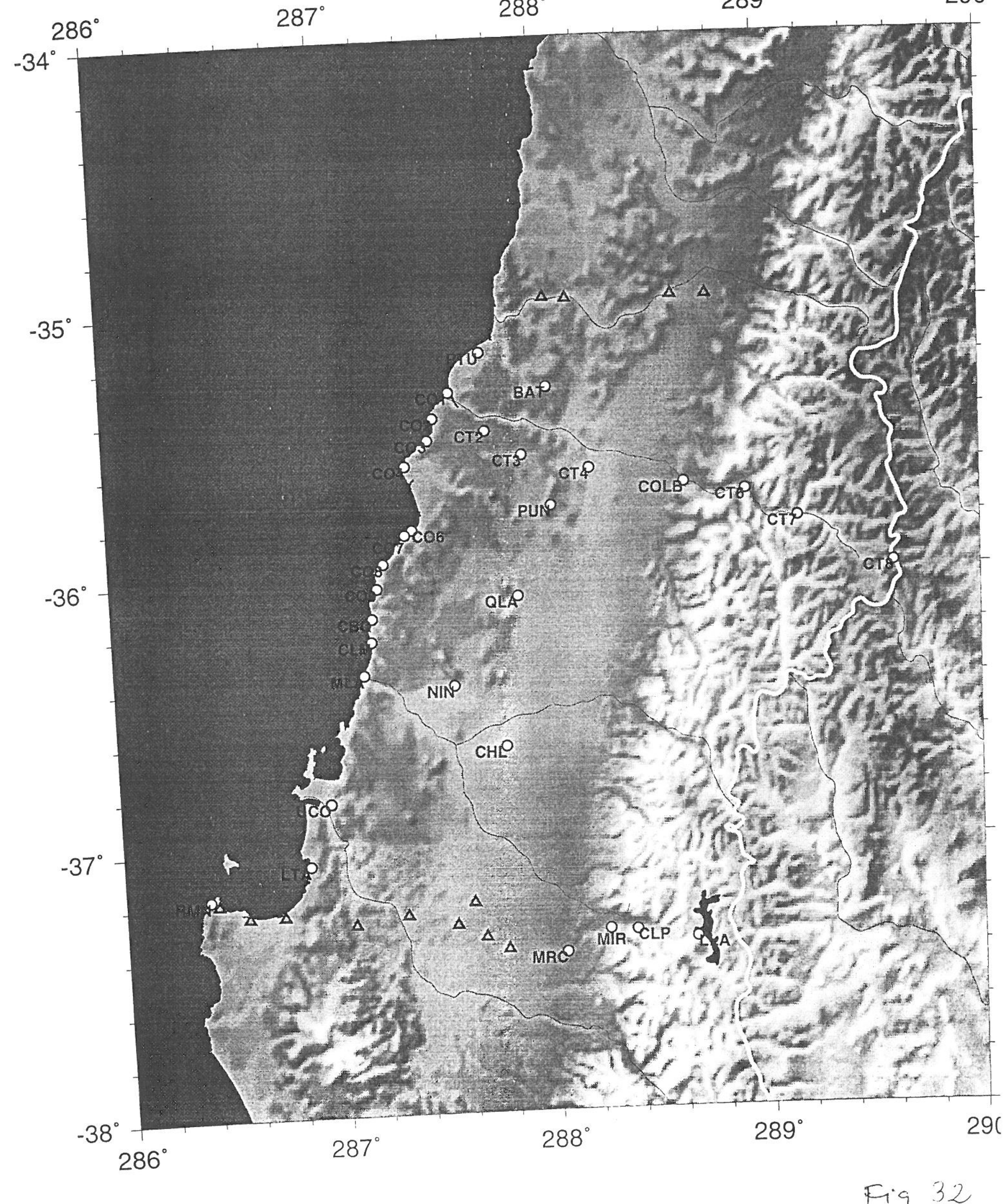

286°
287°
288°
289°
290°
-34°
-35°
-36°
-37°
-38°
BAT
CT2
CT3
CT4
COLB
PUN
CT7
CO6
QLA
NIN
CHL
MIR
CLP
MRC

Fig 32

CI1*-CT94-0109 (DG 12 HSMU).

References

Astiz, L. and H. Kanamori, Interplate coupling and temporal variation of mechanisms of intermediate depth earthquakes in Chile, *Bull. Seismol. Soc. Am.*, **76**, 1614-1622, 1986.

Astiz, L., T. Lay and H. Kanamori, Large intermediate depth earthquakes and the subduction process, *Phys. Earth Planet. Inter.*, **53**, 80-166, 1988.

Barazangi, M. and B.L. Isacks, Spatial distribution of earthquake and subduction of the Nazca plate beneath South America, *Geology*, **4**, 686-692, 1976.

Barrientos, S., Is the Pichilemu-Talcahuano (Chile) a seismic gap? *Seismol. Res. Letters*, **61**, 43, 1987.

Barrientos, S. G. Plafker and E. Lorca, Post-seismic coastal uplift in southern Chile, *Geophys. Res. Lett.*, **19**, 701-704, 1992.

Barrientos, S. and S. N. Ward, The 1960 Chile earthquake: Inversion for slip distribution from surface deformation, *Geophys. J. Int.*, **103**, 589-598, 1990.

Beck, S., S. Barrientos, E. Kausel and M. Reyes, Source characteristics of historic earthquakes along the central Chile subduction zone. *J. South American Earth Sci.*, **11**, 115-129, 1998.

Cifuentes, I. L., The 1960 Chilean earthquakes, *J. Geophys. Res.*, **94**, 665-680, 1989.

Compte, D., A. Eisenberg, E. Lorca, M. Pardo, L. Ponce, R. Saragoni, S. K. Singh and G. Suárez, The central Chile earthquake of 3 March 1985: a repeat of previous great earthquakes in the region?, *Science*, **233**, 449-453, 1986.

Compte D. and G. Suárez, An inverted double seismic zone in Chile: evidence of phase transformation in the subducted slab, *Science*, **263**, 212-215, 1994.

Compte, D., M. Pardo, L. Dorbath, C. Dorbath, H. Haessler, H. Rivera, A. Cisternas and L. Ponce, Determination of seismogenic interplate contact zone and crustal seismicity around Antofagasta, northern Chile, using local data, *Geophys. J. Int.*, **116**, 553-561, 1994a.

Compte D., S.W. Roecker and G. Suárez, Velocity structure in Northern Chile: evidence of subducted oceanic crust in the Nazca plate, *Geophys. J. Int.*, **117**, 625-639, 1994b.

Compte, D. and G. Suárez, Stress distribution and geometry of the subducting Nazca plate in northern Chile using teleseismically recorded earthquakes, *Geophys. J. Int.*, **122**, 419-440, 1995.

Compte, D., L. Dorbath, M. Pardo, T. Monfret, H. Haessler, L. Rivera, M. Frogneux, B. Glass and C. Meneses, A double-planned seismic zone in Arica, Northern Chile using loal seismic data: first approach. submited to *Geophys. Res. Lett*, 1998.

Darwin, C. *Geological observations on coral reefs, volcanic islands and on South America*, 768 pp., Londres, 1851.

Delouis, B., A. Cisternas, L. Dorbath, L. Rivera, E. Kausel, The Andean subduction zone between 22 and 25° (Northern Chile): precise geometry and state of stress, *Tectonophysics*, **259**, 81-100, 1996.

Dorbath, L. A. Cisternas, C. Dorbath, Quantitative assessment of great earthquakes in Peru, *Bull. Seismol. Soc. Am.*, **80**, 551-576, 1990.

Engdahl, E.R., R.D. van der Hilst and J. Berrocal, Imaging of subduced lithosphere beneath South America, *Geophs. Res. Lett.*, **22**, 2317-2320, 1995.

Engdahl, E.R., R.D. van der Hilst and R. Buland, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bull. seismol. Soc. Am.*, **88**, 722-743, 1998.

Fedotov, S. A., Regularities in the disribution of strong earthquakes in Kamchatka, the Kuril Islands and Northeast Japan, *Tr. Inst. Fiz. Zemli Akad. Nauk. SSSR*, **36**, 66693, 1965.

Greve, F., Historia de la Sismolgía en Chile, publicacíon del Instituto de Geofísica y Sismología, Universidad de Chile, Santiago, 1964.

Gutenberg, B. and Richter, The seismicity of the Earth. Special Public. *Geological. Soc. Amer. Special Papers*, 1941.

Kausel, E. and J. Campos, The $M_s = 8$ tensional earthquake of 9 December 1950 of Northern Chile and its relation to the seismic potential of the region, *Phys. Earth Planet. Int.*, **72**, 220-235, 1992.

Kelleher, J. Rupture zones of large South American earthquakes and some predictions, *J. Geophys. Res.*, **77**, 2087-2103, 1972.

Kelleher, J., L. R. Sykes and J. Oliver, Possible criteria for predicting earthquake location and their applications to major plate boundaries of he Pacific and Caribean, *J. Geophys. Res.*, **78**, 2547-2585, 1973.

Korrat, I. and R. Madariaga, Rupture of the Valparaiso (Chile) Gap form 1971 to 1973. Proceedings of 5th Ewing Symposium, American Geophysical Union, Washington D.C., 1986.

Lomnitz, C. , Grandes terremotos y tsunamis en Chile durante el período 1535-1955, *Geofis. Panamericana*, **1**, 151-178, 1971.

McCann, W.R., S.P. Nishenko, L.R. Sykes and J. Krause, Seismic gaps and plate tectonics: seismic potential for major plate boundaries, *Pageoph*, **117**, 1082-1147, 1979.

Madariaga, R. The seismicity of Chile, in press, *Ediciones de la Universidad Complutense de Madrid*, 1998.

Malgrange, M., A. Deschamps and R. Madariaga, Thrust and extensional faulting under the Chilean coast : 1965 and 1971 Aconcagua Earthquakes. *Geophys. J.R. Astr. Soc.*, **66**, 313-332, 1981.

Malgrange, M. and R. Madariaga, Complex distribution of large thrust and normal fault earthquakes in the Chilean subduction zone. *Geophys. J. R. Astr. Soc.*, **73**, 489-506, 1983.

Montessus de Ballore, F. Historia Sísmica de los Andes Meridionales, 6 vols. *Editorial Cervantes*, Santiago de Chile, 1911-1916.

Nishenko, S., Seismic potential for large and great interplate earthquakes along the Chilean and Southern Peruvian margins of South America: a quantitative reappraisal, *J. Geophys. Res.*, **90**, 3589-3615, 1985.

Perrey, A. Documents rélatifs aux tremblements de terre du Chili, *Ann. Soc. Impérial. d'Agriculture*, 206 PP. Barret, Lyon, France, 1854.

Pardo, M., D. Compte, T. Monfret, E. Vera and A. Fuenzalida, Central Chile P-wave tomography: time and space velocity variations within the 1985 earthquake rupture zone, preprint. 1998

Plafker, G. and J. C. Savage, Mechanism of the Chilean earthquake of May 21 and 22, 1960, *Geol. Soc. Am. Bull.*, **81**, 1001-1030, 1970.

Ponce, L., C. San Martín y E. Kausel, Características de la sismicidad (1965-1993, M$\geq$4.7) asociada a la brecha sísmica "Pichilemu-Concepción". *Actas 7o Congreso Geológico Chileno, vol 1*, Univ. de Concepción, 689-694, 1994.

Stauder, W. , Mechanism and spatial distribution of Chilean earthquakes with relation to subduction of the oceanic plate, *J. Geophys. Res.*, **78**, 5033-5061, 1973.

Tichelaar, B. and L. Ruff, Seismic coupling along the Chilean subduction zone, *J. Geophys. Res.*, **96**,11997-12022, 1991.

Urrutia, R. and C. Lanza, Catástrofes en Chile, 1541-1992, *Edit. La Noria*, Santiago, Chile, 1993.

Vita-Finzi, C. and C. D. Mann, Seismic folding in coastal south central Chile, *J. Geophys. Res.*, **99**, 12289-1229, 1994.

Table 1. Seismic Stations deployed in the 1996 campaign

Station	Longitude	Latitude
CAUQ	-72.39466858	-35.89466858
CAU2	-72.39783478	-35.89466858
PEHU	-71.10083008	-35.70283508
FLOR	-72.59183502	-35.56666565
CONS	-72.45549774	-35.36116791
CON2	-72.45383453	-35.36116791
NAME	-72.22566986	-35.74066544
PICH	-72.09566498	-35.49266815
ITAT	-72.81766510	-36.39016724
QUEL	-72.12633514	-36.08499908
VLSC	-71.81083679	-35.86883163
SNIC	-72.21666718	-36.52016830
SJAV	-71.77050018	-35.63916779
SNCL	-71.36299896	-35.56100082
QUIN	-71.42416382	-35.79616547
DIGU	-71.45766449	-36.23116684
NIPA	-72.59166718	-36.62799835
THER	-71.49266815	-36.91600037
CARM	-71.96666718	-36.90000153
PINT	-71.77083588	-36.79666519
FLRD	-72.61916351	-36.79650116
TOME	-72.85766602	-36.63116837
SNFB	-71.53849792	-36.56000137
CACH	-71.72166443	-36.45750046
TORE	-72.32533264	-36.32149887
QUIR	-72.50433350	-36.28049850
COBQ	-72.80783081	-36.09749985
ARME	-71.09716797	-35.69866562

Table 2. Selected events from the 1996 campaign

Date	time			Latitude	Longitude	depth
22/ 3/96	00	01	46.03	-71.74000	-36.13267	77.38
23/ 3/96	02	34	24.76	-71.85033	-33.04483	128.92
23/ 3/96	03	44	5.47	-71.86133	-35.56183	73.65
23/ 3/96	21	01	18.40	-71.42200	-35.56900	91.09
24/ 3/96	05	54	52.12	-72.35250	-37.72800	92.79
24/ 3/96	15	54	58.28	-72.50750	-34.04483	57.88
24/ 3/96	16	01	22.86	-72.37800	-36.04883	70.99
25/ 3/96	02	54	42.17	-72.84333	-36.92433	38.23
25/ 3/96	04	31	45.55	-73.97800	-35.01233	25.23
25/ 3/96	09	34	30.46	-72.59033	-36.57400	40.11
25/ 3/96	09	57	25.48	-71.35083	-35.63917	102.26
27/ 3/96	03	45	19.71	-71.74800	-36.57267	88.57
27/ 3/96	07	27	51.01	-72.79083	-36.75000	53.13
28/ 3/96	00	26	10.96	-70.89750	-35.92167	5.96
28/ 3/96	01	03	59.25	-71.78750	-34.70483	33.86
28/ 3/96	10	43	1.73	-71.60233	-34.70450	67.21
28/ 3/96	11	04	59.20	-71.75000	-34.63817	43.19
28/ 3/96	12	09	12.85	-71.21550	-34.92850	98.45
28/ 3/96	17	53	48.92	-71.52633	-34.04567	94.24
28/ 3/96	19	47	21.72	-72.30450	-35.99183	72.45
29/ 3/96	22	19	43.65	-71.49567	-35.46983	88.97
29/ 3/96	22	42	50.66	-72.37300	-36.58850	53.71
30/ 3/96	00	48	20.79	-71.35300	-35.49783	92.78
30/ 3/96	02	11	4.48	-72.59817	-35.10117	22.45
30/ 3/96	17	35	3.11	-72.67283	-36.33033	35.38
30/ 3/96	18	43	30.32	-73.78350	-37.17517	32.58
30/ 3/96	22	10	11.18	-73.80317	-37.05200	35.69
30/ 3/96	22	26	46.32	-71.09817	-34.91933	100.57
31/ 3/96	00	26	13.85	-74.13200	-35.53450	18.27
31/ 3/96	01	04	37.55	-72.03900	-32.79367	118.72
31/ 3/96	03	58	59.61	-71.03800	-33.43383	111.63
31/ 3/96	05	21	48.90	-70.98450	-35.27767	111.54
31/ 3/96	07	49	18.66	-71.11017	-33.73183	105.99
31/ 3/96	09	16	15.08	-71.72450	-36.22217	82.00
31/ 3/96	12	42	3.27	-72.10767	-34.44350	37.25
31/ 3/96	16	41	18.74	-71.62750	-36.52483	95.24
31/ 3/96	17	53	40.83	-72.12050	-36.63350	62.22
31/ 3/96	23	09	59.34	-71.86483	-35.70417	59.71
1/ 4/96	00	21	33.87	-70.98683	-32.13950	138.63
1/ 4/96	00	31	42.55	-71.41950	-37.51717	126.25
1/ 4/96	05	28	11.07	-72.75667	-35.76483	19.23

Table 2. Selected events from the 1996 campaign

Date	time			Latitude	Longitude	depth
1/ 4/96	05	56	32.61	-70.89533	-35.27850	108.57
1/ 4/96	06	24	51.05	-71.77383	-35.90733	68.19
1/ 4/96	08	47	40.05	-71.79683	-36.31917	83.56
1/ 4/96	10	51	15.66	-72.28883	-36.30783	61.17
2/ 4/96	10	15	18.04	-73.02650	-36.26667	25.46
2/ 4/96	11	18	36.45	-71.37417	-35.58850	95.82
2/ 4/96	13	46	4.23	-71.60050	-36.79583	104.15
2/ 4/96	21	32	30.54	-70.15567	-34.34883	0.30
3/ 4/96	00	56	59.68	-70.71133	-34.82867	154.45
3/ 4/96	01	06	50.66	-70.91950	-34.42800	123.63
3/ 4/96	03	13	54.16	-73.08367	-35.95250	13.72
3/ 4/96	17	53	40.56	-71.80033	-36.28350	73.92
4/ 4/96	08	16	19.73	-71.46433	-36.16267	103.55
4/ 4/96	12	20	55.93	-71.35600	-36.87100	4.69
5/ 4/96	00	58	45.37	-72.05817	-35.92183	59.28
5/ 4/96	01	56	27.93	-72.59867	-36.11783	62.11
5/ 4/96	06	39	22.10	-70.69983	-35.76750	142.70
5/ 4/96	17	39	44.69	-71.56017	-35.99933	85.26
5/ 4/96	19	54	32.30	-71.38083	-35.84650	102.53
6/ 4/96	02	23	49.49	-71.75850	-36.65517	90.67
6/ 4/96	09	58	2.74	-72.94117	-36.38183	25.08
6/ 4/96	10	47	16.02	-73.93850	-34.73700	52.35
6/ 4/96	23	40	3.85	-71.26567	-35.60067	102.63
7/ 4/96	02	27	21.59	-71.77367	-34.67633	40.47
7/ 4/96	06	28	48.18	-71.02500	-35.03967	112.48
7/ 4/96	15	23	24.40	-71.57567	-34.66850	63.65
7/ 4/96	19	47	22.05	-71.27500	-36.46167	126.52
8/ 4/96	07	55	34.98	-74.92783	-38.01233	18.36
8/ 4/96	17	29	37.77	-71.54150	-35.27333	61.57
8/ 4/96	18	19	26.58	-71.58000	-36.10467	90.30
9/ 4/96	02	04	42.54	-70.38217	-32.22750	164.89
9/ 4/96	05	10	1.27	-71.99567	-36.38233	66.19
9/ 4/96	06	01	29.15	-71.68450	-35.90450	84.03
9/ 4/96	11	34	2.11	-71.59967	-35.93433	75.54
9/ 4/96	18	41	34.45	-72.37633	-35.03117	48.03
9/ 4/96	19	53	38.51	-72.12333	-36.87917	70.77
9/ 4/96	21	37	20.06	-71.58517	-35.83917	75.83
10/ 4/96	03	58	21.42	-72.45417	-36.98333	58.93
10/ 4/96	08	15	8.10	-71.20883	-34.46767	57.93
10/ 4/96	09	22	43.23	-72.27633	-37.12250	66.66
10/ 4/96	10	48	22.37	-71.39300	-35.68217	94.09

Table 2. Selected events from the 1996 campaign

Date	time			Latitude	Longitude	depth
10/ 4/96	23	23	33.07	-72.05500	-36.05267	61.49
11/ 4/96	00	02	49.80	-72.76200	-36.53033	39.47
11/ 4/96	01	25	48.98	-71.42000	-35.75950	100.62
12/ 4/96	20	02	51.87	-71.40217	-35.65717	94.05
13/ 4/96	13	26	52.31	-72.25167	-37.48867	91.88
13/ 4/96	13	34	16.49	-71.44233	-35.73533	99.94
13/ 4/96	14	43	22.02	-71.24683	-34.93800	101.89
14/ 4/96	09	25	4.51	-71.74333	-35.65950	68.27
14/ 4/96	10	58	50.86	-71.71550	-36.26067	81.88
15/ 4/96	00	49	23.24	-71.18967	-35.39467	119.28
15/ 4/96	01	59	27.72	-72.20800	-37.01617	61.76
15/ 4/96	03	51	57.11	-72.18217	-36.29867	51.67
15/ 4/96	16	25	4.06	-72.47717	-36.00167	45.20
15/ 4/96	22	21	55.16	-71.92450	-37.05983	102.16
16/ 4/96	01	07	35.75	-71.08850	-35.11217	104.32
16/ 4/96	03	00	44.45	-72.16617	-34.79333	41.68
16/ 4/96	06	18	56.80	-71.90100	-36.12317	64.79
16/ 4/96	13	45	4.69	-71.68350	-35.70117	69.76
16/ 4/96	23	37	20.58	-70.91050	-35.31933	110.61
17/ 4/96	06	21	53.36	-71.45967	-35.64350	75.70
17/ 4/96	07	16	4.83	-71.72717	-35.72917	80.80
17/ 4/96	09	48	26.95	-72.83917	-37.05150	43.27
17/ 4/96	11	11	6.71	-73.25900	-33.60967	69.69
17/ 4/96	11	46	49.81	-72.48183	-35.51267	40.55
17/ 4/96	21	17	55.11	-72.28267	-31.13767	155.88
17/ 4/96	21	44	2.02	-71.85450	-35.85750	78.70
17/ 4/96	23	29	1.89	-72.08183	-36.89400	71.07
18/ 4/96	00	46	18.07	-71.14650	-35.22000	106.61
18/ 4/96	01	54	48.59	-70.84183	-34.64867	121.32
18/ 4/96	11	02	36.27	-72.34383	-37.93283	109.26
18/ 4/96	14	11	8.14	-71.35700	-36.19850	107.50
18/ 4/96	18	52	13.25	-72.03050	-35.63083	15.24
19/ 4/96	03	06	51.18	-71.37700	-35.61383	100.71
19/ 4/96	10	34	24.21	-71.35017	-35.17950	95.21
19/ 4/96	12	03	10.32	-72.64867	-35.36700	28.48
19/ 4/96	12	18	53.50	-72.69750	-35.09767	17.67
19/ 4/96	18	32	40.28	-71.60983	-35.89333	84.12
19/ 4/96	20	25	13.81	-71.37917	-36.48167	105.02
20/ 4/96	02	08	3.30	-72.51233	-34.86700	17.68
20/ 4/96	03	53	54.76	-71.14817	-36.78650	150.69
20/ 4/96	08	59	0.35	-75.01483	-36.95267	11.54
20/ 4/96	09	27	4.84	-71.38250	-35.57533	94.05

Table 2. Selected events from the 1996 campaign

Date	time			Latitude	Longitude	depth
20/ 4/96	09	60	18.20	-71.24850	-35.22050	88.12
20/ 4/96	10	37	50.31	-71.26617	-36.04050	108.55
20/ 4/96	13	14	55.95	-71.12200	-34.97933	104.73
20/ 4/96	13	31	52.51	-71.43350	-35.79583	98.56
20/ 4/96	17	51	5.00	-71.19183	-35.55200	103.37
20/ 4/96	21	21	59.68	-72.49717	-35.93633	34.62
20/ 4/96	23	55	38.20	-71.35417	-35.59233	93.74
21/ 4/96	04	04	54.14	-72.58333	-36.15950	43.69
21/ 4/96	09	34	24.13	-71.10117	-34.90183	103.75
21/ 4/96	10	59	15.71	-73.04500	-37.42767	42.02
21/ 4/96	15	58	23.16	-70.86917	-35.89150	4.51
21/ 4/96	18	20	25.91	-73.35033	-36.52500	12.81
21/ 4/96	20	38	55.15	-71.46750	-35.79033	93.54
22/ 4/96	00	57	36.50	-72.22750	-36.94500	60.19
22/ 4/96	06	33	37.32	-72.22083	-36.96067	62.66
22/ 4/96	07	09	7.11	-70.72333	-35.47667	130.91
22/ 4/96	07	14	14.56	-72.11350	-35.68750	56.84
22/ 4/96	07	54	35.61	-72.88567	-36.53817	41.18
22/ 4/96	09	45	34.48	-71.96500	-36.17217	65.59
22/ 4/96	10	06	7.29	-71.98100	-36.68483	87.37
22/ 4/96	11	35	31.22	-69.74600	-31.91617	350.77
23/ 4/96	05	05	31.14	-73.42717	-36.71400	19.10
23/ 4/96	06	18	33.80	-72.50983	-35.92967	29.05
23/ 4/96	06	59	25.10	-72.05350	-35.82117	26.19
23/ 4/96	19	24	53.21	-71.81933	-36.12183	80.39
23/ 4/96	19	30	52.08	-71.13417	-35.01867	100.92
24/ 4/96	00	24	5.83	-71.96133	-36.03900	58.00
24/ 4/96	03	21	19.59	-72.53833	-36.02550	46.93
24/ 4/96	08	49	41.97	-71.32000	-36.12817	107.01
24/ 4/96	08	52	42.88	-71.79633	-36.01600	68.03
24/ 4/96	17	36	25.22	-71.95533	-35.64700	77.71
24/ 4/96	18	41	49.32	-71.93783	-36.91467	87.13
25/ 4/96	06	29	27.06	-71.73717	-36.15450	88.67
25/ 4/96	17	12	3.57	-73.57233	-34.32450	36.29
26/ 4/96	05	38	59.30	-72.15067	-36.35217	56.39
26/ 4/96	08	23	24.51	-70.50333	-33.47133	161.33
26/ 4/96	08	35	58.83	-73.22617	-36.49183	26.21
26/ 4/96	08	54	27.33	-71.41100	-35.64867	101.20
26/ 4/96	09	16	27.69	-71.17667	-36.73050	136.81
26/ 4/96	13	16	31.64	-71.83550	-37.25733	114.01
26/ 4/96	19	06	43.61	-71.59683	-37.19583	119.79
26/ 4/96	20	51	32.86	-72.65417	-36.38067	46.51

Table 2. Selected events from the 1996 campaign

Date	time			Latitude	Longitude	depth
27/ 4/96	00	52	25.24	-72.32467	-36.98633	58.22
27/ 4/96	12	46	49.24	-71.65850	-35.93483	75.47
27/ 4/96	14	44	42.07	-73.06117	-36.66967	34.72
27/ 4/96	18	51	33.18	-71.37067	-35.84600	97.37
27/ 4/96	21	46	54.74	-71.54967	-35.91767	82.77
28/ 4/96	00	04	22.57	-70.96933	-36.29750	134.31
28/ 4/96	02	39	6.15	-72.08917	-34.70167	69.63
28/ 4/96	03	17	36.98	-72.25250	-35.28867	44.16
28/ 4/96	10	55	45.40	-71.25550	-36.14533	111.35
28/ 4/96	11	44	19.91	-71.81417	-36.14100	68.30
28/ 4/96	16	45	27.37	-72.75500	-36.04783	36.18
28/ 4/96	18	47	34.81	-71.42950	-36.87883	2.90
28/ 4/96	20	58	23.35	-71.50333	-35.45883	93.51
29/ 4/96	00	02	5.88	-71.53733	-36.14000	95.39
29/ 4/96	20	11	27.21	-72.28850	-32.41567	127.76
29/ 4/96	21	38	58.30	-71.34783	-35.06733	81.41
30/ 4/96	04	31	29.91	-72.44917	-35.51667	8.33
30/ 4/96	06	41	25.64	-71.86450	-35.72267	61.22
30/ 4/96	10	21	34.65	-71.81367	-35.85450	65.85
30/ 4/96	14	46	19.34	-70.33600	-31.62300	116.11
30/ 4/96	16	17	23.91	-70.76617	-34.55350	144.32
30/ 4/96	17	28	44.15	-73.02300	-36.40250	28.85
30/ 4/96	20	18	38.00	-71.48700	-36.13050	102.49
30/ 4/96	22	27	51.46	-71.37917	-35.87917	98.79
30/ 4/96	23	47	48.34	-71.17650	-35.49500	110.72
1/ 5/96	03	02	29.54	-72.46333	-35.57967	32.38
1/ 5/96	04	31	29.69	-71.89100	-36.17317	66.09
1/ 5/96	07	56	45.61	-73.71017	-34.93367	66.28
1/ 5/96	11	41	7.55	-72.44033	-35.25250	18.70
1/ 5/96	23	56	46.83	-71.52133	-37.39450	133.81
2/ 5/96	01	51	27.85	-72.78717	-35.28500	12.51
2/ 5/96	02	12	36.50	-71.13367	-34.97183	108.37
2/ 5/96	03	42	18.49	-71.74183	-35.67550	80.84
2/ 5/96	06	11	27.79	-72.76683	-36.17033	48.42
2/ 5/96	08	20	16.47	-71.65683	-33.94683	94.06
2/ 5/96	10	36	21.55	-71.38933	-35.51300	96.33
3/ 5/96	00	55	43.12	-72.41650	-32.18033	99.91
3/ 5/96	01	59	34.99	-72.12667	-37.42433	98.09
3/ 5/96	02	03	4.36	-72.10817	-36.23417	55.07
3/ 5/96	05	16	41.57	-71.22183	-37.49100	162.83

Table 2. Selected events from the 1996 campaign

Date	time			Latitude	Longitude	depth
3/ 5/96	08	01	46.99	-71.50883	-35.85233	90.40
3/ 5/96	17	50	20.15	-72.75100	-36.84800	50.68
3/ 5/96	22	57	32.34	-71.53933	-36.10417	98.12
4/ 5/96	04	42	55.31	-71.32683	-35.42183	93.12
4/ 5/96	05	13	5.95	-72.02717	-36.12950	58.16
5/ 5/96	01	04	22.79	-71.72000	-36.00100	69.58
5/ 5/96	07	42	27.38	-72.97517	-36.25217	19.25
5/ 5/96	10	00	13.49	-70.93650	-34.63200	126.01
5/ 5/96	10	09	30.44	-72.94983	-36.25067	20.14
5/ 5/96	18	21	51.89	-71.06217	-34.18800	134.72
6/ 5/96	03	20	31.84	-70.99250	-35.09100	106.34
6/ 5/96	06	28	13.84	-73.20517	-36.36633	20.51
6/ 5/96	07	11	37.02	-71.35133	-35.60083	96.91
6/ 5/96	09	15	53.13	-73.21667	-36.38567	27.52
6/ 5/96	10	56	4.27	-73.23667	-36.35833	24.39
6/ 5/96	16	40	37.52	-71.37900	-36.17750	99.86
6/ 5/96	19	16	49.86	-70.21467	-33.22300	138.03
7/ 5/96	00	58	54.24	-72.66917	-35.30633	15.82
7/ 5/96	07	12	9.71	-71.78017	-35.44967	64.54
7/ 5/96	13	17	12.90	-71.41317	-32.47667	129.50
7/ 5/96	20	54	25.69	-71.34950	-35.34900	96.83
8/ 5/96	10	23	47.98	-71.75917	-35.92367	70.76
8/ 5/96	10	58	31.24	-71.41500	-35.50867	88.66
8/ 5/96	14	27	33.34	-71.49617	-35.91217	98.55
8/ 5/96	18	49	27.50	-72.82733	-36.32717	39.47
8/ 5/96	23	50	34.58	-73.10067	-39.44583	146.87
9/ 5/96	04	19	12.37	-73.03167	-36.30033	25.51
9/ 5/96	04	59	42.63	-70.25067	-36.54550	1.32
9/ 5/96	05	09	30.35	-70.27867	-36.54750	0.63
9/ 5/96	05	37	36.05	-72.06100	-37.17483	89.45
9/ 5/96	13	39	38.13	-70.95117	-35.33150	110.06
9/ 5/96	22	50	1.12	-71.82250	-36.69883	88.30
10/ 5/96	00	32	20.36	-71.52767	-35.87883	87.86
10/ 5/96	01	27	34.09	-72.10300	-34.49833	38.69
10/ 5/96	02	09	50.13	-72.50667	-35.18483	12.55
10/ 5/96	04	45	26.84	-73.27833	-36.18367	16.27
10/ 5/96	05	36	44.43	-72.05517	-31.99433	123.90
10/ 5/96	06	11	22.17	-71.29733	-35.58233	97.43
10/ 5/96	07	44	9.86	-71.51200	-35.46583	88.34
10/ 5/96	08	03	20.95	-71.86867	-36.13533	78.09
10/ 5/96	08	06	54.74	-73.74983	-38.21517	101.01
10/ 5/96	14	58	8.69	-70.50850	-33.63050	184.48

Table 2. Selected events from the 1996 campaign

Date	time			Latitude	Longitude	depth
10/ 5/96	17	22	48.60	-70.74083	-33.39633	152.20
10/ 5/96	17	48	6.41	-71.04517	-36.11850	130.11
11/ 5/96	00	25	25.97	-73.62383	-36.62450	32.40
11/ 5/96	00	29	52.08	-73.30083	-36.19467	31.38
11/ 5/96	03	13	15.55	-71.31017	-36.84300	5.95
11/ 5/96	17	23	50.76	-73.28567	-36.18750	13.22
11/ 5/96	21	47	39.32	-70.29350	-34.44483	2.37
12/ 5/96	02	51	58.36	-72.18600	-36.15883	56.76
12/ 5/96	03	31	57.04	-70.15817	-37.27750	0.56
12/ 5/96	05	01	3.99	-70.47683	-33.11817	160.42
12/ 5/96	13	22	14.90	-71.09233	-35.01133	107.42
12/ 5/96	13	30	45.04	-73.51567	-33.75200	61.38
12/ 5/96	18	15	16.59	-71.74233	-36.98117	8.92
12/ 5/96	19	12	18.15	-71.91567	-36.00300	58.67
12/ 5/96	19	47	35.07	-72.05017	-35.37767	47.82
12/ 5/96	21	42	37.56	-73.26550	-36.20467	12.47
12/ 5/96	22	15	46.69	-72.41833	-34.59367	2.01
13/ 5/96	02	16	42.48	-71.63900	-36.15883	85.81
13/ 5/96	07	49	22.91	-71.37950	-35.64650	99.30
13/ 5/96	08	56	0.18	-70.97500	-34.95283	115.31
13/ 5/96	10	17	11.72	-72.89033	-35.28683	0.59
13/ 5/96	12	33	56.60	-71.24750	-35.48450	92.23
13/ 5/96	20	53	31.23	-71.89650	-36.64883	75.21
13/ 5/96	23	39	25.51	-71.52850	-36.17250	98.71
14/ 5/96	03	57	43.14	-71.79267	-32.08700	114.37
14/ 5/96	12	00	15.17	-73.48967	-36.97700	14.43
14/ 5/96	16	34	46.37	-71.95800	-36.15617	62.13
14/ 5/96	17	16	12.18	-72.08600	-35.77800	30.49
14/ 5/96	17	19	6.32	-72.96967	-36.35800	23.65
14/ 5/96	18	37	22.18	-71.53783	-35.21150	65.26
14/ 5/96	23	34	34.95	-70.65317	-31.81800	121.24
15/ 5/96	01	36	17.37	-71.46083	-35.59383	77.74
15/ 5/96	01	54	15.29	-72.09733	-35.77533	29.90
15/ 5/96	04	31	34.77	-71.28617	-35.73967	101.04
15/ 5/96	04	42	6.70	-71.69333	-36.04200	66.91
15/ 5/96	09	02	35.19	-71.68533	-36.08333	90.66
15/ 5/96	11	40	0.82	-72.23683	-35.53533	12.51
15/ 5/96	14	58	14.77	-75.45950	-39.31317	146.49
16/ 5/96	14	23	20.35	-72.50500	-37.72017	82.51
17/ 5/96	20	23	10.02	-71.71700	-36.03633	82.36
18/ 5/96	02	45	35.34	-71.44500	-35.54667	88.

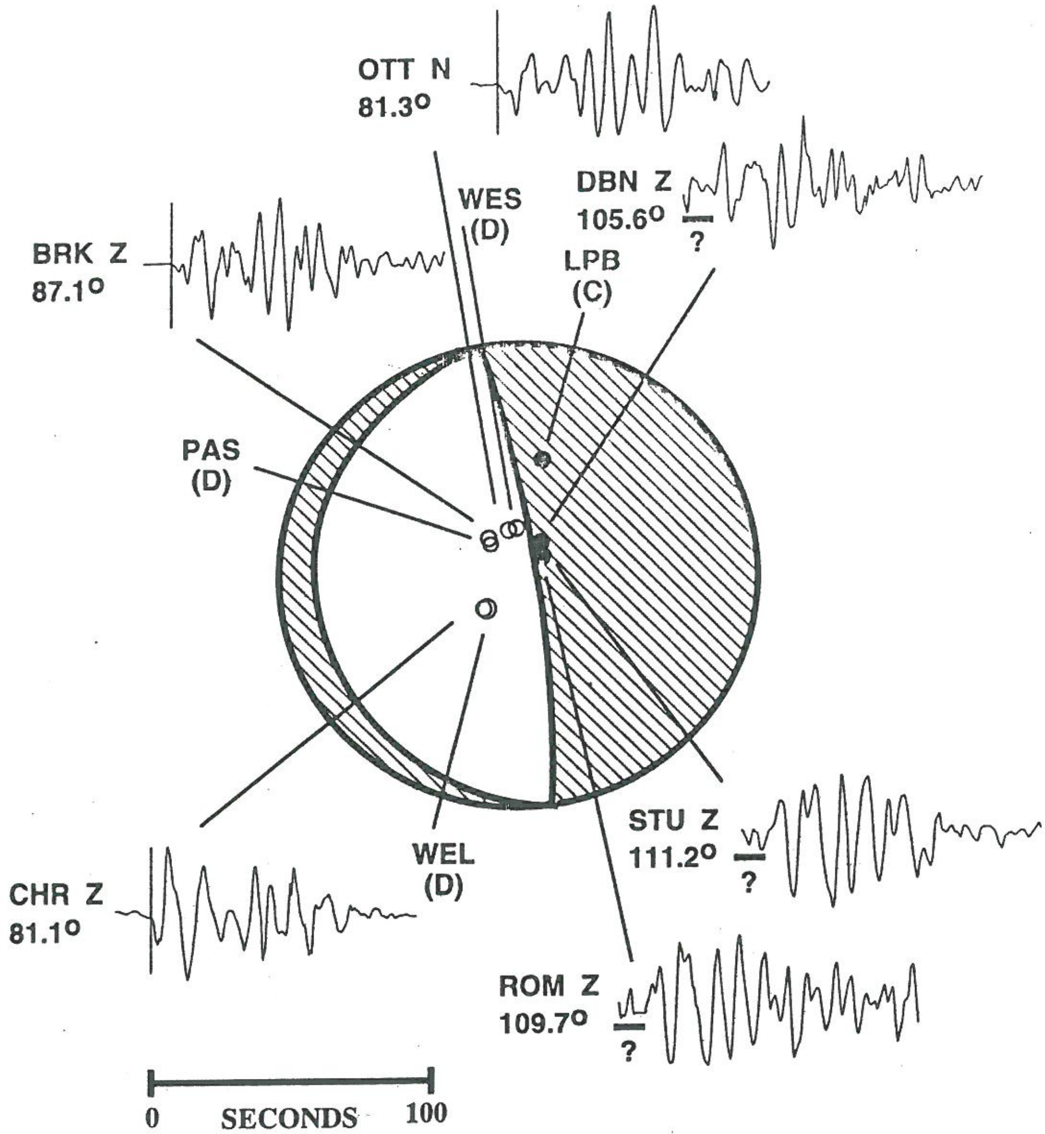
Table 3. Fault Plane solutions for 31 Selected events from the 1996 campaign

Number	date	time	latitude	longitde	depth	az1	pl1	az2	pl2
10	240396	16:01	-36.05	-72.38	71.0	190	85	10	5
14	250396	9:57	-35.64	-71.35	102.3	345	45	245	80
24	280396	19:47	-35.99	-72.30	72.4	195	70	15	20
30	300396	17:35	-36.33	-72.67	35.4	160	40	340	50
40	310396	9:16	-36.22	-71.72	82.0	40	80	220	10
73	040496	8:16	-36.16	-71.46	103.6	330	60	150	30
78	050496	0:58	-35.92	-72.06	59.3	55	60	150	81
103	080496	18:19	-36.10	-71.58	90.3	0	85	180	5
105	090496	5:10	-36.38	-72.00	66.2	45	65	225	25
106	090496	6:01	-35.90	-71.68	84.0	350	80	170	10
120	110496	0:02	-36.53	-72.76	39.5	115	65	210	79
131	140496	9:25	-35.66	-71.74	68.3	80	30	260	60
141	160496	6:18	-36.12	-71.90	64.8	185	45	65	63
143	160496	13:45	-35.70	-71.68	69.8	60	60	240	30
151	170496	11:46	-35.51	-72.48	40.5	105	70	12	81
161	180496	14:11	-36.20	-71.36	107.5	350	60	170	30
162	180496	18:52	-35.63	-72.03	15.2	140	65	235	79
163	190496	3:06	-35.61	-71.38	100.7	10	50	190	40
172	200496	9:27	-35.58	-71.38	94.1	330	70	150	20
174	200496	10:37	-36.04	-71.27	108.6	345	70	165	20
176	200496	13:31	-35.80	-71.43	98.6	335	45	155	45
179	200496	23:55	-35.59	-71.35	93.7	340	60	160	30
201	240496	3:21	-36.03	-72.54	46.9	60	60	160	73
203	240496	8:52	-36.02	-71.80	68.0	30	35	160	65
204	240496	17:36	-35.65	-71.96	77.7	35	80	305	90
234	290496	0:02	-36.14	-71.54	95.4	60	75	240	15
242	300496	10:21	-35.85	-71.81	65.8	235	80	330	63
260	020596	3:42	-35.68	-71.74	80.8	235	85	55	5
272	030596	8:01	-35.85	-71.51	90.4	260	85	80	5
364	150596	1:54	-35.78	-72.10	29.9	30	70	290	64
370	150596	9:02	-36.08	-71.69	90.7	345	70	165	20

Table 4. Network of GPS stations installed in the Concepción-Constitución area

Station	Longitude	Latitude	Longitude	Latitude	height
SANT	-70.66855587	-33.15028957	-70 40 6.8011	-33 9 1.0425	723.059
BAT0	-71.96211695	-35.30664889	-71 57 43.6210	-35 18 23.9360	247.927
CBQ0	-72.80571046	-36.15021016	-72 48 20.5577	-36 9 .7566	28.386
CHL0	-72.20510479	-36.63925028	-72 12 18.3772	-36 38 21.3010	101.883
CLM0	-72.81175938	-36.23645343	-72 48 42.3338	-36 14 11.2323	26.186
CLP0	-71.62550082	-37.33578267	-71 37 31.8029	-37 20 8.8176	669.514
COLB	-71.34676420	-35.67748335	-71 20 48.3511	-35 40 38.9401	454.947
CO10	-72.41488765	-35.31798873	-72 24 53.5955	-35 19 4.7594	64.763
CO20	-72.49094644	-35.41230512	-72 29 27.4072	-35 24 44.2984	26.669
CO30	-72.51917907	-35.49348573	-72 31 9.0446	-35 29 36.5486	35.581
CO40	-72.62578826	-35.58628610	-72 37 32.8377	-35 35 10.6300	48.994
CO60	-72.60555249	-35.82788453	-72 36 19.9889	-35 49 40.3843	102.738
CO61	-72.60449808	-35.82494468	-72 36 16.1931	-35 49 29.8008	63.614
CO70	-72.63903311	-35.84294579	-72 38 20.5192	-35 50 34.6048	27.165
CO80	-72.74438778	-35.94892765	-72 44 39.7960	-35 56 56.1395	27.685
CO90	-72.77787671	-36.04008185	-72 46 40.3562	-36 2 24.2947	29.873
CT20	-72.25542250	-35.46430564	-72 15 19.5210	-35 27 51.5003	264.286
CT30	-72.08610147	-35.55813351	-72 5 9.9653	-35 33 29.2806	190.163
CT40	-71.77653294	-35.61634258	-71 46 35.5186	-35 36 58.8333	164.600
CT60	-71.06891252	-35.70916530	-71 4 8.0851	-35 42 32.9951	553.343
CT70	-70.83353199	-35.81499793	-70 50 .7152	-35 48 53.9925	890.389
CT80	-70.39878456	-35.99073190	-70 23 55.6244	-35 59 26.6349	2539.662
LLA0	-71.34449033	-37.36890626	-71 20 40.1652	-37 22 8.0626	1434.311
LTA0	-73.14226806	-37.05852511	-73 8 32.1650	-37 3 30.6904	23.232
MIR0	-71.74972702	-37.33033010	-71 44 59.0173	-37 19 49.1884	505.988
MLA0	-72.85306803	-36.36053831	-72 51 11.0449	-36 21 37.9379	47.683
MRC0	-71.95459037	-37.41134420	-71 57 16.5253	-37 24 40.8391	372.876
NIN0	-72.43724897	-36.40995016	-72 26 14.0963	-36 24 35.8206	100.003
PTU0	-72.26889660	-35.17222352	-72 16 8.0278	-35 10 20.0047	27.649
PUN0	-71.95685902	-35.74983976	-71 57 24.6925	-35 44 59.4231	203.314
QLA0	-72.12539190	-36.08460777	-72 7 31.4108	-36 5 4.5880	180.757
RMN0	-73.61343000	-37.17381607	-73 36 48.3480	-37 10 25.7378	29.293
UCO0	-73.03531741	-36.82942987	-73 2 7.1427	-36 49 45.9475	58.926

CHILE 1939 EARTHQUAKE



FROMM Beck et al (1998)

Fig 4