

# BROADBAND SEISMIC RECORDINGS OF MINING EXPLOSIONS AND EARTHQUAKES IN SOUTH AMERICA

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## ABSTRACT

*S/P* ratios have shown great promise as discriminants for explosions and earthquakes recorded at regional distances. Spectrograms, or the frequency-time displays of seismograms, have been used to separate explosion populations into those which are single-shot or multiple-hole instantaneous explosions and those which are ripple-fired explosions. However, despite the promise of these discriminants, there are problems of transportability. The character of regional phases is extremely sensitive to differences in propagation paths, and it is essential to calibrate regions of monitoring interest.

We have investigated the seismicity (both natural and man-made) in central Chile recorded on a high-frequency seismic network. We are developing a data base to quantify distance-dependent spectral ratios and other potential discriminants. Within the seismic network is a large open-pit copper mine which has occasional multiple-shot explosions with magnitudes as large as 3.7. We find at close epicentral distances (<~60 km) that mining explosions show spectral scalloping indicative of "ripple-fire" sources and that *S-P* amplitude ratios indicate enhanced *P* wave radiation. However, at epicentral distances of ~100 km the frequency content has decreased, with little energy above 5 Hz. Preliminary analysis indicates that spectral discriminants for earthquakes and ripple-fire explosions at close epicentral distances operate as other investigators have reported for other regions in the world.

**KEYWORDS:** discrimination, regional distance, spectral ratios

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## INTRODUCTION

The spectral characteristics of seismograms recorded at regional distances have been extensively studied in recent years (Bennett *et al.*, 1989; Taylor *et al.*, 1989; Lilwall, 1988) and are some of the most promising discriminants. Most spectral discriminants are based on two conditions: (1) Given the same zero frequency moment, an earthquake will be enriched in high frequencies as compared to an explosion, and (2) earthquakes excite more *S* wave type energy than explosions. Typical spectral discriminants ratio the spectral level or amplitude of *S* and *P* waves. In general, there is good separation of earthquakes and explosion populations, especially at high frequencies ( $f > 6$  Hz) (Kim *et al.*, 1994). Unfortunately, travel path has a strong influence on the "base line" of the trend which separates the explosion and earthquake populations (Lynnes *et al.*, 1990), and travel paths must be carefully calibrated for spectral discriminants to work.

One of the most pressing problems in monitoring a comprehensive test ban is identification of industrial explosions. Richards *et al.* (1992) report that there are literally thousands of industrial explosions in the U.S. every year, many of which have local magnitudes between 2.5 and 3.0. Presently there is considerable discussion on the possibility of clandestine testing using decoupling scenarios. A fully decoupled explosion could produce seismic signals much smaller (factor of 30 to 70) than that of fully tamped events. Thus, clandestine tests of a few kilotons may produce magnitudes of 2.5 to 3.0 and must be discriminated from the mining activity. In general, industrial explosions have spatial-temporal characteristics which can be used to discriminate them from nuclear explosions. Most large mining explosions have a unique signature in the frequency domain due to the "ripple-fire" detonation of "sub" explosions separated by small distances and times. This spectral scalloping is diagnostic of an industrial explosion, but it is most pronounced at frequencies above 10 Hz. In some regions of high seismic attenuation (such as the Basin and Range in the western U.S.), the spectral scalloping disappears beyond a few hundred kilometers. Most of our experience with industrial explosions is limited to a few areas, especially within the U.S. Blasting practice varies dramatically from country to country, so it is essential to calibrate path and source effects in any region of potential monitoring interest.

In this phase of this project we have focused on studying the high-frequency characteristics of seismic events in western South America. In both Chile and Argentina there are very large copper mines which have had chemical explosions in excess of 400 tons. In addition, there are several mines which are in excess of 3 km depth. Many of the mines are in regions of moderate to high natural seismicity, and there are occasional rock bursts with large magnitudes.

## PRELIMINARY RESEARCH RESULTS

The character of regional distance seismograms in South America is extremely complex and poorly mapped. The Andes are regions of *Lg* blockage, and further, some regions show extreme crustal seismic attenuation. For this report we have studied the shallow seismicity in southern Chile recorded in a digital seismic network operated by the University of Chile. The network, known as the Central Chile Seismic Network (CCSN), consists of 16 short-period seismic stations located near Santiago (see Figure 1) between 32.5° and 34.5°S. The network employs 2-Hz sensors which are flat to velocity between 2 and 20 Hz; the data are sampled at 50 Hz. The Disputada de las Condes Mine is one of the largest copper mines in Chile and is located within the CCSN. The mine is mainly an open pit operation, but there is an older section which continues underground operations. The mine produces a significant number of explosions per week, many of which have magnitudes of between 3.4 and 3.6 as reported by the University of Chile. Further, the mine is located in a region of moderate background seismicity. We have analyzed data recorded on the CCSN to investigate regional discrimination.

Industrial explosions are generally classified as three types: (1) single shots, (2) multiple shots, with near instantaneous detonation, and (3) multiple shots, with delayed detonations. This last category is called a "ripple-fired" explosion, and it is the most common blasting practice for large amounts of explosives. Ripple fire maximizes the rock volume fracture and reduces ground

roll vibration which can cause damage to nearby structures and equipment. Since the vast majority of large industrial explosions are ripple-fired, it is essential to develop seismic discriminants which identify single-shot events (potential clandestine underground nuclear explosions) and earthquakes.

The spatial-temporal pattern of ripple-fire explosions produces a characteristic pattern in the frequency domain. Hedlin *et al.* (1989) used *spectrograms* which show the frequency content of an entire regional distant waveform to map "banding" characteristics of ripple fire. Figure 2 shows the waveforms on spectrograms for four events from the Disputada Mine recorded at a digital station located at an epicentral distance of approximately 20 km. The shaped spectrograms show the frequency content in a window centered on a given point on the time axis. The shading is scaled with ground velocity amplitude, so dark spots correspond to large amplitudes.

In Figure 2, events a, b, and c are thought to be ripple-fired explosions. Note that the amplitude ratio of *S* to *P* energy suggests enhanced *P* wave radiation, especially at high frequencies. Note also the banding or scalloping in a given time window; high amplitudes are followed by spectral holes. For all three of these events, the *S*-to-*P* ratio discriminates the events from earthquake populations, and the scalloping indicates industrial explosions. However, event d is problematic. The *S*-to-*P* ratio fits well within the earthquake population, but the event was located near all the explosions (events a, b, c).

The observation of regular spectral banding at high frequencies for the waveforms in Figure 2 is a reliable indicator of industrial explosions. Kim *et al.* (1994) report that this banding persists out to distances of several hundred kilometers for explosions in Norway. However, this is not the case for central Chile. Figure 3 shows the spectrograms of mining explosions recorded at successively increasing epicentral distances. The closest station, FCH (21 km) shows strong banding, particularly at 10 Hz. The most distant station, CACH (114 km) has almost no seismic energy above 5 Hz, and hence evidence of spectral scalloping has disappeared. Further, the *S/P* ratio *increases* with distance, perhaps due to *Rg* to *Lg* scattering. The removal of high-frequency energy is probably due to the extreme crustal attenuation. Wigger (1988) used mine explosions in northern Chile (Chuquicamata Mine) as seismic sources for a refraction profile. Each mine blast was 250 tons, and it was expected that seismic energy could be seen to distances of 300 km or greater. However, for a refraction profile into the Andes, coherent seismic energy was recorded out to only 100 km.

## CONCLUSIONS AND RECOMMENDATIONS

We are developing a large data base of digital recordings of shallow seismic sources in central Chile. The sources include earthquakes, mining explosions, and rock bursts. We are investigating the behavior of spectral discriminants as a function of both epicentral distance and azimuth. In addition to high crustal attenuation, the large variations in topography (station FCH is at 2770 m and station PCH is at 1010 m) and crustal structure also appear to contribute to the behavior of the spectral discriminants. Preliminary analysis indicates that spectral discriminants for earthquakes and ripple-fire explosions at close epicentral distances operate as other investigators have reported for other regions in the world. However, the discriminants appear to be severely limited by high levels of crustal attenuation and/or scattering.

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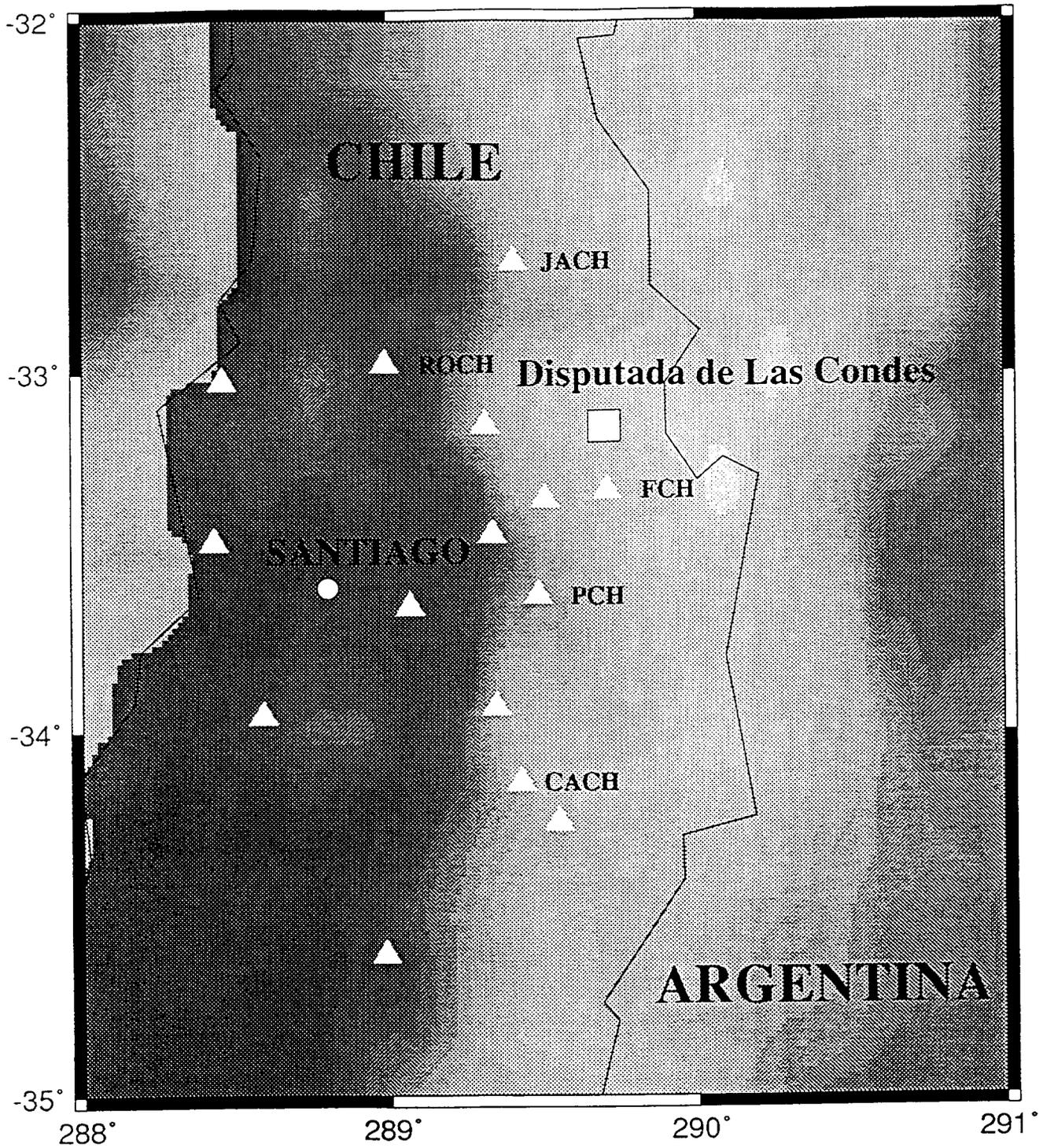


Figure 1. Map showing the location of the Central Chile Seismic Network stations (triangles) and the Disputada de las Condes copper mine (square). Shading indicates elevations with light regions above 2 km.

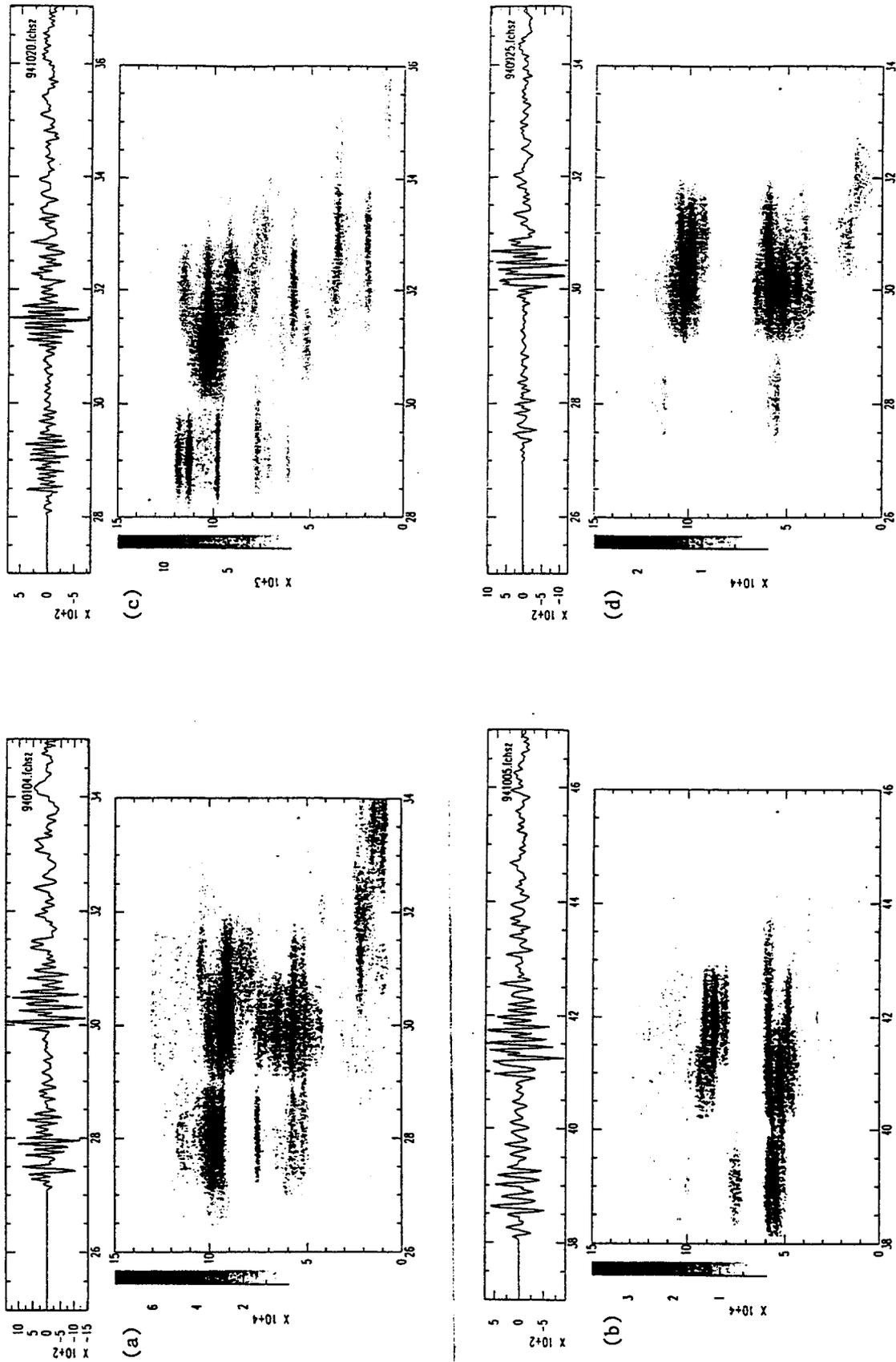


Figure 2. Plots showing seismograms and spectrograms (X, Y, Z plot with time, frequency, amplitude axes respectively) for four different events and recorded at station FCH at a distance of 20 km. In each case 10 seconds of time is plotted. Events A ( $M_L=3.51$ ), B ( $M_L=3.63$ ) and C ( $M_L=3.27$ ) show spectral banding indicative of a ripple fire sources. Event D ( $M_L=3.48$ ) shows very weak  $Pg$  relative to  $Lg$ .

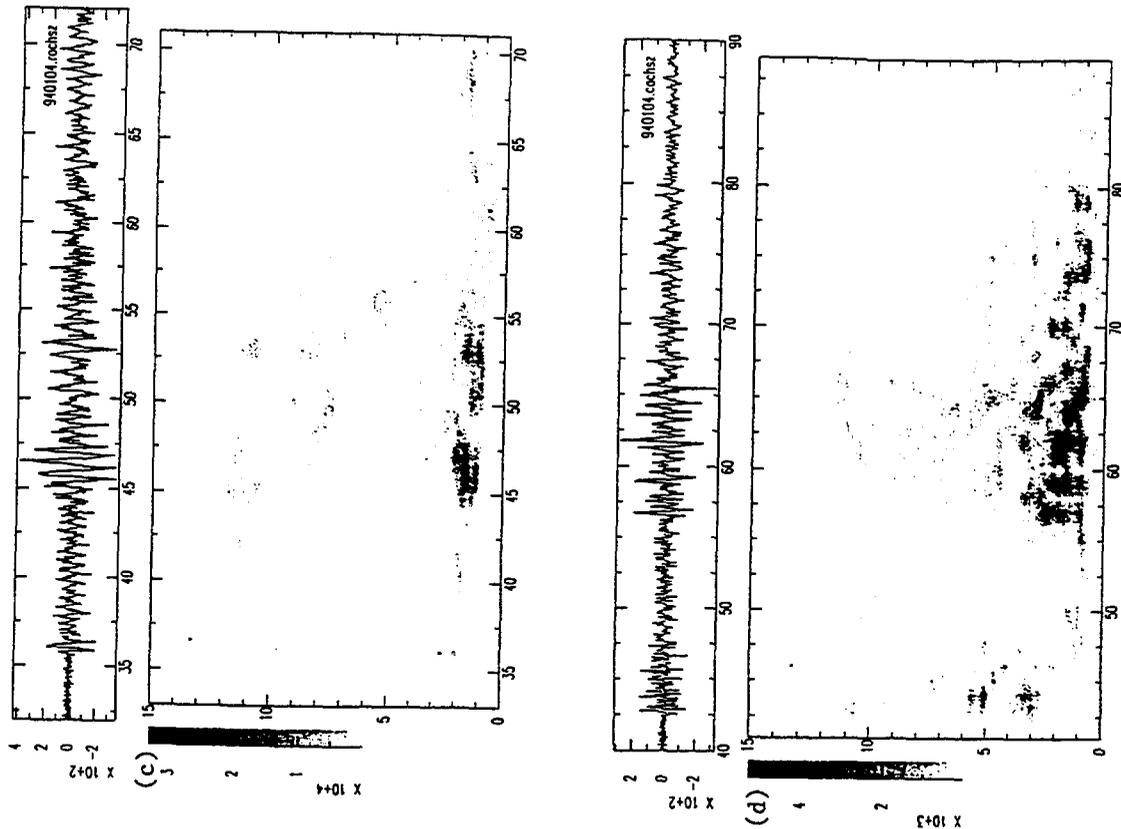


Figure 3. Seismograms and spectrograms for a mine blast on 01/04/94 recorded at four stations with increasing distance. (A) FCH (dist=21 km), (B) PCH (dist=58 km), (C) ROCH (dist=70 km) and (D) CACH (dist=114 km). At a recording distance of 20 km the spectral banding is prominent but decreases quickly with distance.