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## Major Earthquakes and Tsunamis in Chile during the period 1535 to 1955

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With 1 figure and 1 table

### Zusammenfassung

Eine Aufstellung der größeren Erdbeben Chiles (angenommene Stärke größer als 7,5) wird vorgelegt. Dieser Aufstellung liegt eine Lochkartenkartei chilenischer Erdbeben mit mehr als 15 000 Eintragungen zugrunde. Für jedes Beben werden die Auswirkungen einschließlich der Tsunami-Beobachtungen beschrieben und Schätzungen der Lage der Epizentren und der Stärke angegeben. Größere Erdbeben treten in Chile in nur wenigen Bebengebieten auf. Diese sind linear im Meer und entlang der Verwerfungen zwischen der Küstenkette und dem Zentraltal angeordnet. In Mittelchile zwischen Valparaiso und Concepción treten größere Erdbeben hauptsächlich im Innern des Landes auf. Südlich von Concepción liegen die größeren Epizentren im Meer. Jedes Herdgebiet liefert voraussagbare seismische und Tsunami-Effekte.

### Abstract

A catalog of major Chilean earthquakes (magnitude presumed greater than 7.5) is presented. This catalog is abstracted from a punched-card list of Chilean earthquakes with over 15,000 entries. Each event is accompanied by a description of effects, including tsunami observations, and estimates of epicentral location and magnitude. Major earthquakes in Chile occur in a small number

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of source areas. These are aligned offshore and along the range faults between the Coast Range and the Central Valley. In the Central Chile region, between Valparaíso and Concepción, major earthquakes occur chiefly inland. From Concepción to the south the major epicenters occur offshore. Each focal area produces a predictable pattern of seismic and tsunami effects.

### Resumen

Se presenta un catálogo de grandes sismos chilenos (con magnitud presunta mayor de 7.5). Este catálogo representa una selección preparada a base de una lista de más de 15,000 temblores chilenos en tarjetas perforadas. Cada sismo va acompañado de una descripción razonada de sus efectos, incluyendo observaciones de maremotos, además de una estimación de sus coordenadas epicentrales y su magnitud. Los grandes terremotos chilenos se originan en un número limitado de zonas epicentrales, orientadas en una línea frente a la costa por una parte, como también sobre las fallas longitudinales entre la Cordillera de la Costa y el Valle Central. En la región de Chile Central de Valparaíso a Concepción los grandes terremotos tienden a originarse bajo el continente. En cambio, de Concepción al sur los principales epicentros se sitúan frente a la costa. Cada zona epicentral produce un cuadro característico de efectos sísmicos y de maremotos.

### Краткое содержание

Приводится список крупных землетрясений в Чили (амплитуда  $> 7,5$ ), составленный с помощью электронно-счетных машин на основании учета более 15000 землетрясений. На каждой отдельной карте приведены время, место, последствия, эпицентры и длительность землетрясения. Оказалось, что очень крупные землетрясения имеют место только в нескольких областях, расположенных вдоль берега и складок между Coast Range и Central Valley; а также в центральном Чили между Valparaíso и Concepción. На юг от Concepción эпицентры отмечаются по побережью. Каждый центр характеризуется известной сейсмической картиной, предопределяющей последствия землетрясения.

### 1. Introduction

The use of historical data is acquiring increasing importance in seismological studies, particularly for the estimation of earthquake risk. Extrapolation of short runs of instrumental data can be misleading, not merely in regions of low seismicity but even in the more highly seismic areas (LOMNITZ, 1966, 1967, 1969 a).

The study of earthquakes in the American continent was notoriously neglected throughout the colonial period, "for earth- quakes are seldome in those Parts" (BACON, 1625). Recognition of the high seismicity of the Andean region (as of other non-Mediterranean areas of the world) came slowly. PERREY (1854) was the first to complain of the lack of information on Chilean earthquakes, which he attributed to "indifference" on the part of the local population. He naively upbraids the natives for being "oblivious to the scientific interest one may attach to such phenomena".

Among the notable effects of the great Valparaiso earthquake of 1906 was the appearance on the scene of F. DE MONTESSUS DE BALLORE, Chile's first seismologist. The French-born former artillery officer was a prolific writer, a patient scholar, and a pioneer in the field of earthquake tectonics. He was director of the Santiago observatory from 1907 until his death in 1923. By his vast researches on world seismicity he made others aware that "uninhabited areas tend to be attributed a low seismic activity" (MONTESSUS DE BALLORE, 1907). His six volumes on the earthquake history of the Southern Andes (MONTESSUS DE BALLORE, 1911—1916) represent the major source for any investigation of the seismicity of Chile. This paper is gratefully dedicated to his memory.

## 2. Method

A punched-card catalog containing about 15,000 separate entries was compiled from all available references on Chilean earthquakes. This catalog constitutes the source of data for future research. However, it became clear that the material of the catalog was very inhomogeneous and that some standards of uniformity should be introduced.

Thus it was decided to make a selection of those seismic events that could be described as "major", and study this sub-group with all the available information. If it turned out that this information was adequate for modern scientific purposes there would be some hope that the catalog as a whole could be used in problems of risk estimation.

We define "major" earthquakes as shocks whose presumed magnitudes might be in excess of  $7\frac{1}{2}$ . Events below that threshold were likely to escape notice if they occurred in a remote or sparsely populated area. A list of all possible earthquakes in this category was compiled and each event was studied separately. Then a magnitude was estimated by comparing the seismic effects with those of well-known recent shocks in the same epicentral area.

The criterion of magnitude assignment is inevitably a product of the personal equation of the author. Disagreements are likely; thus, several events termed "semi-terremotos" by MONTESSUS DE BALLORE have been listed by us.

Some well-known events such as the Angol earthquake of 1949 have not been included. The Angol shock caused about 40 deaths, mostly in the collapse of an old jail building in the town of Traiguén. It had a magnitude of 6. On the other hand, the Illapel earthquake of 1943 is listed; this earthquake occurred in the middle of the day during a particularly news-glutted period. It was felt as far as Buenos Aires but caused few casualties. Its magnitude was 8.3. It produced no report and is now practically forgotten.

## 3. Intensity and damage observations.

Chilean earthquakes tend to be underrated in their effects, because of a national posture of understatement that is most apparent in jour-

nalism. For, instance, after the 1966 Taltal earthquake "El Mercurio" reprinted telegrams from local correspondents throughout the shaken area. Most of these messages simply read "No damage". Yet the result of subsequent field surveys showed that up to 80% of the houses in these towns had been damaged.

Somewhat similar attitudes may be detected in official reports. Politically, the most successful reaction seems to be a stiff upper lip. When President Alessandri in 1922 sped to the disaster area in a battleship to bring much-needed relief to earthquake victims he was promptly accused in Parliament for spending money on a private junket. (His son did better in 1960.)

In general it is found that Mercalli ratings by Chilean and U.S. observers differ by at least one point. In California practice the intensity for a town is rated by the highest-ranking reported effect on the Mercalli Scale. In Chile the rating is done by mentally averaging the observed effects in the locality.

The concept of "damage" also differs. In the United States and other insurance-conscious countries, any loss worth money is termed damage. In Chile, if some glassware falls off a shelf and breaks it is likely to be described as accidental loss, because it might have happened in a number of other ways and the causal connection with the earthquake is not self-evident. In general, only structural damage is deemed worthy of mention. Quite frequently, damage to poorly built housing is ignored "because it was bound to collapse sooner or later"; yet these same adobe houses last for centuries in non-seismic parts of the world.

The descriptive notes and interpretation of intensity are wholly my own. Since mention of sources in the text would have been too cumbersome the reader is referred to the list of references, and particularly to the Bibliography of Chilean Earthquakes (MONTESSUS DE BALLORE, 1915—1919). A critical reading of the historical material is absolutely essential. MONTESSUS DE BALLORE had almost no instrumental data at his disposal; hence it is hardly surprising to find oneself disagreeing with some of his interpretations. On the whole, the observational material furnished by the early writers is considerably more accurate, detailed and complete than one might expect.

#### 4. Descriptive catalog of major Chilean earthquakes and tsunamis

- 1562 October 28. Apocryphal. The historian LUIS THAYER OJEDA attempts to show that this "great earthquake" in the region of La Imperial was actually a storm.
- 1570 February 8 at 9 a.m. First Concepción Earthquake. The correct date is taken from a protocol signed by the notables of Concepción which certifies that on July 8, 1570, "five months after the earthquake", the lot fell on the Nativity of the Blessed Virgin and that the city was therefore placed under the special protection of the Virgin from that day on. The aftershock activity is said to have ceased afterwards.

Concepción was then located on the shore of the Bay of Talcahuano, near the present site of Penco; it was a poor frontier outpost having a few dozen houses and no important or solid buildings to speak of. At the time of the earthquake most of the adult population was congregated in church hearing Mass, it being Ash Wednesday (a point on which all sources agree). The earthquake was sudden and very strong; most houses fell and many cracks opened in the ground. Some of these cracks expelled large amounts of blackish, sulphurous-smelling ground water. "Men wandered about senselessly, in astonishment, until the quaking ceased".

The tsunami is described as an initial wave which flooded part of the town, then withdrew "more than usual", and returned several times "with very great force and violence", submerging the town. It would seem that much of the damage to houses was caused by the tsunami. "Hardly a body perished", and no victims are actually named, which implies that no Spaniard was killed. The population had time to withdraw to high ground before the major tsunami wave hit the coast.

The earthquake was of greater magnitude than May 21, 1960,  $M = 7.5$  which caused craterlets in the river bed but no major cracking and a very minor tsunami. But possibly the earthquake was not quite as large as May 22, 1960 or February 20, 1835. This leads to an estimated magnitude of  $8-8\frac{1}{2}$ .

- 1575 March 17 at 10 a.m. (Thursday). Santiago region. This earthquake was described as "semi-terremoto", or less than destructive, by MONTESSUS DE BALLORE. It caused no strong impression at the time, but the description corresponds to a major earthquake. The earthquake was "at first light in one direction only, then slowly building up it became so strong that the houses and buildings shook with such violence as to make it likely that the whole town should be finished". No houses actually fell, though some "opened up" with cracks and fissures.

By comparison with other events, such as September 4, 1958, and March 28, 1965, I conclude that the epicenter was more than 100 Km. distant from Santiago, possibly in the La Ligua region. The magnitude may be estimated at  $7-7\frac{1}{2}$ . There were practically no Spanish settlements in the area at the time with the exception of Santiago, so that no other reports would be expected for that earthquake.

- 1575 December 16 about 3 p.m. First Valdivia Earthquake. The Indian Territories south of the Bio-Bio River contained five frontier outposts: Imperial, Valdivia, Villarrica, Osorno and Castro. All five were destroyed by the great earthquake of 1575. According to reports by the Commander of Valdivia and the Governor of Chile there were more than twenty deaths in Valdivia, a large number considering the nature and size of the settlement. Cracks and fissures opened in the ground during the main shock and during some of the larger aftershocks. The tsunami reached Valdivia shortly after the earthquake, "while the earth still shook", i. e. during the initial aftershocks. A bore in the Valdivia River is described as follows: "The earth shaking still after a quarter of an hour a most unusual thing was observed in the great river where ships ordinarily enter without risk: namely, that at a certain spot the waters parted, some running toward the sea and some upstreams, leaving the bottom uncovered so that one could see the stones". MONTESSUS DE BALLORE finds

this "hardly credible", but it was repeated on the same spot and in the same manner on May 22, 1960.

The tsunami was highly destructive along the entire coast of southern Chile, up to Concepción where the amplitudes were too low to cause damage. Nearly 100 Indians were drowned along the coast of La Imperial, north of Valdivia, where Indian settlements exist to this day. Large landslides obstructed the outlet of Lake Riñihue. These landslides were overtopped toward the end of April, 1576, drowning over 1200 Indians and many cattle in the ensuing flood; but the population of Valdivia was saved due to the foresight of its Commander, who had all low-lying houses evacuated well in advance.

The description and extent of damage due to the earthquake and the tsunami match closely the effects of May 22, 1960. The estimated magnitude is  $8\frac{1}{2}$ .

- 1604 November 24, 01:30 p.m. (Wednesday). **FIRST ARICA EARTHQUAKE.** (Arica was probably affected by earlier earthquakes, such as the great Arequipa, Peru, earthquake of January 22, 1582; but no documents exist.) The exact date is given in an inventory of military supplies salvaged from the tsunami, dated December 5, 1604 and signed by the Corregidor of Arica. The port of Arica, formerly located near the center of the bay, was completely destroyed by the tsunami and the town was rebuilt at its present location, close to the famous Rock or "Morro" of Arica.

Arequipa, in the Peruvian interior at a distance of about 260 Km., was almost completely destroyed; only the convent of San Francisco remained standing. People were thrown to the ground by the earthquake; the losses were estimated at more than a million gold pesos. The tsunami is not accurately described, but it is known that at least three successive waves flooded the coast line along an extension of 300 "leguas", or 1200 Km. The Peruvian port of Pisco more than 800 Km. northwest of Arica, was damaged by the tsunami according to one report. Damage from the tsunami extended across the Pacific Ocean.

The effects of this great earthquake, as far as they are known, were similar to those of the great Arica earthquake of August 13, 1868. The magnitude is estimated at  $8\frac{1}{4}$ — $8\frac{1}{2}$ .

- 1615 September 16 (half an hour before nightfall). **ARICA.** There is no direct mention of a tsunami following this earthquake, but MONTESUS DE BALLORE assumes that the tsunami occurred. This is likely, since the report to the Viceroy of Peru dated September 23, 1615, says "two little Negroes were nearly drowned"; but it cannot have been very severe. No casualties occurred, but the main church and the fort were destroyed. Most adobe houses were badly damaged. The damage extended inland and northward to Tacna, but no reports are known from Arequipa. Official reports from Arica were somewhat exaggerated, with the intention of obtaining official assistance; the earthquake is described as "the most terrible and frightful that ever was seen", thus avoiding all reference to the destruction of Arica only 11 years earlier, in 1604.

Many aftershocks are mentioned. The description corresponds to an event of magnitude about  $7\frac{1}{2}$ ; certainly the earthquake was smaller than the great shocks of 1604 and 1868.

- 1647 May 13 (Monday) at 10:30 p.m. **GREAT SANTIAGO EARTHQUAKE.** Santiago contained about 300 houses at the time. The number of victims

was estimated at "about a thousand", or one to every five inhabitants. The shock in Santiago was sudden and violent. Cracks opened in the Plaza, which is founded on compact river conglomerate. The houses and buildings began to collapse as soon as the motion started; no "preliminary waves" or "rumbling sounds" were felt. Large rocks broke off Santa Lucia Hill, an andesitic plug near the center of town. The strong motion lasted "the time to say three Credos", according to one witness.

All descriptions point to an epicenter within 50 miles of Santiago at most. A more accurate estimate of epicentral location is difficult to obtain. In all likelihood the epicenter was on (the prolongation of) the Coast Range Fault which separates the Central Valley from the Coastal Batholith. Most of the more recent earthquakes seem to have occurred on this structure, between Combarbalá—La Ligua and the region east of Melipilla. The assumption is further supported by the following data: (a) destruction in Valparaiso; (b) many fissures expelled smelly ground water and large amounts of silt "ten or twelve leguas (40—50 Km.) from the ocean"; (c) in the Valley of Quillota "everything perished", and a man fell into an earthquake crack. No effects of similar magnitude were reported elsewhere. MONTESSUS DE BALLORE assumes that Quillota was the epicentral region.

The possibility of an epicenter on the Pocuero Fault, along the foothills of the Andes, has never been discussed. The large amount of rockslides reported in the Andes does not necessarily favor this possibility; such landslides may be caused by large earthquakes in the Coast Range. The lack of reported damage at Mendoza, on the Argentine flank of the Andes, also speaks against the Pocuero Fault as a possible source of the earthquake. On the other hand, the 1906 Valparaiso earthquake caused no landslides in the Andes.

The report that "in the fields underground thunder resembling artillery fire was heard for a fortnight within an extension of six leguas = 24 Km.," indicates that the countryside just beyond Santiago was in the aftershock region. Of course, the aftershock distribution must have been quite widespread for an earthquake of this magnitude. The fact that the aftershocks were not heard in the town itself seems to imply, however, that they could be heard in a specific area of the countryside (the mention of "fields" seems to exclude the Andean foothills). The estimated magnitude is 8½.

1657 March 15, 8 p.m. *Second Concepción Earthquake*. Concepción was the only remaining Spanish stronghold on the Indian Frontier, and contained about 20,000 people including many refugees from the outposts that had been overrun by Lautaro and his Indian braves. The Indian armies were encamped around the city. The earthquake destroyed most houses completely; only one church remained standing. The largest and destructive tsunami wave occurred two hours later (around 10 p.m.), and apparently caught much of the population by surprise. It covered the lower part of town and reached the center of the Plaza. More people died by drowning than from the effects of the earthquake proper. The Indians lifted the siege and withdrew from the city in terror.

The damage extended at least as far as Chillán, where the only remaining church was ruined. Several sources assume mistakenly that Santiago was also destroyed; actually it seems that the earthquake was not felt, or barely felt, at Santiago. MONTESSUS DE BALLORE assumes that the area of

perceptibility was between the Maule River to the North and the Cautin River to the South.

The size of the tsunami was comparable to that of 1570 and of 1835 but the earthquake itself seems to have been slightly less severe. At any rate, it did not leave as deep an impression on contemporary writers. There is no mention of fissures in the ground or of craterlets, and the aftershock sequence cannot have been as alarming as in 1570. Combining these data with the late arrival of the tsunami leads to the assumption of an offshore epicenter located about 100 Km. from Concepción. The magnitude of the earthquake may have been in the neighborhood of 8.

- 1681 March 10 (Monday). Arica. This earthquake was similar in its effects to September 16, 1615. There was no tsunami. The Arica Archives mention that the population, "including some veteran survivors of the terrible sea wave of 1604" climbed the Morro in order to escape a possible repetition of that disaster. This is an indirect proof of the absence of a destructive tsunami in 1615.

There are no notices of damage beyond Arica. The magnitude may be estimated at  $7-7\frac{1}{2}$ .

- 1687 or 1688 July 12 at 1 p.m. Earthquake in the Aconcagua Valley, which ruined the Convent of San Felipe and caused damage in Santiago. Magnitude about  $7-7\frac{1}{2}$ .

- 1715 August 22 at 7 p.m. Great earthquake in Moquegua (Peru), which also ruined Arica and caused large landslides, etc. Magnitude about  $7\frac{1}{2}$ .

- 1730 July 8 at 4:45 a.m. First Valparaíso Earthquake (assumed to be the largest Chilean earthquake by MONTESSUS DE BALLORE). The destruction in Santiago was almost as serious as in 1647; Concepción was destroyed by the tsunami.

The main shock was preceded by a series of large foreshocks, beginning on July 8 after 1 a.m. The foreshocks caused no damage in Santiago, but were strong enough to cause the population to spend the rest of the night out of doors. As a result, only two persons were killed in Santiago.

The earthquake caused no damage in Concepción but did damage La Serena and Coquimbo. The tsunami was very large. Arrival times at Concepción are unknown. The second wave was the largest; the population had withdrawn to the hills in time. The water rose higher than in 1657 according to the olders inhabitants, but this testimony may be doubtful on account of the large time interval (73 years). Certainly the damage must have been more important as the city had grown since 1657.

In Valparaíso the earthquake caused destruction of houses even on the hillsides, which were largely spared in the 1906 disaster. The tsunami razed the lower part of the city. The mining towns of Petorca, Illapel and Tiltil were severely damaged. Toward the south, moderate damage was reported as far away as Chillán. The tsunami was still important at Callao, though no damage ensued. Some destruction was caused by the tsunami in Japan.

The observations agree with an offshore epicenter at the latitude of Valparaíso. The magnitude may be estimated at  $8\frac{3}{4}$ .

- 1787 December 24. Second Valdivia Earthquake. This earthquake is known to have destroyed Valdivia and localities to the south, including most towns on the island of Chiloé. Few details are known, except that it must have been a great earthquake, Magnitude about  $7\frac{1}{2}-8$ .



- During the following five to ten years earthquakes in Southern Chile must have been relatively frequent. JOHN BYRON felt several large shocks, one on Wager Island on August 25, 1741; a very large one on Chonos Archipelago or Southern Chiloé, about Easter of 1742; and several smaller shocks on Chiloé, through 1748.
- 1751 May 25 after 1 a.m. **Third Concepción Earthquake.** A large foreshock on the evening of May 23 caused many people to spend that night and the following night in readiness; another large foreshock occurred 10—15 minutes before the main shock. The latter was felt as a succession of at least six distinct earthquakes. The tsunami came about half an hour after the earthquake, with an initial withdrawal followed by three large waves. The oscillations of the sea continued with lesser amplitudes at least through noon. Aftershocks were extremely frequent. Only 25 to 30 people were killed in Concepción, largely thanks to the foreshock. A quantity of debris flushed out by the tsunami were washed up on the shore of Quiriquina Island; many valuables were recovered in this fashion, including "many images and treasures from all the churches, coffers, boxes, trunks, desks, paper baskets, beds and other articles from the entire city". Uplift in the offshore islands was recorded. Chillán and Talca were destroyed and Santiago suffered some damage. The tsunami was destructive on Juan Fernández Islands and damaging at Callao, though no casualties were reported "it having dawned already so that everyone could run to safety". In Santiago great difficulty in standing was experienced during the earthquake; aftershocks were felt in Santiago every day. The population of Santiago slept in tents and shacks during the following nights; many churches and wineries were ruined throughout the Central Valley. Valparaíso was also seriously damaged. The tsunami was the largest ever experienced in the city of Concepción. "On Santo Domingo street the water rose to within less than two blocks of the foothills". The convent of the Trinitarians was beyond the reach of the tsunami but was destroyed by the earthquake. A large aftershock occurred on June 26, 1751; this earthquake caused widespread damage to temporary shelters. The location of the city was abandoned and Concepción was rebuilt inland at its present location. The tsunami was also destructive on the coast of Japan.
- The extent of damage and the size of the tsunami point to a magnitude in the neighborhood of  $8\frac{1}{2}$ .
- 1796 March 30 at 6:45 a.m. **First Copiapó Earthquake.** (Possibly there were two earlier undocumented destructive earthquakes between 1774—1796.) The earthquake destroyed Vallenar, Copiapó, Huasco and Coquimbo, and caused serious damage in La Serena. A large aftershock on August 24, 1796 completed the destruction of Copiapó. No tsunami has been reported. Comparison with the 1922 earthquake indicates that the present event was smaller, perhaps in the magnitude range of  $7\frac{1}{2}$  to 8.
- 1819 April 3 at 10 a.m. **Second Copiapó Earthquake** (triple event). This earthquake, which caused widespread damage in Copiapó, was a foreshock to the destructive earthquakes of April 4 and April 11. These three shocks destroyed Copiapó completely. A large tsunami was generated, which was reported felt up to 800 Km. from the Huasco coast. The tsunami was initiated by a withdrawal of the sea and was destructive at Caldera. At Constitución a ship was beached by the tsunami of April 11.

- The indications are that the largest of three earthquakes (perhaps the one on April 11) was of the order of  $8\frac{1}{4}$ — $8\frac{1}{2}$ .
- 1822 November 19 at 10:15 p.m. **Second Valparaíso Earthquake.** Many aftershocks, especially during the following three days. A large aftershock on November 25 at 8:15 a.m. destroyed buildings which had been damaged by the main shock. Viña del Mar, Concón, Casablanca, Limache, Quillota, La Ligua and Santiago were seriously damaged. No damage was recorded at San José de Maipo in the Andes. Large-scale fissuring of the ground was observed chiefly near the mouth of the Aconcagua River; craterlets were formed and ground water was expelled through cracks. Ships at anchor in Valparaíso Harbor were damaged; pieces of naval cannon were dislodged from their supports. 72 people were killed in Valparaíso, largely in adobe buildings. No wooden house was damaged. A moderate tsunami (wave height about 12 feet) was generated; three major withdrawals of the sea were observed. No tsunami damage was reported.
- Detailed descriptions of damage in public buildings are available for Santiago. They indicate an intensity of 7 to 8 on the Mercalli Scale. The distribution of intensities and the general effects were largely similar to August 16, 1906. Elevation of the coast was observed in the same areas and amounts as in 1906; there are also observations of slow recovery until pre-earthquake elevation of the coast appeared to be reestablished. Most observations estimate vertical geodetic displacements of the order of three to six feet.
- The epicenter was in the vicinity of Valparaíso. The magnitude is estimated at  $8\frac{1}{2}$ .
- 1829 September 26 at 2 p.m. Valparaíso. This earthquake appears to have been a shock of magnitude about 7, near the epicenter of the 1822 and 1906 shocks. Damage was largely confined to Valparaíso and its surroundings. Intensities in Santiago were of order 6 to 7 on the Mercalli Scale.
- 1835 February 20 at 11:30 a.m. **Fourth Concepción Earthquake.** This shock is among the most widely documented Chilean earthquakes. Destructive effects were more prevalent to the North and Northeast of Concepción, possibly because of the higher population density. CHARLES DARWIN felt the earthquake in Valdivia as a distant shock. The intensity there may be estimated at 6—7 on the Mercalli Scale. No damage occurred; construction in Valdivia is largely of timber.
- Descriptions of the phenomenon at various localities show that there were at least two main shocks within a period of two minutes. The first shock was felt at Concepción but was not strong enough to produce panic. The main shock destroyed most buildings in town within a matter of seconds. On Quiriquina Island (Bay of Talcahuano) the local superintendent told DARWIN his earliest recollection of the earthquake was being thrown to the ground together with the horse he had been riding. It seems likely that the earlier and weaker shock was not felt on horseback, and that the epicenter of the second shock was near Quiriquina Island.
- There were 5 persons dead plus 30 missing in Concepción, but other deaths occurred in Talcahuano, Chillán, Constitución, Cauquenes, Talca, and perhaps other towns. All cities in the Central Valley south of Rancagua were damaged. There was no damage to buildings in Santiago; seiches in many irrigation ditches were observed. Craterlets and fissuring

of the ground occurred in the alluvial areas around Concepción and in the Central Valley. A series of large cracks (up to a foot wide) opened in the alluvium at the base of the Concepción Hills, parallel to the foothills.

The earthquake was felt in widely separated localities, such as Southern Chiloé Island, Copiapó, Juan Fernández Islands, and throughout Western Argentina. DARWIN gave a detailed description of the geologic effects on Quiriquina Island, where the Paleozoic basement rock is exposed. The rock, a crystalline schist, was shattered at the surface as from explosions. Large north-south fissures had opened up, and great masses of rock had broken away from the cliffs into the sea or on the narrow beach. The entire island was raised about 8 feet above its former level. Similar coastal uplift was observed on Santa María Island (8 to 10 feet, maximum at the north end of the island); Talcahuano (4 to 5 feet); Tubul (6 feet), etc. Reports indicate that the uplift may have been localized along the Arauco coast and the offshore islands (including Mocha Island). Negative observations at other coastal points were used by SUESS and MONTESSUS DE BALLORE to discredit DARWIN's conclusions on uplift. Most of the uplift disappeared through slow recovery within the period of the aftershock sequence. According to FITZROY, many residents reported subsidence in the estuary of the Maule River.

A technical report submitted six months after the earthquake gave percentages of collapsed buildings according to construction type as follows: brick, 33%; adobe, 71%; stone masonry, 95%. The tsunami began with a great withdrawal of the sea; half an hour after the earthquake most of Talcahuano Bay was empty and vessels formerly at anchor at depths of seven fathoms were beached. The first wave in the bay reached 25—30 feet above the high-water mark. It was followed at relatively short intervals of withdrawal by two larger waves. The waves appeared to come from the ocean and were parted by Quiriquina Island. Tsunami heights at Tomé were about 14 feet, lower than Talcahuano. Houses on Quiriquina Island were destroyed by the tsunami up to 40 feet above mean water level. The tsunami caused some damage as far away as Castro. Waves continued to be observed at intervals through the following day. In Valparaíso the amplitudes were quite small. The tsunami flooded the port installations at Juan Fernández Island, then withdrew rapidly and came back with greater amplitude. An offshore volcano became active at the time of the first withdrawal of the sea. This vent was intermittently active for about 24 hours but not observed from close quarters. A strong report was heard, accompanied by the tremor of the initial explosion; then the plume of steam and smoke was seen rising in the distance. Intermittent flashes of light were observed through the night. No falling of ash or other volcanic products is described; soundings revealed no changes in the bottom topography near the place where the eruption was believed to have occurred. MONTESSUS DE BALLORE questions the occurrence of the volcanic episode; but the descriptions by the Governor of Juan Fernández, THOMAS SUTCLIFFE, are consistent and credible.

The magnitude of the earthquake may be estimated at 8 to 8<sup>1</sup>/<sub>4</sub>.

- 1837 November 7 at 8 a.m. Third Valdivia Earthquake. This was undoubtedly another large South Chilean shock, like 1575, 1737, and 1960; damage was comparable at Castro and Valdivia, and tsunami effects were more noticeable near the coast of Chiloé Island. The small amount of damage was attributed to the prevalence of timber construction.

C. LOMNITZ — Major Earthquakes and Tsunamis in Chile

- MONTESSUS DE BALLORE claims that no "maremoto" was generated; yet the reports of tsunami damage on Samoa, Hawaii, and the coast of Japan must be connected with this event. Three successive fluctuations of the sea were observed in Ancud, but no wave was generated along the east coast of the island. On some flat shores the flooding extended up to 1000 yards inland, but no damage was reported. These effects are not unlike those observed in 1960, except for Valdivia which was spared by the tsunami in 1837. All these data put together appear to indicate an offshore epicenter south of the latitude of Valdivia.
- Landslides occurred throughout Southern Chile. On Chiloé Island large cracks and fissures appeared in the ground; many trees were uprooted or snapped off, as in 1960. Coastal uplift of the order of eight feet was observed at one point of Lemus Island (Chonos Archipelago), south of Chiloé Island. No other observations on coastal changes appear to exist. The magnitude of this earthquake is difficult to estimate on account of the uncertainty of epicentral location. However, the general effects correspond to an earthquake of magnitude 8, at least.
- 1847 October 8 at 11 a.m. Earthquake with epicenter in the Petorca-La Ligua area. Felt in Santiago with intensity about 6. One dead in Illapel. Strongly felt in Coquimbo, La Serena, and weakly as far as Mendoza. Estimated magnitude around 7, possibly  $7\frac{1}{2}$ .
- 1849 November 17 at 6 a.m. Poorly documented Central Chilean earthquake. From the few available descriptions the epicenter may have been offshore NW of Coquimbo. A tsunami 10 minutes after the earthquake caused damage in Coquimbo; the sea reportedly rose 16 feet above the high-water mark. In Santiago the intensity was about 6 on the Modified Mercalli Scale. The estimated magnitude of this earthquake is  $7\frac{1}{2}$ .
- 1850 December 6 at 6:42 a.m. Maipo Valley earthquake, similar to September 4, 1958. The intensity in Santiago was about 7 on the Modified Mercalli Scale. Damage was widespread but relatively light; two persons were killed. Large rockslides were reported about 14 Km. south of San José de Maipo, indicating a similar epicenter as in 1958. The magnitude is estimated at  $7-7\frac{1}{2}$ .
- 1851 April 2 at 6:48 a.m. Casablanca earthquake. This shock reached a very high intensity in Valparaíso-Viña del Mar and intensities around 7 in Santiago. A few persons were killed. Damage was high throughout the Quillota Valley and in the Aconcagua Valley. In Viña del Mar ground water was expelled through cracks in the ground. MONTESSUS DE BALLORE assumes that the epicenter was the same as in 1906; but the distribution of isoseismals indicates that the latter must have been nearer to Valparaíso. The magnitude is estimated at 7 to  $7\frac{1}{2}$ .
- 1851 May 26 at 1:14 p.m. Earthquake off the Huasco coast. This shock caused a minor tsunami which was damaging at Huasco. The maximum amplitude was 10 feet above the high-water mark.
- The earthquake caused damage at Copiapó, Vallenar, Freirina, Huasco and the mining camps around Copiapó. The magnitude must have been between  $7-7\frac{1}{2}$ .
- 1859 October 5 at 8 a.m. Third Copiapó Earthquake. This earthquake is poorly documented. The railway tracks between Copiapó and Caldera were damaged. More than 100 houses were demolished in Copiapó. The smelting furnace in Caldera was destroyed. Port installations in Caldera were seriously damaged by the tsunami.

- The magnitude may be estimated at  $7\frac{1}{2}$  to  $7\frac{3}{4}$ .
- 1868 August 13 at 4:45 p.m. **Second Arica Earthquake**. This is one of the most widely documented earthquakes of the 19th Century in South America. Damage extended throughout southern Peru and northern Chile. The shock was felt as far as Guayaquil to the north and Valparaíso to the south. The epicentral area was off the coast of southern Peru, probably SW of Mollendo. There were 150 dead in Moquegua alone and 3000 in the entire Department of Arequipa, according to one report. The true figure seems to have been smaller; however, the towns of Arequipa, Moquegua, Mollendo, Ilo, Arica, etc. were largely destroyed. Most other cities in the area were severely damaged. The tsunami was damaging throughout the Pacific, particularly in New Zealand, Australia, Samoa, Hawaii, San Pedro (California), and Japan. In Islay, Peru the sea withdrew immediately after the earthquake; in Arica there was a delay of less than 20 minutes. The first wave at Arica reached about 34 feet above the high-water mark and destroyed what remained of the town. It seems that the third or fourth wave was the largest; it is described as a wall of water about 45 feet high. This wave carried several ships and deposited them nearly three miles inland. One of them, the U.S.S. *Waterree*, remained almost intact and its crew participated in the rescue operations. In southern Chile the tsunami was observed as a long sequence of high and low seas, with a period of half an hour. There was considerable damage in Coronel, Talcahuano, Tomé, Constitución, Coquimbo, Carrizal Bajo, Mejillones, Cobija, Tocopilla, Iquique, Pisagua, and in many Peruvian ports including Callao. The tsunami was negligible in Valparaíso. The magnitude of this earthquake was probably around  $8\frac{1}{2}$ .
- 1869 August 24 at 1:30 p.m. This poorly documented earthquake may have been a large aftershock near the southern end of the epicentral area of August 13, 1868. If so, it was the largest aftershock felt since the day after the earthquake. A tsunami was generated, according to reports from Arica, Iquique, and Pisagua.
- The S.S. „*Payta*“ steaming south close to the Chilean coast, just north of Pisagua, felt the earthquake with great intensity. Passengers were unable to stand and navigational instruments and thermometers were broken. „The sea seemed to boil around the ship and small jets of water squirted up, as it were, to a height of 8 or 9 inches above the surface. The coastline seemed to move and large masses of rock collapsed down the cliffs into the sea, raising clouds of dust which hid the coast from sight for many miles.“
- The earthquake was strongly felt in Arequipa. The only reports of damage came from inland localities of northern Chile (Pica); it seems, however, that the maximum intensity was in the vicinity of 6—7. The magnitude is estimated at 7 to  $7\frac{3}{4}$ .
- 1871 October 5 at 5 a.m. Heavy damage at Iquique and towns of the interior. Felt from Copiapó to Lima. The epicenter is uncertain. The magnitude may be estimated at 7 to  $7\frac{1}{2}$ .
- 1877 May 9 at 8:30 p.m. **Tarapacá Earthquake**. This great earthquake was felt from Santa, Peru, to Constitución. The highest intensities were felt between Iquique and Antofagasta. Changes in the coastline (uplift as well as subsidence) were described at various points including Iquique and Pisagua. Damage was relatively minor in the ports (because

of light timber construction), and somewhat more serious in the interior of the Province of Tarapacá.

The tsunami was destructive throughout the Pacific, including New Zealand, Acapulco (Mexico), Gaviota Beach (California), Hawaii, Samoa, and Japan. The seismic surface waves were noticed on the meridian telescope at Pulkovo Astronomical Observatory, Russia.

In Tocopilla and Cobija the tsunami began five minutes after the earthquake, as a slow progressive flood. The initial rise was variously estimated at between 30 to 45 feet. The second wave occurred 15 minutes later. At Mejillones the second wave was said to have reached a height of 70 feet; at Cobija the first and slower initial flooding was described as the largest. Descriptions are generally vague because of the late hour of the night. Many ports of Chile and Peru suffered serious damage. In Arica the U.S.S. „Wateree“ which had been shipwrecked inland by the tsunami of 1868, was refloated and came to rest close to shore at a point several miles north of its initial location. The height of the wave was estimated about the same as in 1868. The seventh wave was the largest. A Chañaral the initial withdrawal of the sea occurred about 1½ hour after the earthquake. There was no damage at Valparaíso and little at Talcahuano. The oscillations of the sea continued for more than two days and were observed as far as Chiloé. To the north the tsunami was noted in Tumbes, Peru, but not in Guayaquil, Ecuador. Most of the damage and loss of life was caused by the tsunami. There were about 30 dead in Iquique, 14 in Cobija, etc. In Arica the population withdrew to high ground immediately, thus avoiding casualties. A large aftershock on January 23, 1878 caused damage throughout the interior of the Province of Tarapacá.

The magnitude of the main shock is estimated at 8 to 8½.

- 1879 February 2 at 3:30 a.m. Magellan Straits earthquake. The earthquake caused no damage in the wooden houses of Punta Arenas, though its intensity was 7 on the Modified Mercalli Scale. It was strongly felt on Tierra del Fuego (intensity 8?). Few details are known of this earthquake. It may have been similar in location and strength to December 17, 1949.

The estimated magnitude is 7—7½.

- 1880 August 15 at 8:48 a.m. Illapel earthquake. Two persons were killed and many buildings destroyed in Illapel; Petorca was also seriously damaged. The earthquake caused some damage to buildings in Valparaíso, Santiago and the towns of Central Chile. Church bells rang in Rancagua but no damage was reported from that town on the south. However, in Concepción the shock was still strong enough to damage some unstable masonry walls. Damage was also recorded in La Serena. All railroad stations of the Santiago-Valparaiso line reported damage. The submarine cable was broken at a depth of 1800 meters off the estuary of the Limari River. Several landslides occurred in the Illapel-Petorca area.

The epicenter of this earthquake could have been offshore; the epicentral area (intensity 7) is more than one degree long. There are no reports from the sparsely settled coast except for Los Vilos, a locality on firm ground which shows consistently low intensities (e.g. in the 1906 Valparaíso earthquake). The argument of MONTESSUS DE BALLORE for an inland epicenter is not conclusive. The cable break near the mouth of the Limari River could indicate an epicenter in this vicinity. The magnitude was probably 7½ to 8.

- 1906 August 16 at 8:40 p.m. Great Valparaíso Earthquake. Destruction and Fire of Valparaíso. This disaster is the first fully documented Chilean earthquake, from the point of view of contemporary science. The origin time was August 17 at 00:40 GCT. The epicenter was near the city of Valparaíso. As in most Chilean earthquakes the isoseismals were elongated in the North-South direction. The intensity 9 (Mercalli) isoseismal extended from Papudo to the mouth of the Rapel River, and eastward to Tiltil and Melipilla. Santiago was within the 8 isoseismal and suffered considerable damage. From some descriptions the initial shock seems to have been a foreshock; the main shock apparently occurred about 2 minutes later. The times of "foreshock" and "main shock" as quoted in seismological studies of the time usually referred to different phases of the main shock as recorded at distant stations, however. Vertical acceleration in Valparaíso was quite severe. Two German steamers in port at the time suffered seismic damage. They describe two major blows to the hull, directed upward. On the S.S. Thuringia the gangway plates in the machine room were thrown into the air and a leak in the hull was suspected. A 50-ton crane on the pier keeled over, narrowly missing the docked ship. On S.S. Varda, which was at anchor inside the harbor, the life boats were ordered clear in case that the ship should break in two. Flanges and pipes were broken in the engine, yet the anchor was not lost. The British steamer "Iron" had left port half an hour before the earthquake. A tremendous blow was felt, as if running aground on a rock, but there was no damage on board. The destruction of the lower part of Valparaíso was almost complete especially in the area of artificial fill (Almendral). Damage on the hillsides resulted largely from fire. The tsunami was relatively minor. Maximum amplitudes were of the order of 3—4 feet above the high-water mark. The tsunami effects reported in Japan must be attributed to the Aleutian earthquake of August 17 at 00:10 GCT, magnitude 8.3. No tsunami damage was noticed in Valparaíso harbor. Coastal uplift was observed in various amounts (40 cm. to 80 cm) in certain coastal areas (Zapallar-Quintero and Pichilemu-Llico) and in Valparaíso itself. The uplift apparently was not permanent, and was later denied by MONTESSUS DE BALLORE. The felt area included Tacna (Peru), Buenos Aires, Chiloé Island and Juan Fernández Islands. The shock was felt on shipboard off Point Deseado (Atlantic coast of Patagonia). The magnitude as given by GUTENBERG and RICHTER is 8.6.
- 1918 December 18 at 7:44 a.m. Copiapó. This earthquake was preceded by two foreshocks, one at 0:30 a.m. and the other about 1 minute before the main shock. 20% of the houses in Copiapó were completely destroyed, and an equal number were seriously damaged. There was damage also in several small towns around Copiapó but not in Vallenar or Caldera. At Caldera the sea withdrew immediately after the earthquake returning four or five times to an height of up to 5 meters above mean tide. No coastal changes in level were observed. Magnitude  $7\frac{1}{2} +$ .
- 1922 November 10 at 11:53 p.m. (November 11 at 04:32 GCT). Atacama Earthquake. Apparently there were at least two great shocks within eight minutes. With the corresponding S-arrivals this gave the impression

of four to six distinct shocks. Many large aftershocks followed immediately after the main shocks. Bailey Willis places the epicenter just SW of Vallenar, but the field evidence which he quotes is compatible with a coastal or offshore epicenter in the vicinity of Huasco. The following account from Freirina (about 10 miles inland) is characteristic. "The first indication was a sharp blow like that of a bomb exploding beneath the earth. It came from below upward. Following the first blow there came oscillations of great rapidity, at first from the sea toward the Cordillera (west to east), and afterward from north to south. The destructive shock lasted half a minute." The observer (Rev. FELIX MOREY AMENGUAL, Curate of Freirina) was unable to go out by the doors and finally escaped through a gap between the roof and the walls. He did not clearly recall the number of shocks but would say that there were three or four destructive ones and afterward many strong ones which followed each other very rapidly, during the night and following day. The first movements were extremely rapid and brusque. The others were not equally so but nevertheless were rapid and brusque. He states: 'I do not feel able to define the duration of the individual shocks, but in my judgment during the 24 hours following, the earth did not cease to oscillate, the heavier shocks succeeding each other at irregular intervals. No sound of any kind accompanied the first shock, which felt like an explosion. The following shocks produced a noise which was amazing and terrifying. They all came like explosions' (B. WILLIS, 1929, p. 33). The epicenter was at first believed to be in the vicinity of Copiapó, where the damage was extremely severe; but the telegraph operator at Vallenar was invariably able to forewarn the Copiapó operator of each major aftershock, by keying the words "Está temblando" (It quakes), upon which the shock would be felt in Copiapó. The earthquake was strongly felt on San Félix Island, 800 Km. off the Chilean coast; an increase of volcanic activity on San Félix was noted. Submarine cables were broken at a depth of 1200 fathoms. The tsunami struck immediately along the coastal section between Huasco and Caldera. The initial motion here was a very gradual rise of the water level. The period of successive waves was 15—20 minutes. The first rise at Caldera was about 5 meters above high tide, and the largest is estimated at 7 meters. At Chañaral the tsunami was very destructive. It reached a height of 9 meters above high tide but rose slowly. Presumably most of the damage was caused by the withdrawal of the water. The tsunami reached Coquimbo Bay about two hours after the earthquake; maximum height of the third and largest wave was estimated at 7 meters above mean sea level. However, major damage was caused by the earthquake and not by the tsunami. A large aftershock on November 26, 1922 caused some additional damage in weakened structures. The tsunami extended across the Pacific and caused some damage at Hilo.

Changes in level have not been studied but were almost certainly present. BAILEY WILLIS quotes one observation of uplift in Chañaral: "The day following the earthquake it was observed that the sea had withdrawn, leaving a great extent of the beach uncovered." Newspaper reports state that the river had swollen considerably at Copiapó, presumably from snow slides in the Andes.

The magnitude of the main shock was 8.4, according to RICHTER. The epicenter obtained from seismic records at distant stations may be in error by more than one degree. The shock was felt in Buenos Aires.



1928 December 1st. at 00:06 a.m. (04:06 GCT). **Talca Earthquake.** This large earthquake ruined the towns of Talca and Constitución, and caused some damage from Valparaíso to Concepción. The dead numbered 108 in Talca, 67 in Constitución and about 50 in neighboring towns and villages. The shock was felt in Antofagasta, Puerto Montt, and Buenos Aires. The distribution of intensities was very irregular and depended more on soil conditions than on epicentral distance. The earthquake was apparently a single shock. The Barahona copper tailings dam in the upper Cachapoal Valley failed; apparently the failure occurred with some delay, i. e. after the strong motion due to the earthquake had subsided. At least 54 persons were buried by the sediments.

Some ocean unrest and abnormal tides were observed; maximum elevation above normal tide at Constitución was 1.5 meters. The steamer "Santa Elisa" may have been in the source area of the tsunami 6 or 7 miles off the coast at the latitude of Constitución. It reported "a terrific shock, and it seemed as if the ship was raised bodily from the surface and then attracted into the water. Great waves of unusual dimensions came from every direction. The moonlight showed the wave action extending over a considerable distance". This phenomenon lasted for less than half a minute. No geodetic changes were reported at Constitución "except for the sea walls being thrown out of plumb". However, 10 miles to the north near the small locality of Putú the beach was uplifted, and the water line receded more than 200 meters. Seismic intensities at Putú were extremely severe; the damage was nearly total and the rate of casualties was highest.

The epicenter was probably somewhat to the west of the approximate location given by GUTENBERG and RICHTER ( $35^{\circ}$  south and  $72^{\circ}$  west). It was within 20 Km. of the town of Putú, possibly offshore. Intensities were high along the coast and in the Central Valley. The magnitude was 8.4 according to RICHTER.

1939 January 24 at 11:32 p.m. (January 25 at 03:32 GCT). **Chillán Earthquake.** This earthquake destroyed Chillán and caused great damage in the surrounding towns of the Central Valley, and in the Concepción area. There were about 30,000 dead, chiefly in Chillán and Concepción.

The area of greatest damage was of the order of 45,000 square kilometers, and included the Central Chilean region west of the Andean foothills, between the towns of Linares and Los Angeles. The amount of damage and the number of casualties make this the most destructive earthquake in Chilean history. The high number of deaths may partly be attributed to its occurring close to midnight. A survey of damage in Chillán showed that adobe houses were mostly demolished, but other types of construction also suffered important damage; this must be connected with the virtual absence of engineering design or provisions against lateral forces.

The Coast Range batholith was uplifted by more than 5 feet near the Central Valley margin; but no fault displacement was observed, and the uplift was not visibly connected with known structures. No tsunami and no coastal uplift were described. Apparently there were no changes in level in the Concepción area. There was no very obvious relationship between intensity and surface or subsurface geology. The earthquake was felt throughout the southern part of South America.

The instrumental epicenter falls slightly northwest of Chillán, near the inferred fault contact between the batholith and valley sediments. This

- agrees fairly well with observed intensities. The computed focal depth was of the order of 60 Km. The magnitude was 8.3. The aftershock sequence was very important and lasted many months.
- 1943 April 6 at 12:07 p.m. (16:07 GCT). **Illapel Earthquake**. This great earthquake destroyed most of the towns of Combarbalá, Ovalle and Illapel, about 200 Km. north of Santiago. There was damage in a wide region, including Santiago. Curiously, there is an almost complete lack of references to this earthquake. The epicentral area is mountainous, sparsely inhabited and of minor economic importance. In addition, its occurrence in the middle of the day must have contributed to its being forgotten. There are no references in the technical literature. An unpublished isoseismal map by Greve shows an extension of the region of damage similar to the 1939 Chillán earthquake. The shock was felt as far as Buenos Aires, where dishes were broken and ink spilled from inkwells in some of the taller buildings. Northwest of Illapel, toward the coast, there were large landslides and the roads were blocked, particularly on the coastal highway and the road from Illapel to the coast. A minor tsunami caused damage to fishing vessels in Los Vilos. Damage extended throughout the Province of Coquimbo. A tailings dam collapsed at the mine "Cocinera", near Ovalle, killing five. The total number of dead was 11. The only conspicuous damage in Santiago was pounding damage along an expansion joint near the west entrance of the Ministry of Defense, Plaza Bulnes. This damage recurs at every important earthquake in Santiago, and is still visible essentially as in 1943.
- The computed epicenter is offshore, opposite the mouth of the Limari River. The magnitude was 8.3 and the focal depth was around 60 Km. There were many strong aftershocks during the following week, some of which caused additional damage in weakened houses throughout the area.
- 1949 December 17 at 11:06 a.m. local time (15:06 GCT). **Punta Arenas Earthquake**. A foreshock was felt at about 02:50 a.m. The intensity at Punta Arenas was around 7; no casualties occurred in the town itself. Most of the damage was due to the collapse of firewalls between wooden houses. No damage was reported from the oilfields on Tierra del Fuego Island. About 2 dozen aftershocks were felt the first day. Landslides occurred along the west coast of Tierra del Fuego, particularly at San Nicolás, in Admiralty Bay, and along the banks of Lake Fagnano and the Belverde River. Three persons were killed at a lumber mill which was destroyed by a large landslide at San Nicolás, about 50 Km. south of Punta Arenas. Jets of salt water were reported squirting from the ground at that locality. Local tsunami waves and abnormally strong tidal currents were observed on Porvenir, in Admiralty Bay, in the Zigzag Channel near Gabriel Canal, and at other points. The epicenter was located presumably on the fault structure which includes Lake Fagnano and the western arm of the Magellan Straits; but it was closer to Lake Fagnano than to Punta Arenas. The magnitude was  $7\frac{1}{2}$ .
- 1953 May 6 at 1:18 p.m. (17:18 GCT). **Chillán**. This earthquake occurred much in the same epicentral region as the great Chillán shock of 1939. Extensive damage occurred in Chillán, Concepción, and other towns. Nine persons were killed. This earthquake was widely interpreted by engineers as a test of the

Aufsätze

Table 1. Summary of major earthquakes and tsunamis in Chile.

Date	Epicentral region	Origin	Magnitude	Observations
1562 October 28	So. Chile			Apocryphal
1570 February 8	Concepción	Offshore	8—8 <sup>1</sup> / <sub>2</sub>	Destructive tsunami
1575 March 17	Santiago	Coast Range	7—7 <sup>1</sup> / <sub>2</sub>	More than 100 Km. from Santiago
1575 December 16	Valdivia	Offshore	8 <sup>1</sup> / <sub>2</sub>	As in 1960
1604 November 24	Arica	Offshore	8 <sup>1</sup> / <sub>4</sub> —8 <sup>1</sup> / <sub>2</sub>	Major tsunami
1615 September 16	Arica	Offshore	7 <sup>1</sup> / <sub>2</sub>	Small tsunami
1647 May 13	Santiago	Range Fault	8 <sup>1</sup> / <sub>2</sub>	Epicenter between Santiago-Valparaíso
1657 March 15	Concepción	Offshore	8	Major tsunami
1681 March 10	Arica	Offshore ?	7—7 <sup>1</sup> / <sub>2</sub>	No tsunami damage
1687 July 12	San Felipe	Aconcagua Valley	7—7 <sup>1</sup> / <sub>2</sub>	Few data
(1688 ?)				
1715 August 22	So. Peru	Coastal	7 <sup>1</sup> / <sub>2</sub>	Damage in Arica
1730 July 8	Valparaíso	Offshore	8 <sup>3</sup> / <sub>4</sub>	Major tsunami
1737 December 24	Valdivia	Offshore, Valdivia-Chiloé	7 <sup>1</sup> / <sub>2</sub> —8	Prob. tsunami
1751 May 25	Concepción	Offshore	8 <sup>1</sup> / <sub>2</sub>	Major tsunami
1796 March 30	Copiapó	Inland or near-coastal	7 <sup>1</sup> / <sub>2</sub> —8	No tsunami
1819 April 3, 4, 11	Copiapó	Coastal	8 <sup>1</sup> / <sub>4</sub> —8 <sup>1</sup> / <sub>2</sub>	Large tsunami
1822 November 19	Valparaíso	Coastal	8 <sup>1</sup> / <sub>2</sub>	Moderate tsunami; geodetic changes
1829 September 26	Valparaíso	Coastal	7	No tsunami
1835 February 20	Concepción	Offshore	8—8 <sup>1</sup> / <sub>4</sub>	Major tsunami
1837 November 7	Valdivia	Offshore	8 +	Tsunami
1847 October 8	Illapel	Near-coastal	7—7 <sup>1</sup> / <sub>2</sub>	No tsunami
1849 November 17	Coquimbo	Offshore	7 <sup>1</sup> / <sub>2</sub>	Moderate tsunami
1850 December 6	Maipo Valley	Andean	7—7 <sup>1</sup> / <sub>2</sub>	As in 1958
1851 April 2	Casablanca	Range Fault	7—7 <sup>1</sup> / <sub>2</sub>	No tsunami
1859 October 5	Copiapó	Coastal	7 <sup>1</sup> / <sub>2</sub> —7 <sup>3</sup> / <sub>4</sub>	Moderate tsunami
1868 August 13	Arica	Offshore	8 <sup>1</sup> / <sub>2</sub>	Major tsunami
1869 August 24	Pisagua	Offshore	7—7 <sup>3</sup> / <sub>4</sub>	Aftershock? Moderate tsunami
1871 October 5	Iquique	Coastal	7—7 <sup>1</sup> / <sub>2</sub>	Few data
1877 May 9	Pisagua	Offshore	8—8 <sup>1</sup> / <sub>2</sub>	Major tsunami
1879 February 2	Magellan	Near-coastal	7—7 <sup>1</sup> / <sub>2</sub>	As in 1949
1880 August 15	Illapel	Coastal	7 <sup>1</sup> / <sub>2</sub> —8	No tsunami report.
1906 August 16	Valparaíso	Coastal	8.6	Small tsunami; geodetic displacements
1918 December 18	Copiapó	Coastal	7 <sup>1</sup> / <sub>2</sub> +	Moderate tsunami
1922 November 10	Huasco	Coastal	8.4	Destructive tsunami
1928 December 1	Talca	Near-Coastal	8.4	Small tsunami; some geodetic displacements
1939 January 24	Chillán	Coast Range Fault	8.3	No tsunami
1943 April 6	Illapel	Coastal	8.3	Minor tsunami
1949 December 17	Punta Arenas	Near-coastal	7 <sup>1</sup> / <sub>2</sub>	Minor tsunami
1953 May 6	Chillán	Coast Range Fault	7 <sup>1</sup> / <sub>2</sub>	As in 1939

new building code and practices introduced after the 1939 disaster. None of the newer buildings suffered structural damage; but the intensities were lower than in 1939. The performance of the new code was nevertheless impressive.

The magnitude was about  $7\frac{1}{2}$  and the focal depth was about 60 Km.

## 5. Conclusions

This paper started out as little more than an exercise in bookkeeping. It turned out to be more than that. No one can fail to be impressed by the difference in insight afforded through a reading of this catalogue, as compared, say, to analysis of the C & GS catalogue for the past 10 or 20 years. A map of instrumental epicenters of Chile starting at magnitude 4 to 5 shows the earthquakes to be fairly evenly distributed from North to South; yet major shocks appear to be restricted to less than a dozen discrete source regions.

Chile emerges as perhaps the most highly seismic region in the world, with the possible exception of Japan. The mean return period of events of magnitude  $8 +$  is of order 1 decade, according to the instrumental record of the present century.

In the highly-populated countries much of the earthquake toll may be attributed to shocks of moderate magnitude. Not so in Chile, where earthquakes of magnitude 6 are common occurrences. All the disastrous earthquakes are large-magnitude events. This result justifies our selection criterion at the  $M = 7.5$  level. However, as the population density increases so does the earthquake risk. The central part of Chile has already become a great deal more vulnerable to moderately large shocks, as the example of the 1965 La Ligua earthquake demonstrates. This trend implies a clear warning to Chilean development planners.

Pains were taken to include the maximum relevant information on tsunamis. Most Chilean offshore sources produce large tsunamis, which tend to be damaging throughout the Pacific area. The Spanish term "maremoto" as found in historical and contemporary sources is not equivalent to "tsunami": it is used only in connection with damaging sea waves, particularly breakers. A 10-foot tsunami accompanied by temporary flooding of harbor installations is not necessarily described as a "maremoto" in the literature.

At present there is no evidence that important tsunamis can be generated by inland epicenters. The often-quoted example of the 1922 Atacama earthquake is inconclusive, because the epicentral location is doubtful. On the basis of available data we incline toward a coastal epicenter for this shock.

The tectonic setting of major Chilean shocks is shown in fig. 1. Relationship with surface tectonics is particularly difficult to establish, because (1) no surface breakage from fault motion has ever been reported, and (2) most major earthquakes appear to have their focus below the Mohorovicic Discontinuity. It is usually assumed that the major shocks originate on north-south trending structures. However, transverse structures exist

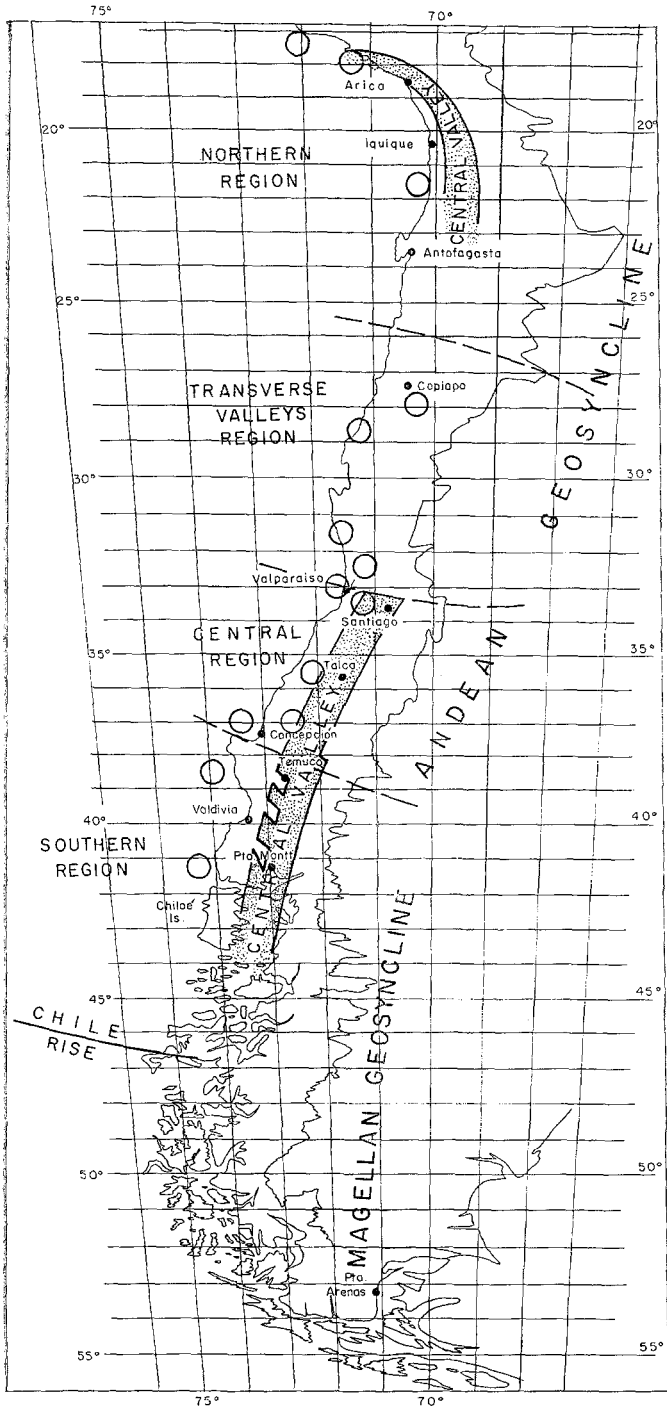


Fig. 1. Epicentral regions of major historical earthquakes in Chile, 1535—1955 (longitude exaggeration 2 : 1).

and cannot be excluded as possible sources of major earthquakes, particularly in the Transverse Valleys Region ( $27^{\circ}$  S to  $33^{\circ}$  S).

Epicenters under the Range Fault which forms the western margin of the Central Valley seem to be connected with uptilt of the Coast Range. Re-surveying of precise geodetic lines after the 1939 Chillán earthquake showed a definite uplift of the Coast Range with respect to the Central Valley. Geodetic movements from offshore epicenters are more complex. The pattern of uplift and subsidence in the 1960 earthquake may possibly be explained by buckling of the earth's crust (LOMNITZ, 1969 b).

The shift of major seismic activity from the Range Fault to an offshore structure near the latitude of Concepción ( $37^{\circ}$  S) is one of the main findings of this paper. Physiographically this shift is expressed by the appearance of transverse ranges which intrude the Central Valley. It implies that Central Chile between Santiago and Concepción must be regarded as a separate tectonic unit, in agreement with earlier results based on time-correlation studies of earthquake sequences (GAJARDO & LOMNITZ, 1960). Thus the Valparaíso and Concepción coastal epicenters should be regarded as the boundaries of the Central Chilean tectonic Province.

The North Chilean seismicity pattern is less clear, partly because of incomplete data. The Province of Antofagasta includes much of the intermediate-depth activity but lacks major shallow shocks. North of Tocopilla ( $22^{\circ}$  S) the Central Valley is well developed and we find major offshore epicenters, as well as some probable major shocks on the Range Fault. Finally, the Range Fault intersects the coast at the latitude of Arica ( $18^{\circ} 30'$  S) and the tectonic picture changes radically. Most of the destructive Arica earthquakes appear to originate off the coast of Southern Peru.

Each major source area is associated with a characteristic pattern of seismic and tsunami effects. Repetition of this pattern was the cause of relocation of the towns of Arica (1604) and Concepción (1751). In the case of Concepción the relocation proved effective to prevent major tsunami damage in subsequent earthquakes, though the city remains vulnerable to seismic damage. The following major Chilean cities have been seriously damaged by earthquakes at least 5 times (MONTANDON, 1962): Arica, Concepción, Copiapó, Coquimbo-La Serena, Santiago, Valdivia, and Valparaíso. The most severely crippling events have been from the Concepción and Valparaíso sources, both of them coastal. The Central Valley sources have not been as active but they represent a most serious threat to the Santiago area.

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