A STUDY OF THE MAIPO VALLEY EARTHQUAKES OF SEPTEMBER 4, 1958.

by

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INTRODUCTION

Successful field techniques for earthquake studies usually require a close collaboration between the structural engineer, the geologist and the seismologist. The two latter types of specialists are not always available and particularly seismologists are at a premium even in more advanced countries. It is frequently necessary, therefore, that the engineer himself be prepared to carry out seismological investigations, or at least that he be sufficiently familiar with basic seismological techniques to interpret the data critically, separating facts from fiction among the confused panorama of an earthquake-stricken area.

Unfortunately, structural engineers seeking documentation on seismological interpretive techniques are apt to become disappointed. The few existing books on earthquake seismology (with at least one important exception[1]) remain silent on the subject. References in journals are scarce and comparatively inaccessible to engineers, as a rule.

The present study is meant to illustrate some of the difficulties of earthquake research in regions where few reliable seismic stations are in operation. In 1958 Chile had one first-class seismic station at Santiago, and one Montana accelerograph at the same location. Smoked-paper recording mechanical seismographs were operated at Antofagasta, at Concepcion, and at O'Higgins Base on the Antarctic Peninsula.

The nearest modern station outside of Chile, La Paz, was 1,900 km distant from the epicenter. The list of modern stations in South America is extremely brief: Bogotá with its three subsidiary stations, Huancayo, La Paz and Santiago. However, some of the Argentine stations, particularly San Juan, wrote valuable records though equipped with obsolete instruments.

PRELIMINARY AND HISTORICAL

Shortly before 6 p.m. on September 4, 1958 a series of violent earthquakes shook Central Chile. The earthquakes had been preceded by an unusual sequence of foreshocks, one among which had been destructive in the small locality of Las Melosas on the upper Maipo river, principal stream in Santiago Province. (fig. 1)

First reports after the earthquake indicated that the mining town of El Volcán, about 6 km from Las Melosas, had been destroyed. There were no other major population centers in the immediate vicinity which is mountainous and scarce of cultivable land. However, the earthquakes had been

1. Numbers refer to the Bibliography at the end. (Author's note)

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strongly felt over a wide area and had caused widespread panic in Santiago.

Early the next day an Institute of Geophysics truck equipped with geophones and recording equipment, attempted to reach the epicentral area, but was detained by police roadblocks some 10 km downstreams of El Volcan. Recordings made at this spot showed numerous small aftershocks having distances between 9 and 25 km (fig. 2). The larger among these were both sensible and audible in the form of thunder-like detonations.

No major damage was apparent at less than 10 km from the presumptive epicenter. Some mud and stone dwellings showed minor damage, and the railroad line had been blocked by rockfalls. Yet the entire population was abandoning the area, obviously demoralized by the continuous aftershock activity. Four killed and several dozen wounded were reported.

Most observers agreed that there had been two earthquakes, a few minutes apart. However, the accelerogram at Santiago showed clearly three major shocks. The largest horizontal acceleration read from this accelerogram (fig. 3) was 0,05 g, corresponding to an intensity of slightly less than 6 on the Modified Mercalli Scale. The exact times of the second and third shocks were later taken from seismographs of distant stations, since the Santiago seismograms were illegible except for the instant of first motion.

While waiting for the road to be cleared in order to visit the earthquake area, a rapid check (Table I) established the seismicity background information. The historic earthquakes in the region are rare. Most of the shocks felt in the capital originate from coastal epicenters. Even those felt specifically in the Maipo Valley area are frequently intermediate shocks from epicenters on the Argentine border or in the Argentine province of Mendoza.

During the present century a single seismic event of any importance was found to correspond roughly with the present epicenter. This was 1945 September 13 at 21:17 local time. However, this shock had been much milder, causing no recorded damage in the Valley. A somewhat stronger shock on 1942 June 29 had its epicenter more than 100 km to the North. While this shock had not been larger than the present (M=6,9) its effects in San José de Maipo had been about equally severe, perhaps on account of its greater depth (60 to 100 km).

Several of the older inhabitants in the upper Valley affirmed they had never been in an earthquake during their lifetime (small tremors excepted).

FORESHOCKS

Table II gives a list of the principal foreshocks. These occurred in the immediate vicinity of Las Melosas (see map), causing rumors as to the impending eruption of a new volcano, the nearest known crater being at a distance of 70 km of Las Melosas. Indeed, an observer in the area could easily determine that the frequent small shocks were very shallow, having an interval of one to two seconds between the sound wave (P) and the main tremor (S). Yet no indications of volcanic activity were apparent.

The largest foreshock on August 28, 1958 caused considerable damage in Las Melosas and on the hydroelectric canal of the Queltehues power plant. Foreshock activity was given credit for the low number of casualties on September 4 owing to withdrawal of the population from Las Melosas and the general state of alert among the remaining inhabitants of the region. It should be added that September 4, 1958 was Election Day and that a large part of the population of the Valley had gone to the cities to vote.

THE MAIN SHOCKS

As soon as land communications with the stricken area were reestablished an extensive survey of the damage was initiated by structural engineers[2]. Some attention was given to the direction of overturning of buildings and structures, but at the destroyed town of El Volcán the evidence was contradictory. It was later found from instrumental evidence that the main shocks had had different directions of motion, a fact which complicated the analysis of structural damage. The maximum intensity at the epicenter was estimated at 10 on the Modified Mercalli Scale.

The epicentral area was unusually small, its average radius not exceeding some 10 km (fig. 4). The highly concentrated nature of the damage indicated a shallow focus since a greater depth should have resulted in a more even distribution of damage over a wider area. Fig. 5 shows the intensity of illumination from a light source on a plane as a function of distance of the light source. The seismic intensity distribution on an ideal plane surface is essentially similar. From this analogy it would seem that the focal depth of the earthquake had been of the order of the radius of significant damage, or about 10 km. All major damage outside this radius was caused by landslides in unstable slopes, rockfalls and the like.

An outstanding feature of the earthquake was the lack of a clearly visible fault trace. Without entering into geological detail it should be mentioned that among the numerous visible faults in the canyon walls none could be traced across the soil cover to any significant extent.

However, maximum intensities were more or less concentrated along the contact of a granodioritic intrusion (fig. 4) which seems related to the earthquake fault. There are geological reasons to believe the earthquake to have originated within this batholith. The contact itself is rather straight and parallels the important tectonic trends of the region.

INSTRUMENTAL ANALYSIS

Seismograms of the September 4, 1958 earthquakes were obtained from many stations throughout the world. Table III resumes the essential data obtained from these stations.

The time intervals between earthquakes were firstly determined, as these remain practically constant at all distances. The Santiago times for the three main shocks were fixed provisionally at 21:51:18, 21:52:34, 21:55:18. A fourth large earthquake, seconds after the initial shock, has been detected by P. Saint Amand[3].

The interval of P-O (Santiago arrival minus origin time) was calculated at about 10 seconds on the base of distance. Thus a tentative origin time of 21:51:08 (Greenwich Central Time) was assumed.

The next step was to calculate the P-O times for each station, using the tentative origin time as computed above. Each value of P-O corresponds to a distance in the Bullen-Jeffreys tables. This distance was compared with the measured distance of the station to the assumed epicenter, and the residuals were tabulated (Table IV). By Gutenberg's procedure these residuals were then plotted against the azimuth of the station. The resulting sine wave was extremely flat, thus showing that the epicenter required no adjustment within the limits of error (fig. 6). Therefore the epicenter was fixed at

Latitude 33°50' 15" South ±15"
Longitude 70°10' 15" West ±15"

Thirdly the directions of first motion (compression or dilatation) at each of the stations were utilized in a fault-plane solution. The procedure requires first to find the "extended distances" of each station with respect to the epicenter. The values of the extended distances are taken from the Hodgson-Storey tables[4], and fig. 7 shows the corresponding plot. The circle which divides compressions from dilatations is drawn with due regard to the relative clearness of the readings at each station, and a rather satisfactory solution is obtained, considering the relatively small number of stations used.

The fault-plane solution is tangent to the fault-plane circle at the origin. Its strike is N13°E. The dip of the fault is given by

$$\tan \delta = \text{Diameter of fault-plane circle} = 4.52$$

which gives

$$\delta = 77°32' \text{ towards the West}$$

There are not enough data at close distances to find the strike-slip component of motion, if any.

Since the dominant orientation of the tectonic features in the area is about N10°E it is believed that this fault-plane solution corresponds to the true mechanism of the first shock. As has been mentioned earlier, the subsequent shocks may have occurred along different faults and the direction of motion was probably a different one, certainly opposite for the second shock (21:52:24).

Finally, the magnitude of the three main shocks was computed from amplitudes and distances of the seismograms at distant stations (Table V). This calculation is elementary and the average result was determined as follows:

Shock I M = 6.9
Shock II M = 6.7
Shock III M = 6.8

The condensed provisional results of the instrumental analysis are presented in Table VI. A more complete analysis will be published elsewhere[5].

AFTERSHOCKS

A long sequence of aftershocks has followed in the wake of the 1958 earthquakes in the Maipo Valley. Table VII gives a list of aftershocks of magnitude about $3\frac{1}{2}$ and larger, taken from the smoked-paper records of the Santiago pendulum and from photographic records of the San José de Maipo Benioff instruments installed as an auxiliary station shortly after the earthquake. This station is located on the Maipo river about 25 km from the epicenter in a downstreams direction.

The magnitudes are internally consistent but may require a constant correction as the station factor at Santiago is not known at present. This constant factor will not affect the shape of the aftershock curve, which is shown in fig. 8. The curve has a "classical" logarithmic shape. Another interesting curve is obtained by plotting the aftershocks in chronological order, without regard to time of the shocks (fig. 9). The straight line means that the average magnitude of aftershocks has remained constant during the sequence. These results have been utilized in another paper on earthquake mechanism[6]. The graph of fig. 8 will be found useful for obtaining the strain of an aftershock of given magnitude.

CONCLUSION

A brief summary of seismological investigations on the occasion of the 1958 Maipo Valleys earthquakes, has been presented. It has been our intention to show what kind of data could be obtained directly in the field and which had to be extracted from instrumental evidence.

Even in a case such as the present with a low density of seismic stations in the region, the information which can be obtained from distant seismograms compares favorably with field data both as to quantity and to quality. One might say that instrumental studies furnish the quantitative backbone of information around which the engineer and the geologist must invariably build their interpretation.

On the other hand, a field observer who is aware of the type of data to be furnished by instrumental analysis will be in a position to complement this information in the most efficient manner. He may appreciate focal depth in shallow earthquakes (which is difficult to achieve from seismograms), and help resolve the ambiguity of the fault-plane solution as has been shown above. While the exact location of the epicenter is usually difficult to appreciate, at least in sparsely settled country, a good initial guess for computation purposes may be obtained in the field.

In this connection as well as for determining fault motion, the direction of fall in objects and structures is of great importance. Unfortunately the present case does not lend itself to this type of analysis, since it is impossible to decide a posteriori which of the shocks caused the displacement in a given object. Of course the occurrence of triplet or quadruplet earthquakes having approximately the same magnitude is extremely rare, this being the first case that comes to our notice.

ACKNOWLEDGMENTS

The present study was made possible by the cooperation of colleagues in many countries who sent us their seismograms of the September 4, 1958 shocks. These seismograms contain much valuable information which will be discussed in a later paper[5]. Therefore the results in the present work are to be regarded as provisional only.

All computations in the paragraph on "Instrumental Analysis" were carried out by Mr. Eduardo Piderit, in partial fulfilment of the requirements to obtain the degree of Civil Engineer at the University of Chile.

Instituto de Geofísica y Sismología
Publication No. 10.

BIBLIOGRAPHICAL FOOTNOTES

1.- C. F. Richter, Elementary Seismology (W. F. Freeman San Francisco 1958).

2.- R. Flores (1960), "Engineering Aspects of the Earthquake in Maipo Valley, Chile 1958." 2nd World Conference on Earthquake Engineering, Proceedings (submitted).

3.- P. Saint Amand (oral communication).

4.- J. H. Hodgson and R. S. Storey (1953), "Tables extending Byerly's fault-plane techniques to earthquakes of any focal depth." Seismological Soc. America Bull. 43, pp. 49-61.

5.- P. Saint Amand, G. Ericksen and C. Lomnitz (paper in preparation).

6.- C. Lomnitz, "A Note on Earthquake Theory" (to be published).

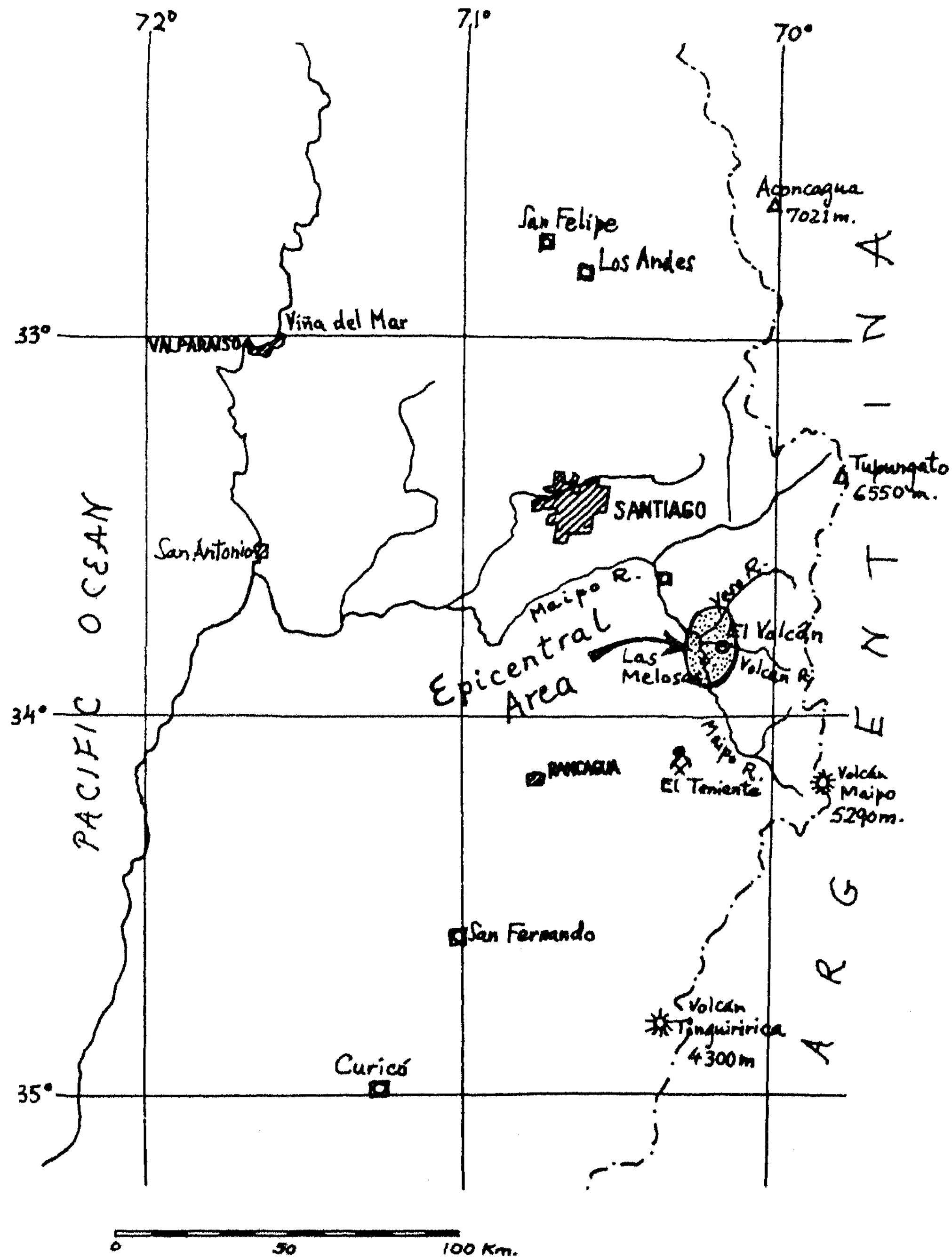
72°
71°
70°
33°
34°
35°
San Felipe
Los Andes
Aconcagua 7021m.
Viña del Mar
VALPARAISO
Tupungato 6550m.
SANTIAGO
San Antonio
PACIFIC OCEAN
Maipo R.
Epicentral Area
El Volcán
Las Melosas
Volcán R.
RANCAGUA
El Teniente
Maipo R.
Volcán Maipo 5290m.
San Fernando
Volcán Tinguiririca 4300m
Curicó
ARGENTINA
0
50
100 Km.

Fig. 1

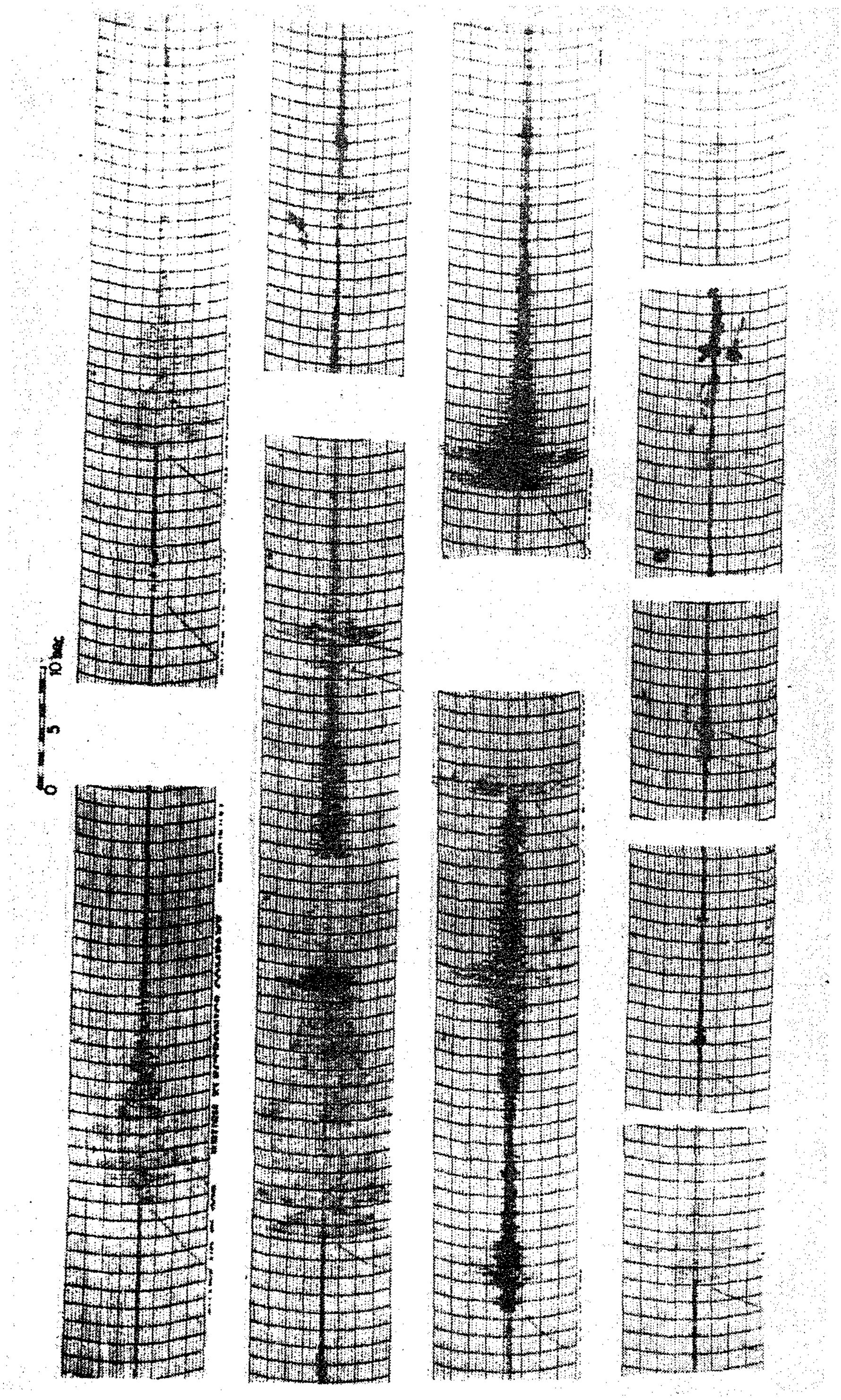

Fig. 2

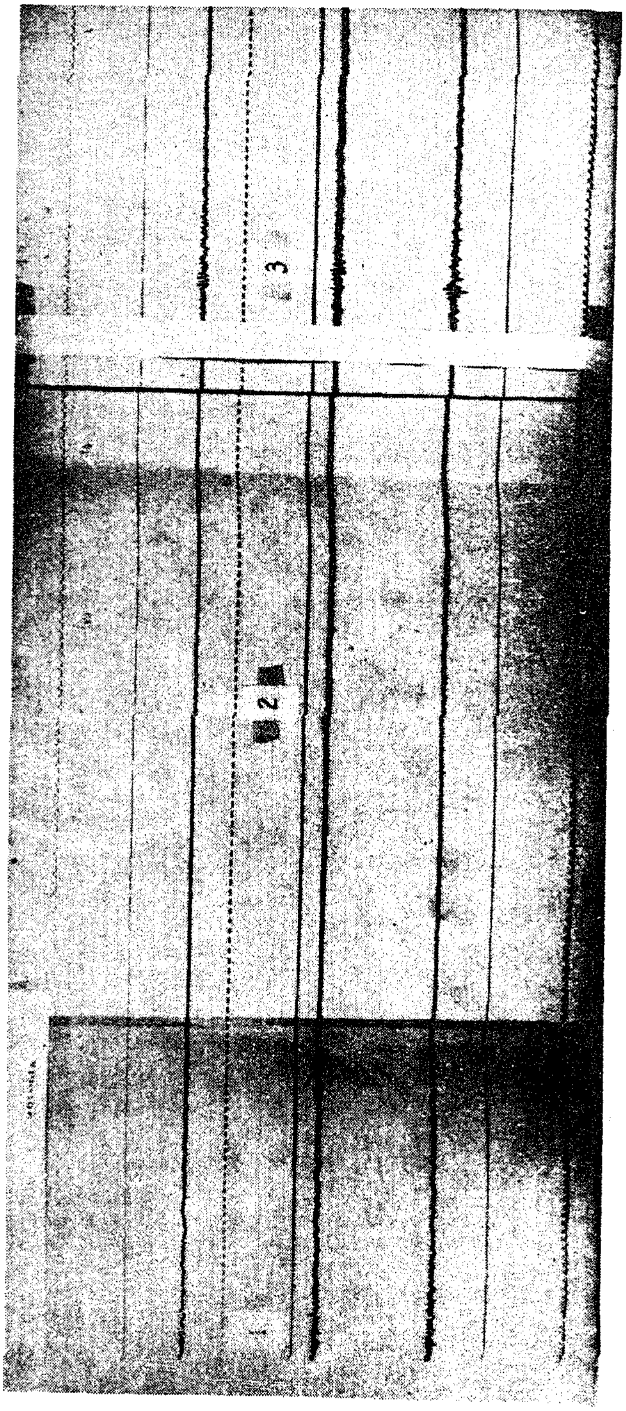

Fig. 3

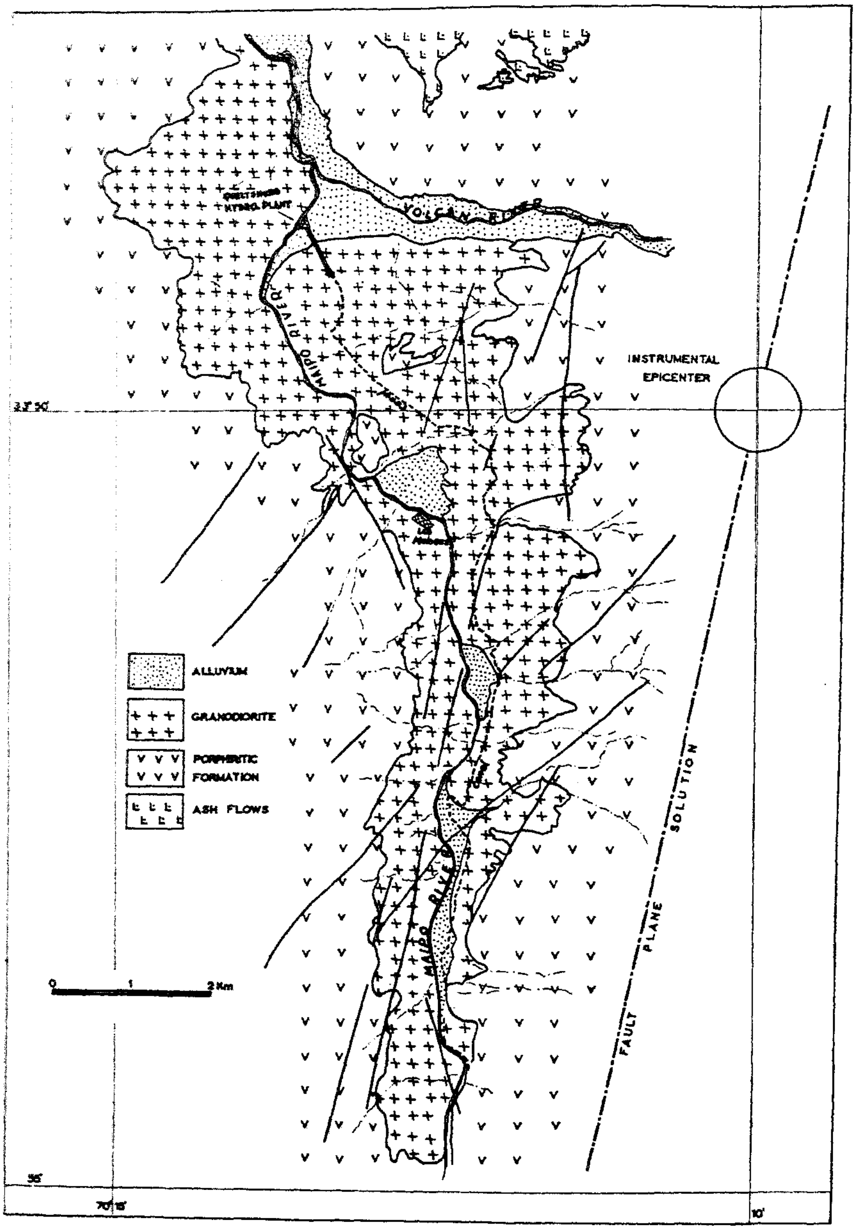
HYDRO. PLANT
MAIPO RIVER
INSTRUMENTAL
EPICENTER
ALLUVIUM
GRANODIORITE
PORPHYRITIC
FORMATION
ASH FLOWS
0
1
2 Km
FAULT PLANE SOLUTION
10'

Fig. 4

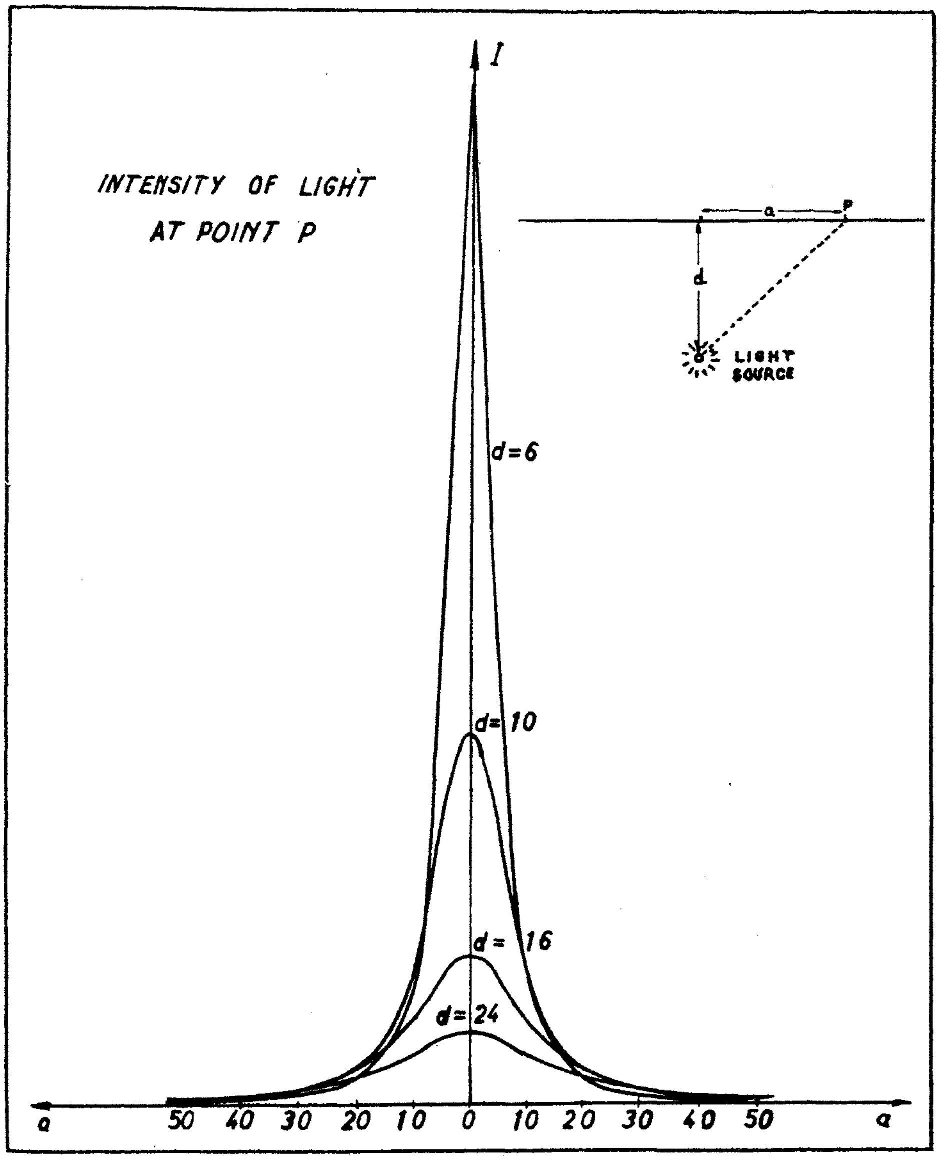
I
INTENSITY OF LIGHT
AT POINT P
a
P
d
LIGHT
SOURCE
d=6
d=10
d=16
d=24
a
50 40 30 20 10 0 10 20 30 40 50
a

Fig. 5

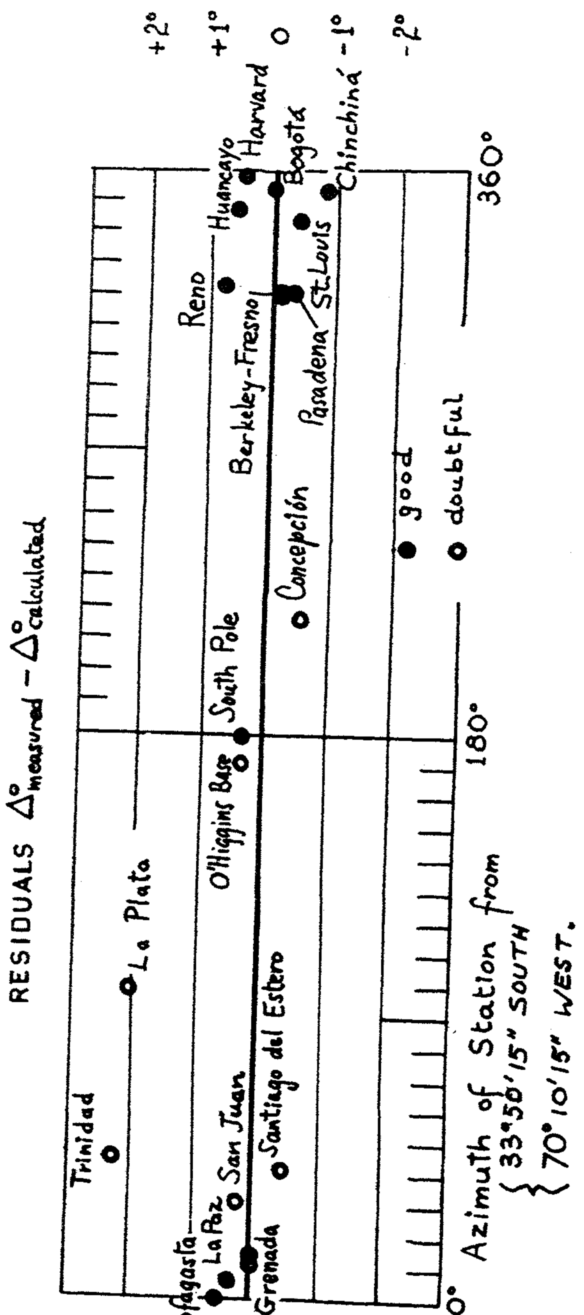
RESIDUALS $\Delta^\circ_{measured} - \Delta^\circ_{calculated}$
+2°
+1°
0
-1°
-2°
Antofagasta
La Paz
Grenada
San Juan
Santiago del Estero
Trinidad
La Plata
O'Higgins Base
South Pole
Concepción
Berkeley-Fresno
Pasadena
Reno
St. Louis
Huancayo
Harvard
Bogotá
Chinchiná
good
doubtful
0°
180°
360°
Azimuth of Station from
33°50'15" SOUTH
70°10'15" WEST.

Fig. 6

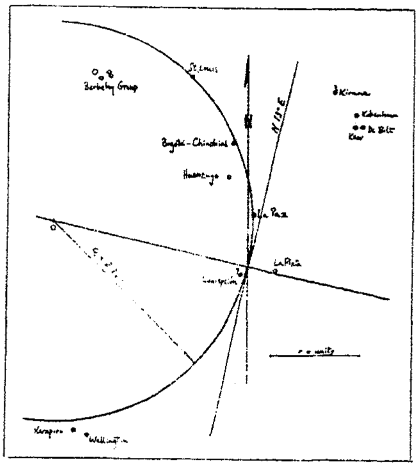

Fig. 7

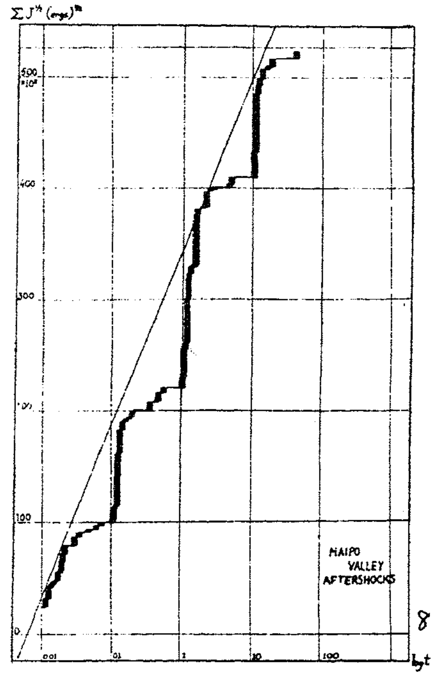

Fig. 8

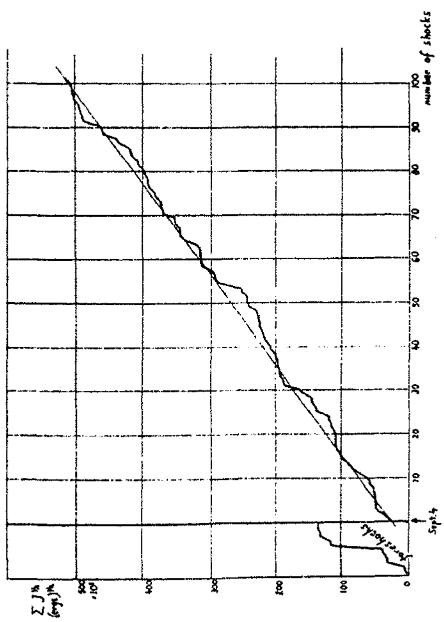

Fig. 9

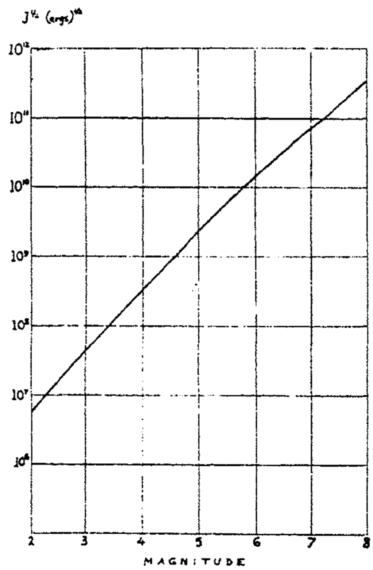

Fig. 10

TABLE I

HISTORICAL EARTHQUAKES IN THE SANTIAGO AREA.-

DATE		LOCAL TIME	INTENSITY M.M.	EPICENTER
1575	March 17	10:00	8-9	Uncertain
1582	August 7	?	8-9	"
1643	September 6	5-6	8-9	"
1647	May 13	22:30	11	"
1687	July 12	13:00	8-9	Andean (San Felipe)
1688	July 12	?	8-9	Uncertain
1690	July 9	?	8-9	"
1724	May 24	?	8-9	"
1730	July 8	4:00	11-12	Coastal (Valparaiso)
1782	May 22	20:21	10	Andean (Mendoza)
1804	October 27	?	7	Andean (Mendoza)
1822	November 19	22:15	11	Coastal (Valparaiso)
1822	November 23	16:00	10	Uncertain
1824	August 29	?	8-9	"
1825	December 24	16:30	8-9	"
1829	September 26	16:30	8-9	Coastal (Valpo)
1829	October 1	12:03	8-9	Uncertain
1851	April 2	6:41	10	Coastal (Valpo)
1871	March 25	0:56	8-9	Uncertain
1873	July 7	2:26	10	"
1873	November 24	7:05	8-9	Andean (Mendoza)
1874	September 27	0:06	8-9	Uncertain
1880	August 15	8:45	8-9	Andean (Mendoza)
1890	April 22	9:30	8-9	Uncertain
1896	March 13	20:30	8-9	"
1906	August 16	19:58	10-11	Coastal (Valpo)
1927	April 14	02:23	8-9	Andean (Los Andes)
1933	November 14	10:05	6	Andean
1940	April 8	04:49	6	Coastal
1942	June 29	02:26	7	Andean (San Felipe)
1943	April 6	14:08	7	Coastal (Combarbalá)
1945	September 13	17:17	7	Andean (Maipo Valley)
1958	September 4	17:51	6	Andean (Maipo Valley)

TABLE II

FORESHOCKS

DATE 1958	GCT Time	M (Approx.)
August 6	02:37:42	4,4
12	12:11:30	3,5
13	23:24:22	4,3
20	19:50:24	3,5
23	07:32:44	3,6
25	20:48:32	3,6
27	00:01:26	3,7
27	02:54:32	3,8
28	09:36:16	5,4
28	14:29:30	4,4
28	19:23:52	3,7
30	20:01:54	3,8
30	21:10:12	3,6

TABLE III

Instrumental Readings for the shocks of 1958 September 4.

Station	Distance	P of 1st Shock	P of 2nd Shock	P of 3rd Shock
Santiago	0,6°	21:51:20		
San Juan	2,8	58		
Concepción	3,8	52:01 C		
Stgo. del Estero	7,0	46 D		
La Plata	10,2	53:41 D		
Antofagasta	10,5	53:49,5		
La Paz	17,4	55:17 D		
Huancayo	22,2	56:13 D		
O'Higgins	30,6	57:29		
Bogotá	38,3	58:32 C		
Chinchiná	39,9	39 C	59:48	02:41
Trinidad	45,7	59:32		
Grenada	46,6	39		
South Pole	56,2	22:00:52		
St. Louis	74,2	02:46 D	04:04	06:46
Harvard	76,3	03:01	04:18	07:03
Pasadena	81,5	27 D		
Wellington	84,0	42 C		
Karapiro	86,0	53 C	05:11	07:54
Berkeley	87,8	54 D	13	57
Kew	104,9	PP 09:42		PP 13:45
De Bilt	108,5	05,5		
Kiruna	121,2	P' 10:07	PP 13:00	PP 15:55

TABLE IV

STATION	DISTANCE Δ_1°	AZIMUTH	TIME OF P	P-O	Δ_2°	RESIDUAL $(\Delta_2^\circ-\Delta_1^\circ)$
San Juan	2,8	31°35'	21 51 58	00 50	3,0	+0,2
Concepcion	3,8	217°26'	52 01	00 53	3,2	-0,6
Stgo del Estero	7,0	41°53'	52 46	01 38	6,5	-0,5
Antofagasta	10,5	1°13'	53 49,5	02 41,5	11,0	+0,5
La Paz	17,4	5°39'	55 11,7	04 09	17,7	+0,3
Huancayo	22,2	347°35'	56 13,5	05 05,05	22,8	+0,6
Base O'Higgins	30,6	170°49'	57 59	06 21	30,9	+0,3
Bogotá	38,3	353°46'	58 32	07 24	38,3	0,0
Chinchiná	39,9	354°02'	58 39	07 31	39,1	-0,8
Trinidad	45,7	12°56'	59 32	08 24	44,6	-0,1
Grenada	46,6	11°24'	59 39	08 31	46,5	-0,1
Polo Sur U.S.A.	56,2	180°00'	22 00 52	09 46	56,5	+0,3
Saint Louis	74,2	343°53'	02 46	11 38	73,8	-0,4
Harvard	76,3	359°01'	03 03	11 55	76,8	+0,5
Pasadena	81,5	321°33'	03 27	12 19	81,2	-0,3
Fresno	84,6	322°07'	03 44	12 36	84,5	-0,1

TABLE V

STATION AND COMPONENT	MAGNITUDES		
	SHOCK 1	SHOCK 2	SHOCK 3
Pasadena PH	6.7-6.9-7.2	6.9-6.9	6.9-6.6-6.8
PZ	6.6	6.7-6.6	6.5-6.7
PPH	6.8		
SH	6.7-7.0-6.9	6.6	6.9
M	6.9	6.7	6.7
Berkeley PZ	6.9	6.7	6.7
Uppsala PPZ	6.9-6.7	6.7-6.6	6.8-6.8
PPH	6.9		
Kiruna PPZ	7.0-6.9		6.7-7.0
PPH	6.8-7.1		6.9
De Bilt SH	7.0		6.9
AVERAGE	6.9	6.7	6.8

TABLE VI

RESUME OF SHOCKS OF 1958 SEPTEMBER 4
MAIPO VALLEY, CHILE.

A. Location of Epicenter:

Lat. 33°50'15" South
Long. 70°10'15" West
Error ±15"

B.		Origin Time	Magnitude
Shock 1		21:51:18	6.9
Shock 2		21:52:34	6.7
Shock 3		21:55:18	6.8
	Error	±3 seconds	

C. Maximum Intensity: 10

D. Maximum recorded acceleration: 0.05g at Santiago (distance from epicenter, 65 km).

E. Fault-plane solution:
Strike N 13° E
Dip 77°32' West

F. Estimated Epicentral Area: 700 km^2

G. Estimated depth: 10 km.

TABLE VII

LIST OF AFTERSHOCKS

DATE	TIME	M
Sept. 4	22:09:39	4,98
	25:00	4,45
	36:49	4,45
	46:42	3,5
	46:45	3,5
	57:44	3,8
	23:00:48	3,5
	05:38	3,5
	08:41	4,35
	14:47	3,68
	19:00	4,45
	19:28	4,20
	23:40	4,45
	40:38	3,80
	48:24	4,5
	58:47	3,8
Sept. 5	00:04:54	3,98
	09:00	3,98
	26:46	3,5
	01:04:33	3,5
	34:00	3,68
	02:01:58	3,9
	04:08	3,98
	35:09	3,68
	03:21:06	3,5
	41:36	4,86
	48:05	3,8
	04:23:51	4,2
	40:57	3,5
	45:00	4,65
	05:26:55	4,35
	06:13:10	4,96
	34:40	3,8
	07:26:52	4,1
	09:43:15	3,58
	10:50:44	3,68
	12:08:08	3,98
	28:08	3,68
	13:24:36	3,68
	17:32:33	4,35
	18:03:14	3,5
	52:16	4,35
	20:04:59	4,2
	22:20:38	3,98
	22:29:34	3,98
	23:43:41	3,68
	56:46	3,5
Sept. 6	02:27:34	4,04
	05:21:00	3,98

DATE	TIME	M
Sept. 6	05:34:45	4,45
	06:57:36	4,1
	08:13:10	4,1
	21:43:55	4,24
Sept. 7	00:41:45	4,24
	05:14:47	4,9
	09:54:10	4,58
	10:14:46	4,28
	12:37:56	3,98
	13:49:01	4,73
	16:58:58	3,5
	18:22:52	3,5
	21:56:11	3,5
	22:31:37	3,5
Sept. 8	21:55:22	4,24
	22:25:09	5,26
	23:38:53	4,20
Sept. 9	03:52:14	3,5
	10:21:59	3,5
	11:30:06	4,20
Sept.10	11:57:37	3,5
Sept.11	00:59:55	4,70
	19:31:30	3,5
Sept.12	06:51:18	3,90
Sept.13	16:45:57	3,80
	21:13:32	4,28
Sept.14	23:12:28	3,5
	23:47:14	4,28
Sept.16	17:52:58	3,5
Sept.18	12:16:40	3,68
Sept.19	07:35:46	4,61
Sept.20	02:43:49	3,98
Sept.21	10:27:34	4,84
	13:25:27	3,73
Sept.22	18:08:53	3,5
Sept.24	13:53:17	3,09
Sept.26	06:08:47	3,68
	09:51:20	4,04
Sept.27	09:33:20	3,80
Oct. 1	15:09:57	3,50
	22:24:26	4,15
Oct. 6	00:07:08	3,68
	02:29:47	3,80
	18:37:15	4,10
Oct. 15	18:10:54	3,5
Oct. 20	04:54:28	3,68
Oct. 30	17:04:48	4,20
Nov. 26	21:19:43	4,31