BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 47 (1969), pp. 635-672

28. *Characteristics of Seismicity in South America.*

By Tetsuo SANTÔ,

Earthquake Research Institute and International Institute of Seismology and Earthquake Engineering.

(Read April 22, 1969 and May 27, 1969.—Received May 30, 1969.)

Summary

Seismicity of South America during the period from August 1960 to September 1968 was investigated using the earthquake data of Preliminary Determination of Epicenter (P. D. E.) by Coast and Geodetic Survey, U.S.A. Several characteristics were found in the seismic activity especially in the intermediate and deep earthquakes. Six "earthquake nests" were discovered in the upper mantle with the depth ranging from 100 km down to 250 km. It was practically shown that the development of the net of the observation stations has produced remarkable effects on the determination of epicenters and depths of earthquakes for the foci distributions of two nests. The net of observation stations for other earthquake regions was also studied.

The investigation indicated that about 60% of earthquake took place in the upper mantle shallower than 200 km, while the earthquakes with the depth from 320km to 520km took place only eight times in 1964.

Earthquake deeper than 550 km occurred around two separate lines, and the energy released by these deep earthquakes is quite predominant. Both the upper mantle earthquakes and deep ones along the northern active line were noticed to contain some multiple events, closely related with each other both in space and time.

Distribution of the earthquake energy released from the meshes of $1^\circ \times 1^\circ$ in South America was illustrated, and its relation with the frequency distribution in the same meshes was studied.

Distributions of frequency and released energy of shallow earthquakes along the western coast were investigated also.

1. Introduction

Circum-Pacific seismic belt can be divided into two systems according to the mechanism of earthquake generation. One of them is the belt running along the western side of North America. Along this belt only shallow earthquakes occur being associated with the marine seismic belt which is extended from the East Pacific Rise. Along the other belt deeper earthquakes associated with the trench-island arc system occur, and it can be explained that the events in this system are generated due to the underthrusting of an lithosphere layer into the upper mantle.

It is for certain that western South America has some geophysical similarities with other island arcs. For instance, the trench deeper than 6 km and parallel, to the coast exists, or foci distribution of deep earthquakes accompanying young volcanoes is characteristic. Because of these similarities, seismic zone along the Andes is often taken in the island arc system. It is also rather easy to assume, on the other hand, that there may be some special features in the seismicity in South America which are different from those in other pure island-arc system because of the geographycal exceptionality in South America. A few of these special features have actually been recognized. The value of b in Gutenberg-Richter's formula $\log N = a + b(8 - M)$, for instance, is $0.4 - 0.5$ in South America, which is significantly lower than the values in any other island arc regions.[1),2)]

The purpose of the present work is to discover some special characteristics of seismicity in South America, if any, and to offer new materials for studying earthquake mechanism of intermediate (70km$-$300km) and deep ($>$300 km) shocks, and for studying mantle situation beneath the Andes. Only evidences will be reported without deep discussions. Earthquake data were taken from Preliminary Determination of Epicenter (P.D.E.) by Coast and Geodetic Survey, U.S.A. In order to avoid the disturbing effect of aftershock activity associated with a great earthquake on May, 22, 1960 on the detection of small earthquakes around the aftershock area, the data related with the period before July 1960 were excluded.

2. General view of the distribution of the earthquakes epicenters in South America

Figure 1 gives a general view of the distribution of epicenters of earthquakes by several different depth ranges. In several zones in the Circum-Pacific seismic belt a typical feature of earthquake foci distribution in island-arc trench system has been recognized; that is the foci are found in deeper spots as they go towards continental side. Figure 1 clearly shows this feature. However, the following characteristics can also be noticed by the figure.

1. Epicenters of the upper mantle earthquakes (filled circles in (c)

1) S. MIYAMURA, "Seismicity and Geotectonics (in Japanese)", *Zisin*, **15** (1962) 23-52.

2) S. MIYAMURA, "Seismicity of Island Arcs and Other Arc Tectonic Regions of the Circum-Pacific Zone", *The Crust and Upper Mantle of the Pacific Area*, Amer. Geophys. Union, (1968), pp. 60-69.

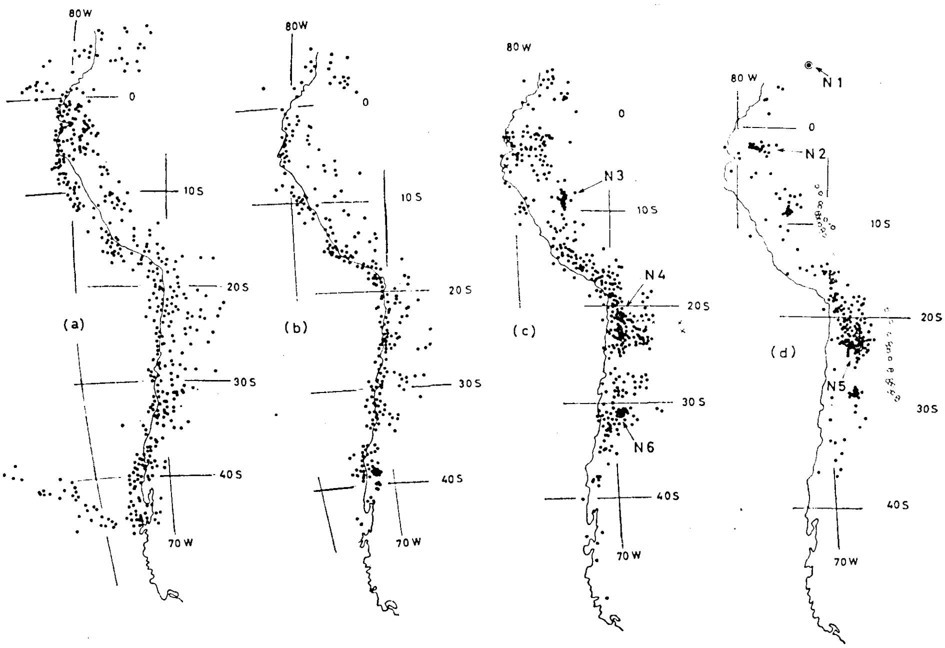


Fig. 1. Epicenter distributions of the earthquakes for different depth ranges. (a) d ≦ 35 km. (b) 35 km < d ≦ 70 km. (c) filled circles: 70 km < d ≦ 150 km. Crosses: 300 km < d ≦ 500 km. (d) Filled circles: 150 km < d ≦ 300 km. Open circles: 500 km < d. **N1—N6** are the intermediate earthquake nests.

and (d)) crowd in several small areas, that is, they form some "earthquake nests" adopting the term after C. Tsuboi. The depths of these "nests" are different from those found in and around Japan, where the depths of nests are shallower than about 80 km[3] excepting one intermediate earthquake nest which is found in the central part of Japan[4].

2. There are some "silent" areas as follows:

i) a silent area for the activity of crustal earthquakes around 8°S, 79°W (Fig. (a)).

ii) a silent area for the activity of deeper than 35 km around 0°S latitude (Figs. (b), (c) and (d)).

iii) a silent area for the activity of intermediate earthquakes between 25°S and 27°S (Figs. (c) and (d)).

A silent area given in item iii) is the most distinctive and it contains another interesting evidence, which will be mentioned later.

3. Activity of shallow earthquakes associated with island-arc trench

3) M. Katsumata, "Vertical Distribution of Earthquake Foci in and near Japan," *Quart. Journ. Seism.*, **20** (1955), 59-63.

4) T. Usami, T. Utsu and M. Ichikawa, "Seismicity in and near Japan, 1926-1956, *Geophys. Mag.*, **28** (1958), 273-289.

system along the Andes and those associated with the oceanic ridge* is disturbed with each other in the southern part of Chile (Fig. (a)).

4. Deep earthquakes with the depth ranging from 300km to 500km are quite a few, and excepting two cases near the coast of northern part, epicenters in the central part scatter $E-W$ direction (crosses in Fig. (c)), while epicenters of the earthquakes deeper than 500 km distribute around two separate lines both approximately 1000 km long (open circles in Fig. (d)).

3. Detailed view of the distribution of the foci in the upper mantle earthquake nests

In Fig. 1-(d) there is a mark ⊙ which is named **N1** at the northernmost part. This mark indicates the position beneath which a lot of upper mantle earthquakes 150 km – 160 km in depth have taken place. Fig. 2-(a) gives the frequency distribution of epicenters in each $0.1° \times 0.1°$ mesh in and around this spot. The data collected at three stations, **BOG** (Bogota, Colombia, 4°37′ 23.0″N, 74°03′ 54.0″W), **CHN** (Chinchina, Colombia, 4°58′ 00.0″N, 75°37′ 00.0″W) and **CAR** (Caracas, Venezuela, 10°30′ 24.0″N, 66°55′ 39.5″W), which closely surround the area in question, have been contributing to determining the foci in this district with especially high accuracy. (Refer to Fig. 10.) Most of the earthquakes are concentrated in a small area whose center is at around 6.85°N, 73.10°W, about 25 km southeast of Bucamanga, Colombia. Frequencies seem to disperse more or less NW–SE direction. Fig. 2-(b) gives the vertical distribution of foci along the profile bounded by l and l′ in (a) including the foci whose depths are not between 150 km and 160 km.

The foci gather around a surface with the dip of approximately 39°. About 80 earthquakes were observed densely crowded in such a small area as 10 km² within the depth ranging from 150 km down to 160 km. In Fig. 2-(c), the frequency of the earthquakes versus time is shown for the small rectangular area N1 in Fig. 2-(a). C.G.S. magnitude m of these earthquakes distribute with such frequency f as follows: $m=6(f=1)$, $m=5.9-5.5(f=12)$, $m=5.4-5.0(f=12)$, $m=4.9-4.5(f=25)$, $m=$

* There is such a supposition that the oceanic ridge may gradually change its extension southward off the coast of around 45°S and enter into the Archipelago forming the tail of the southernmost Chile[5]. If this is the case, the shallow earthquake zone extending to the Antarctica through the tail of the South America may be associated with seismic zone along the oceanic ridge.[6].

5) S. K. RUNCORN (editor), *Continental Drift.* (Academic Press, New York, 1962), p. 261.

6) R. W. GIRDLER, "How Genuine is the Circum-Pacific Belt?" *Geophys. Journ. Roy. Astr. Soc.*, **8** (1964), 537-540.

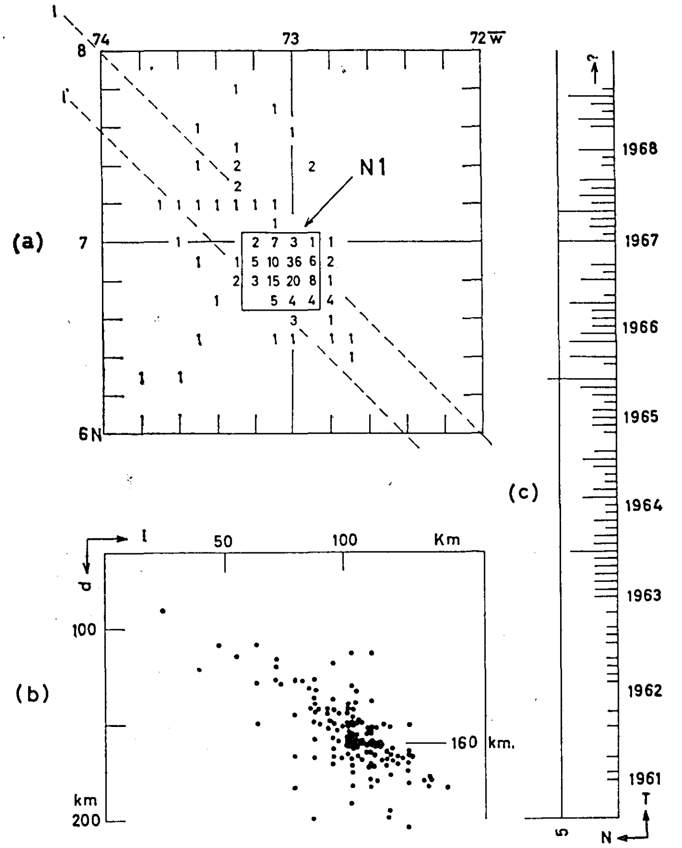


Fig. 2. (a) Frequency distribution of the earthquakes (150 km$\leq$d$\leq$160 km) in and around the earthquake nest N1 in each 0.1°×0.1° mesh. (b) Depth distribution of all foci including those of shallower and deeper ones around the nest N1 along the profile bounded by 1 and 1′ which are shown in (a). (c) Variation of the frequency of the earthquakes with time in the area N1 in (a).

4.4–4.0(f=40), m<3.9(f=31), unknown m(f=6). As will be mentioned later again, the nest N1 contains ten events which are followed by another event closely related with the formers both in space and time. The occurrence of the events in this nest, therefore, looks like having inductive character to some extent.

Horizontal and vertical distributions of the earthquake foci which belong to the nest N2 (see Fig. 1-(d)) are shown in Fig. 3. The occurrence of these earthquakes is quite at random in time and is found between 150 km and 200 km in depth.

Similar figures for N3 are presented in Fig. 4. Vertical distribution of foci was examined along a profile I of NS direction. They are clearly isolated from those of shallower earthquakes, and their depths

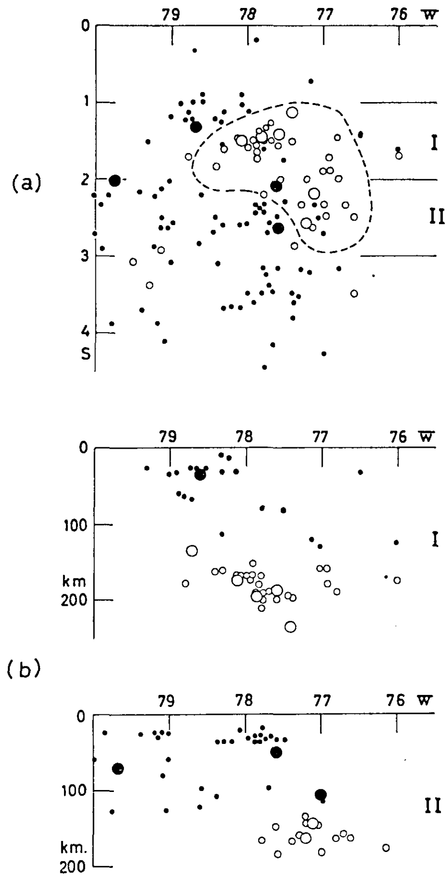


Fig. 3. (a) Epicenter distribution in the earthquake nest N2 (open circles). Large circles: m ≧ 5.0. (b) Depth distributions of the earthquake foci in the nest N2 (open circles) along the two profiles I and II which are given in (a).

are restricted to around 150 km.

Two nests N4 (depth: 125 km ± 25 km) and N5 (depth: 200 km ± 50 km) are neighbors. In Fig. 5, the epicenters distributions of foci with the depth ranges of 125 km ± 25 km (crosses), 200 km ± 50 km (open circles) and less than 100 km (filled circles) are shown for two different periods (a) and (b). These distributions show that the activity of the two groups of earthquakes seems to separate clearly since the beginning of 1966. Fig. 6, on the other hand, shows the depth distributions of foci in the same two periods as above along a curved profile bounded by ll and l′l′ in Fig. 5-(b). Since the beginning of 1966, foci have also been closely packed together into a narrow seismic layer approximately 40 km thick. As the vertical scale is about 2.8 times as exaggerated as the horizontal one, true inclination of this layer is about 21.5°. In order to see more closely when did such concentration begin, depth distribution of the foci was re-examined for each month from July 1963 to December 1965. This examination revealed that the concentration of the foci began

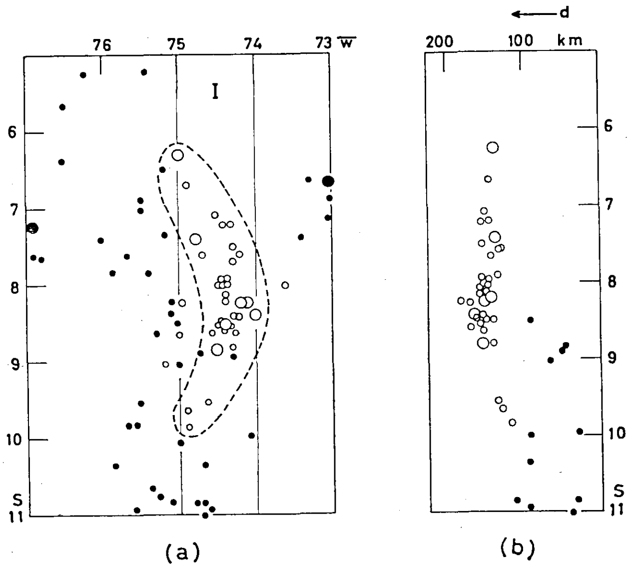


Fig. 4. (a) Epicenter distribution in the earthquake nest N3 (open circles). Large circles: m≧5.0. (b) Depth distribution of the earthquake foci in the nest N3 (open circles) along a profile I which is presented in (a).

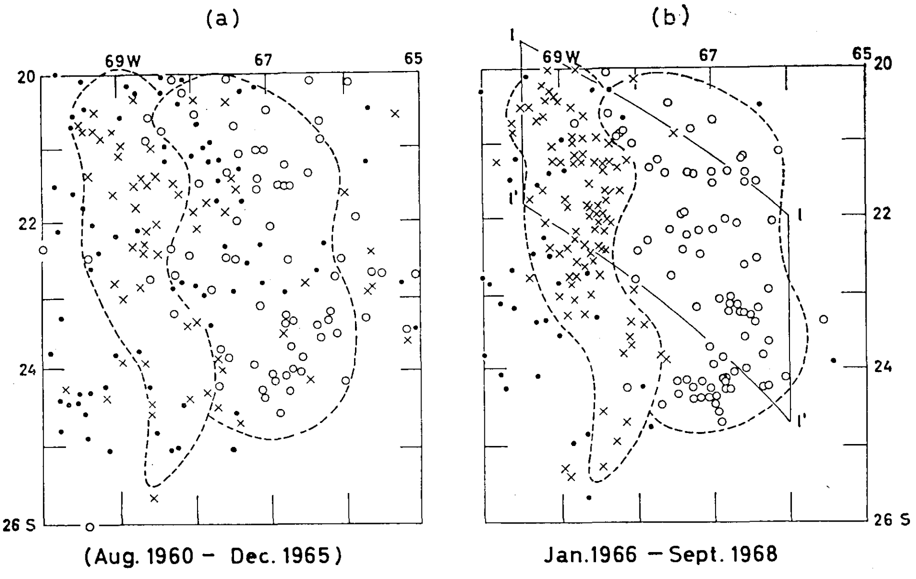


Fig. 5. Epicenter distributions of the earthquakes with the depth range of 100 km–150 km (crosses) and 150 km–250 km (open circles) during two periods. Filled circles are the epicenters of the earthquakes shallower than 100 km.

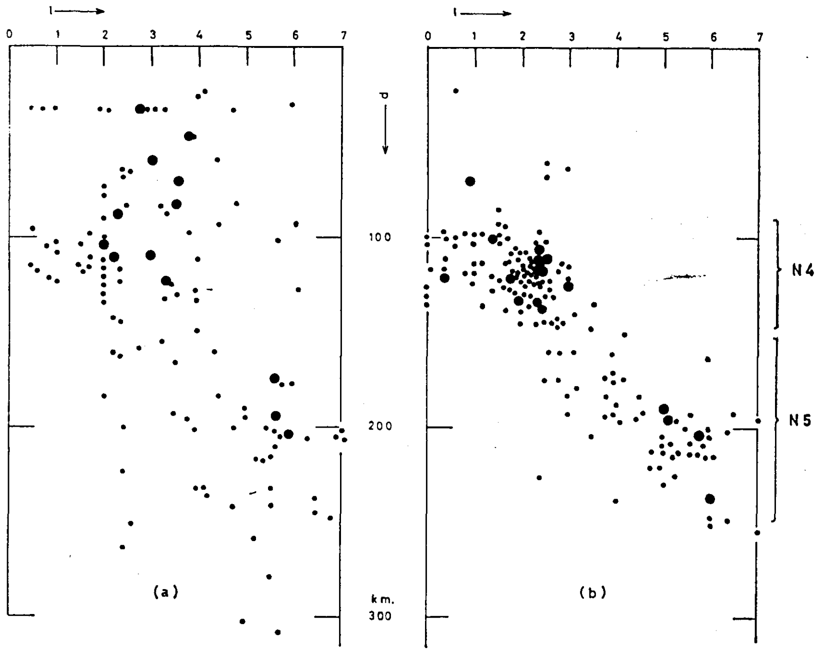
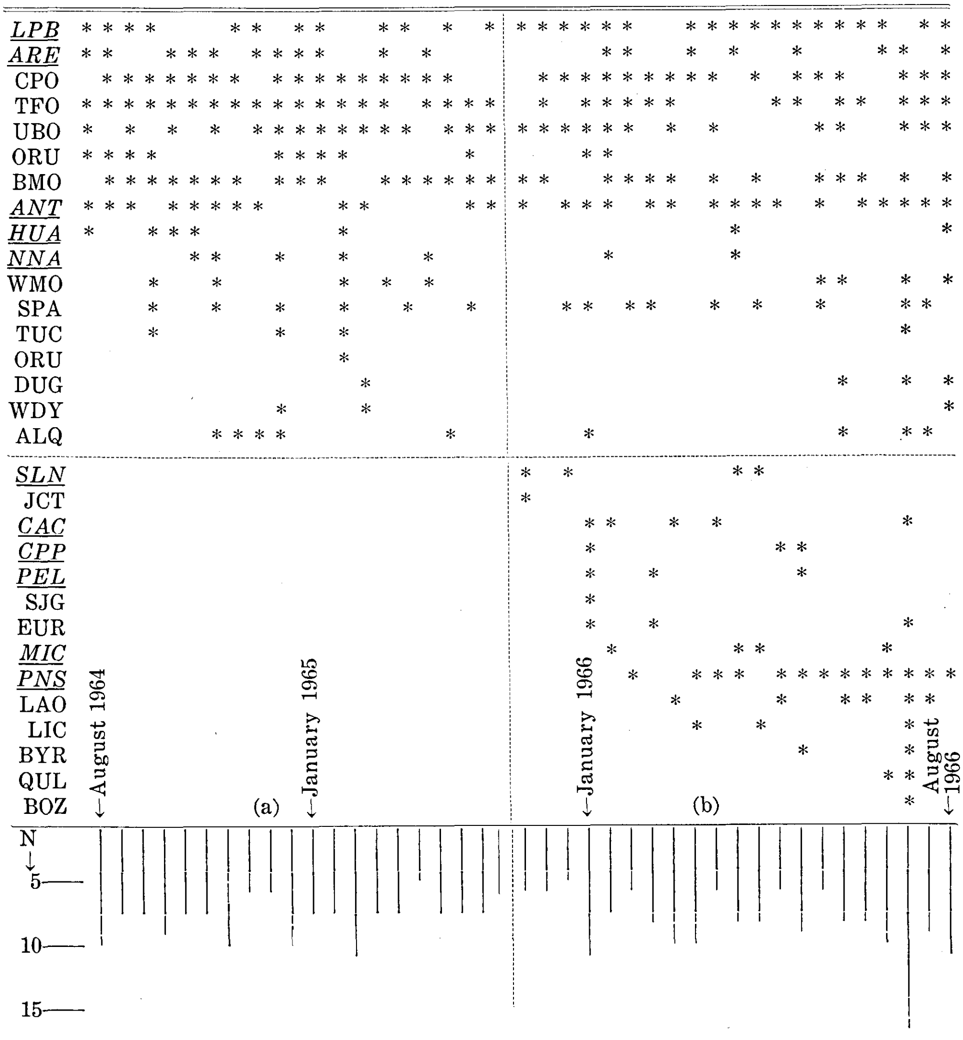


Fig. 6. Depth distributions of the earthquake foci in two different periods along the curved profile bounded by 11 and 1′1′ which are presented in Fig. 5-(b). Vertical scale is 2.8 times as exaggerated as the horizontal one. Large circles: m≧5.0.

approximately in August 1965.

Further investigation was made to see if the concentration of the foci in the later period (b) had been resulted from the developement of the observation net around the two nests N4 and N5. This brought us an instructive result. Table 1 gives the stations the data of which were used to determine the foci of the smaller events (4.0≦m≦4.2) in and around the nests N4 and N5 between August 1964 and August 1966. Since the time when the two nests were seperated, the seismological data at six new stations (see also Fig. 7) have come to use of USCGS to determine the epicenters and dephs of the events in and around the area we are now concerning with. Though the total numbers of the stations used for determining the epicenters and depths are about the same for two periods (a) and (b), it is quite obvious that the six stations above-mentioned made a great contribution to much more accurate foci determination since August 1965. Broad scattering of epicenters and depths in the earlier period (a) was considered to be resulted from lack of the data especially at **ANT** (Antofagasta, Chile), the only station close by and with azimuth different from that of any other station with the area in question in the period (a). Eight such unfavourable cases out of twenty are seen in Table 1.

Table 1. Stations whose date were used by USCGS to determine the epicenters and depths of the smaller earthquakes ($4.0 \leq m \leq 4.2$) between August 1964 and August 1966. Two periods (a) and (b) corresponding to those used in Figs. 5 and 6 are divided by a dotted vertical line. Stations in South America are underlined. All others are located in the U.S.A. The number of stations N used for epicenter determination for each event are shown in the lowermost figure.



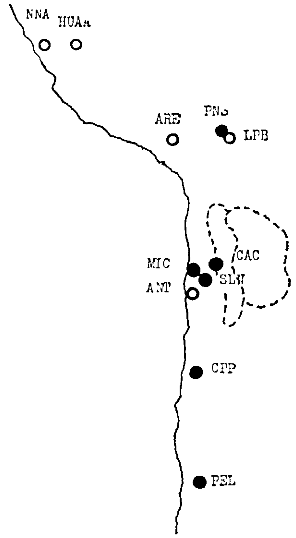


Fig. 7. Distribution of the stations in South America whose data were used by USCGS to determine the epicenters and depths of the smaller earthquakes ($4.0 \leqq m \leqq 4.2$) in and around the nests N4 and N5 shown by dashed curves.
Open circles: the stations in the earlier period.
Filled circles: the stations added in the later period.

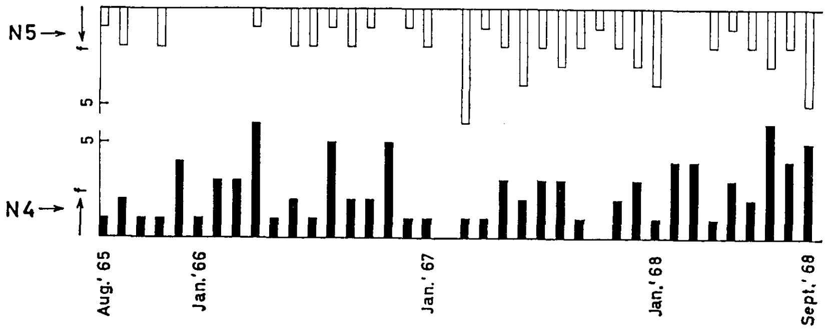


Fig. 8. Frequency variations of seismic activity versus time in the nests N4 and N5.

From the study above, we can not suppose that the two neighboring nests N4 and N5 did not exist before September 1965.

Fig. 8 shows the frequency variation of seismic activity with time in N4 and N5 groups since August 1965. A reversal correlation to some extent looks like existing.

Epicenters of the earthquakes belonging to the southernmost nest N6 form a round shaped area (Fig. 9-(a)). Depths of the foci along five profiles A, B, C, D and E parallel to the longitude seem to distribute around concaved surfaces around the depth of 100 km as shown in Fig. 9-(b).

Predominant seismic activity of this nest has been investigated by F. Volponi et al.[7], based upon the seismograms at four stations around

7) F. VOLPONI and H. MARCONI, "On the Spacial Distribution of Earthquakes near San Juan, Argentine, *Annual Rep. Sep. Terr. Mag. 1966—1967.* (1968), 37-42.

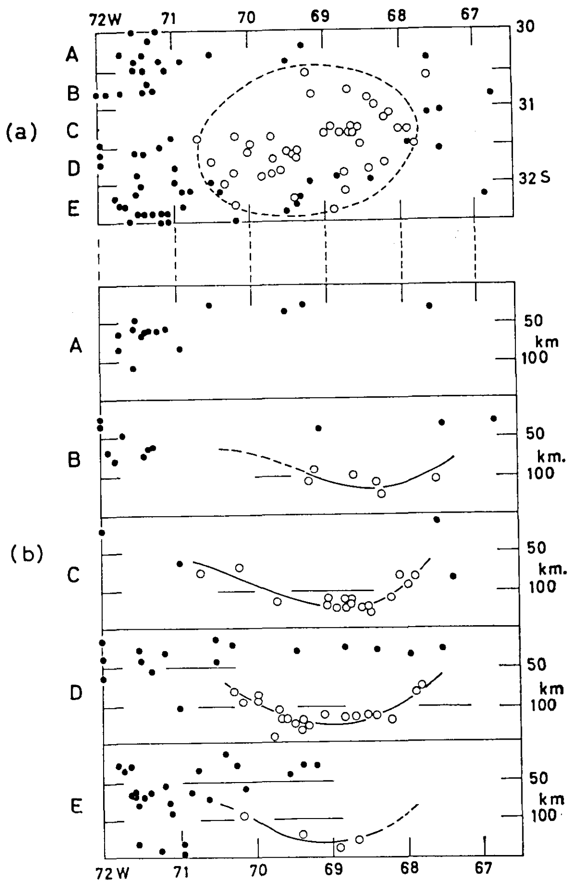


Fig. 9. Epicenter (a) and depth (b) distribution of the earthquakes in the nest **N6** (open circles).

this area. They obtained 1.6 for the value of m in Ishimoto-Iida's formula $nA^m=$constant where n is the frequancy of earthquakes with maximum amplitude $A\pm\Delta A$ on the seismograms. The value of m they obtained corresponds to $b=0.8$ in Gutenberg-Richter's coefficient and is a little larger than the value of b obtained by the seismicity in whole South America.[8)]

Being stimulated by the result of the investigation on the distributions of available stations around the nests N4 and N5 before mentioned, the similar studies were made for various seismic regions based on the "Earthquake Data Report" by USCGS around the end of 1963. The results are given both in Table 2 and Fig. 10. Seismic zones asyned by **D1**−**D4** in the lowermost two maps mean deep earthquakes which

8) *ibid.*, 1).

Table 2. Seismological stations whose data were available for USCGS to determine epicenters of small shocks (m: 4.0 – 4.2) in various seismic areas around the end of 1963. Stations underlined and marked with an asterisk are located in South America and in Antarctica respectively. All other stations are in the U.S.A.

Seismic area	Seismological station
N1	*CAR* *BOG* *CHN* WMO TFO CPO UBO
N2	*ANN* *HUA* *BOG* CPO WMO ALQ UBO BMO ALQ TUC ORV
N3	*NNA* *HUA* *LPB* CPO WMO TFO ORV MBC URO BMO UBO ALQ TUC
N4, N5	*ANT* *LPB* *ARE* CPO TFO UBO EUR ORV BMO WMO UBO ORV
N6	*SAN* *ARE* *LBP* *HUA* CPO WMO TUC ALQ TFO ORV BYR* SPA*
around 46°S	*SAN* *ANT* *ARE* CPO WMO TUC ALQ TFO BYR* SPA*
D1	*HUA* *ARE* *NNA* *LPB* CPO WMO TUC TFO UBO ORV BMO
D2 – D4	*ANT* *ARE* *LPB* *PEL* HUA CPO WMO ALQ TFO UBO DUG EUR

will be reported later in section 4.

Remarkable fact is that many stations in the U.S.A. did not miss any of the events even if its magnitude m was as small as 4.0 and its location was as far as more than 8000 km.

Two stations in Antarctica, **SPA** (South pole) and **BYR** (Byrd) sometimes played an important role for the determination of epicenters and depths of the events in southern seismic areas in South America, though both stations are still far from South America. Quite regrettable fact is, on the other hand, that there are almost no services of eastern stations, especially that no data for smaller events are available from Argentine even quite recently. Since they are located in quite important areas for determining the epicenters of earthquakes in South America, their active services are very much desirable for developing the accuracy of the epicenter determination much more.

Locations of the six nests of intermediate earthquakes above mentioned were geographically examined. **N1**, **N2** and **N6** are located under the slope of the Andes, being partly situated right beneath the crest. No other geographical features could be found. Only **N3** was located beneath the plain. Locations **N4** and **N5** could be related with the distributions of contour lines of Bouguer's gravity anomaly.[9] Shallower

9) Gravity Chart of the Southern Andes, compiled by Department of Geophysics and Geodesy, Univ. of Chile (1963)

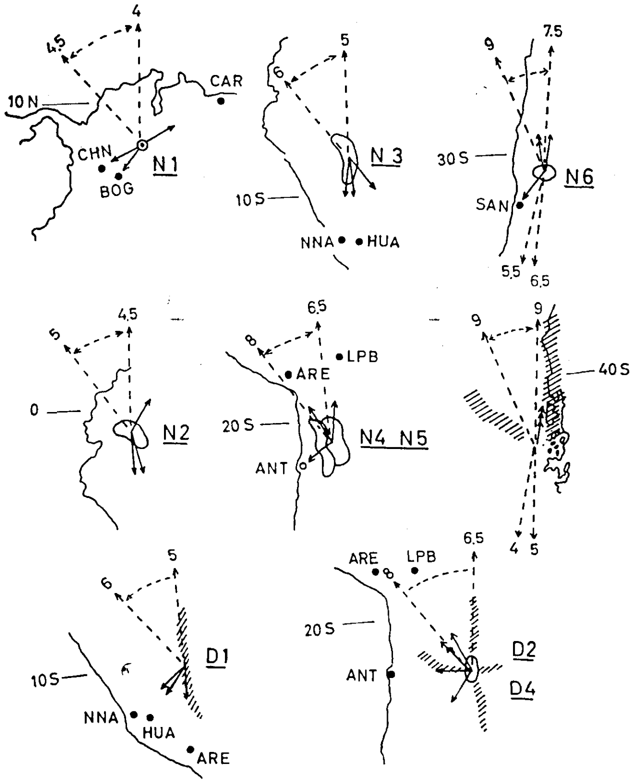


Fig. 10. Directions of seismological stations whose data were available for USCGS to determine the epicenters of small shocks ($4.0 \leqq m \leqq 4.2$) around the end of 1963. Directions of the stations outside South America (North America and Antarctica) are marked by dashed arrows, and the attached numerals show the distances in 1000 km.

nest N4 was located beneath the dense portion of the contour lines, while deeper one N5 beneath the sparse portion.

Besides the existence of the earthquake nests there are many special events in the intermediate earthquakes group whose depths are between 100 km and 200 km, that is, these special events are followed by one, two or sometimes three events which are closely related with previous ones both in space and time. In Table 3, events that occurred at a short interval of less than one day within a distance of less than 50 km are listed, although the determination of foci in P.D.E. may still not be accurate enough to obtain reliable values of the distance. The locations of these multiple events above mentioned are shown by framed regions in Fig. 11, in which the frequency distribution of intermediate earthquakes with the depth of 100 km$-$200 km originated in every $1° \times 1°$ mesh is presented. Excepting one case which occurred in the mesh

Table 3. Multiple intermediate (depth 100km – 200 km) earthquakes which are closely related with one another both in time and space. In the last column, the names of earthquake nests are given.

Year	Date		Origin Time (G.M.T.)			Epicenter		Depth	Mag.	Location (mesh No.)	Rem.
						λ	φ	(km)	(m)		
1962	May	2	08^h	56^m	31.6^s	23.7S	66.4W	177		34-VII	N5
			12	33	08.3	23.8S	66.6W	177		34-VII	N5
1963	June	1	04	05	27.3	6.7N	73.1W	150		4-XIV	N1
			12	50	25.6	6.9N	73.1W	155		4-XIV	N1
	May	25	01	50	58.0	23.8S	66.8W	216		34-VII	N5
			07	56	58.8	24.2S	66.8W	185		34-VII	N5
	Sept.	19	21	10	18	18.1S	69.2W	174	4.2	29-X	
		20	02	21	29.1	17.9S	69.6W	154	3.7	29-X	
		20	07	25	11.8	21.5S	68.3W	125	4.7	32-IX	N4
			14	41	22.6	21.5S	68.0W	155	4.8	32-IX	N4
	Nov.	25	06	50	08.8	6.9N	73.3W	167	4.2	4-XIV	N1
			17	53	36.8	6.8N	73.0W	160	4.0	4-XIV	N1
1965	May	16	05	38	38.2	6.6N	72.8W	183	4.0	4-XIII	N1
			19	53	57	6.5N	72.8W	189	3.4	4-XIII	N1
	June	26	09	56	43	6.7N	72.9W	175	4.3	4-XIII	N1
		27	12	55	4.4	6.7N	72.9W	178	4.7	4-XIII	N1
		28	06	20	11.1	6.7N	72.9W	172	4.2	4-XIII	N1
		29	10	00	15.6	6.7N	72.8W	179	4.8	4-XIII	N1
	July	14	12	29	56.0	17.6S	69.5W	143	5.1	28-X	
			13	37	36	17.2S	69.3W	170	4.2	28-X	
		30	13	35	21	19.3S	69.1W	206	3.9	30-X	
		31	10	38	52	19.3S	68.8W	190	3.9	30-X	
	Sept.	15	07	48	21	7.0N	73.1W	142	4.2	4-XIV	N1
			08	39	33.1	6.8N	73.0W	165	4.6	4-XIV	N1
		25	20	59	18.6	24.5S	68.6W	102	5.1	35-IX	N4
		26	00	20	37	24.3S	69.2W	115	4.5	35-IX	N4
	Dec.	7	11	15	07	18.9S	69.6W	116	4.3	29-X	
		8	06	25	56.8	18.4S	69.3W	131	3.8	29-X	
1966	Apr.	29	06	45	21	6.9N	73.0W	157	4.3	4-XIV	N1
		30	01	27	54	6.9N	72.9W	153	3.7	4-XIV	N1
	May	1	16	22	56.3	8.5S	14.3W	165	5.7	19-XV	N3
		2	10	55	48	8.2S	14.1W	148	5.1	19-XV	N3
	July	11	07	28	17.3	6.9S	73.0W	161	4.6	4-XIV	N1
			09	29	54.7	6.8N	73.1W	172	4.7	4-XIV	N1

(to be continued)

Table 3. (continued)

Year	Date	Origin Time (G.M.T.)			Epicenter λ	Epicenter φ	Depth (km)	Mag. (m)	Location (mesh No.)	Rem.
	Aug. 25	22 h	20 m	34.8 s	22.5 S	68.6 W	115	4.4	33-IX	N4
		23	18	50.8	22.4 S	68.6 W	112	5.3	33-IX	N4
	26	00	15	49.5	22.5 S	68.6 W	116	4.5	33-IX	N4
	6	23	49	54.1	20.3 S	69.2 W	100	4.4	31-X	N4
	7	07	00	02	19.7 S	68.9 W	119	4.1	31-X	N4
	Nov. 14	12	58	36.2	18.3 S	69.2 W	123	5.4	29-X	
		21	44	29	18.3 S	69.3 W	111	4.7	29-X	
1967	June 22	08	18	14.4	6.8 N	73.0 W	158	4.6	4-XIV	N1
	23	09	27	48.1	6.9 N	73.0 W	150	4.2	4-XIV	N1
	25	09	33	09	6.9 N	73.2 W	158	3.8	4-XIV	N1
	Feb. 10	00	39	38	3.1 N	73.7 W	100	3.9	8-XV	
		06	39	12	2.9 N	74.4 W	130	4.0	8-XV	
	12	13	55	05	2.8 N	74.4 W	100	3.8	8-XV	
	May 23	11	53	00	22.8 S	68.0 W	135	4.2	33-IX	N4
		18	05	51.1	23.5 S	68.1 W	134	4.3	33-IX	N4
	June 15	03	03	16	22.4 S	67.2 W	182	3.9	33-VIII	N5
		10	45	46	22.0 S	66.8 W	215	3.6	33-VIII	N5
	27	12	24	39	23.9 S	67.0 W	213	4.1	34-VIII	N5
		23	19	01.8	24.1 S	67.2 W	198	4.1	34-VIII	N5
	Aug. 14	14	46	24	6.9 N	73.0 W	159	4.0	4-XIV	N1
	15	04	06	55.8	6.8 N	72.9 W	164	4.5	4-XIV	N1
	Sept. 3	14	32	38	6.9 N	72.9 W	173	4.0	4-XIII	N1
		17	02	07	6.9 N	72.9 W	173	4.0	4-XIII	N1
	Dec. 27	09	17	55.7	21.2 S	68.3 W	135	6.4	32-IX	N4
			54	02	21.3 S	68.4 W	115	4.7	32-IX	N4
1968	Feb. 20	21	35	29.2	27.9 S	66.4 W	157	4.9	38-VII	
	21	10	27	06.4	28.0 S	66.3 W	139	4.5	38-VII	
	Sept. 9	00	35	18.4	8.7 S	74.5 W	144	5.3	19-XV	N3
			37	43.2	8.7 S	74.5 W	120	6.0	19-XV	N3
	22	21	52	59.2	24.1 S	66.9 W	194	5.5	35-VII	
	23	07	52	17.6	24.3 S	67.0 W	161	4.2	35-VII	
	23	10	26	54.6	20.9 S	68.7 W	139	3.7	31-VIII	N5
	24	01	43	33.9	20.9 S	68.2 W	159	4.7	31-VIII	N5

XV-08 of low seismicity, all multiplets take place in active regions. It seems, therefore, that the occurrence of the multiple events is related only with the seismic activity of the region around them. In average, 31 such multiple events have taken place out of 950 intermediate earthquakes in the depth ranging from 100 km to 200 km. The percentage of the occurrence of these special events is, therefore, about 3.3%.

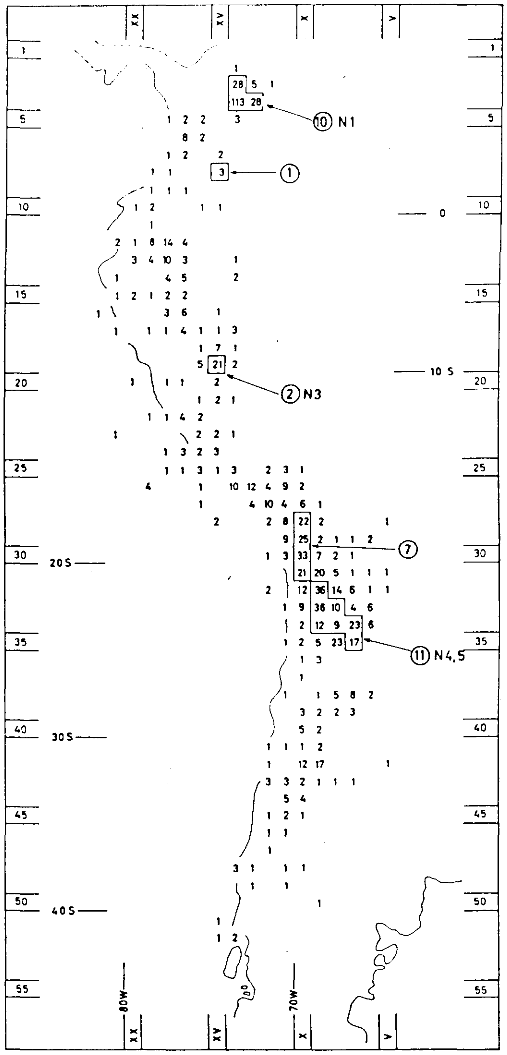


Fig. 11. Frequency distribution of epicenters of the upper mantle earthquakes with the depth range of 100 km–200 km in 1°×1° meshes. Region where multiple events took place and the frequencies of these events is respectively shown by framed area and numbers in circles.

The similar ratio for the earthquakes shallower than 40 km is 40/805, that is about 5.0%. Remarkable difference of the multiple events in these two groups, intermediate and crustal events, is that the latter has eight events being followed by aftershocks (see Table 4), while the former has no such a event. One of the possible reasions for missing the aftershocks in the intermediate earthquakes is that there was no event which was large enough to accompany the aftershocks. Actually, the magnitude of the largest event was $m=6.0$ in the nest **N1**.

In the present section it must especially be noticed that the upper mantle earthquakes in South America around 150 km deep is remarka-

Table 4. Shallow ($d \leqq 70$ km) and large ($m \geqq 6.5$) earthquakes in South America (August 1960- September 1968). In the column "Rem.", the number of forshocks F and of aftershocks A is respectively given in parentheses. Two events whose m is less than 6.5 are also listed because they have remarkable aftershocks.

Year	Date	Origin Time (C.M.T.)	Epicenter		Depth (km)	Mag. (m)	Rem.
			λ	φ			
1960	Aug. 13	$14^h\ 14^m 57.7^s$	39.7 S	74.8W	61	6.9 (M)	
	Oct. 30	21 32 47.7	22.8 S	68.0W	60	6.75	F(6), A(2)
	Nov. 1	08 46 01.9	38.4 S	74.4W	55	7.2 (M)	
	Dec. 2	09 37 38.6	24.3 S	69.8W	64	6.75	F(1), A(3)
1961	Oct. 18	16 52 00.2	36.7 S	72.6W	67	6.5	A(6)
	Dec. 9	11 18 08.9	43.7 S	75.2W	34	6.5	
1962	Feb. 14	06 36 01.3	38.1 S	73.1W	44	7.25	A(10)
	July 30	20 18 52.3	5.2N	76.4W	69	6.75	A(1)
	Aug. 13	06 35 56.0	2.1N	83.5W	33	6.6	
	Nov. 11	22 14 18.7	43.2 S	76.0W	33	6.6	
	Dec. 29	10 41 04.6	20.2 S	70.3W	49	6.75	
1963	May 10	22 22 42.7	2.1 S	77.6W	30	6.75	
	May 19	01 03 06.2	46.3 S	74.8W	48	6.8	
	Aug. 29	15 30 31.4	7.1 S	81.6W	23	6.5	
1966	Oct. 17	21 41 56.3	10.7 S	78.7W	38	7.5 (M)	A(23)
	Dec. 28	08 18 07.4	25.5 S	70.7W	47	6.9	A(22)
1967	Feb. 9	15 24 47.2	2.9N	74.9W	58	6.3	A(10)
	Sept. 3	21 07 30.8	10.6 S	79.8W	38	6.5	
1968	June 19	08 13 35.0	5.6 S	77.2W	28	6.4	A(45)

bly active, and that this depth corresponds to the depth where a low-velocity layer is supposed to run globaly. Frequent occurrence of earthquakes in South America in the depth of around 150 km is in sharp contrast to the earthquake frequency in and around Japan where the minimum frequency of earthquakes exists in the depth between 100 km – 250 km[10]. It does not show either the general feature of island-arc trench system which has relatively low seismicity in the depth ranging from 150 km to 250 km[11]. A regional study on the vertical velocity distribution of seismic waves beneath the Andes is required.

In the previous section 2, a silent area of the upper mantle earthquake activity between 25°S and 27°S was remarked. In order to make the situation much clearer, distributions of epicenters and foci around this silent area were particularly examined by plotting them on a larger

10) A. Sugimura, "Complementary Distributions of Epicenters of Mantle Earthquakes and of Foci of Volcanoes in Island Arcs (in Japanese)," *Zisin*, **19** (1966). 96-106.
11) *ibid.*, 10)

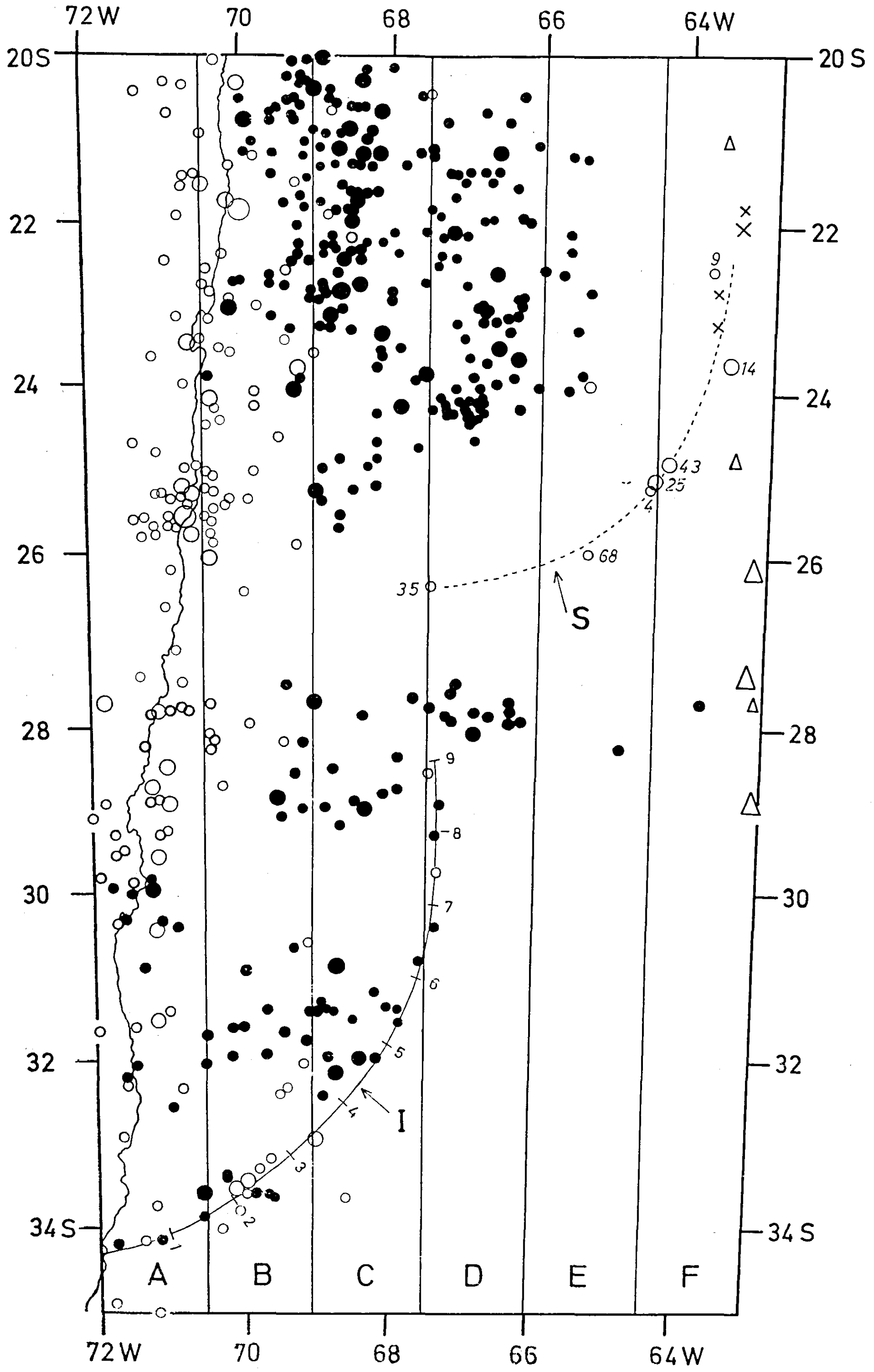


Fig. 12. Epicenter distribution of earthquakes observed in the central part of South America since the beginning of 1966. Open circles: d $\leqq$ 70 km. Filled circles: 70 km $<$ d $\leqq$ 300 km. Crosses: 500 km $\leqq$ d $\leqq$ 525 km. Triangles: d $>$ 580 km. Size of each symbol indicates the magnitude of earthquakes. Large: m $\geqq$ 6; middle: m $\geqq$ 5; small: m $<$ 5 Numerals beside open circles along the shallow earthquake zone S indicate the depth.

map. The data after 1966 were used for this purpose; this period belongs to (b) previously denoted when the determination of the locations of the origin of earthquakes around the area in question has remarkably progressed.

The results are given in Figs. 12 and 13. In both figures, a group of shallow earthquakes is shown around 25.5°S near the coast. This group is nothing but the group of aftershocks associated with a great Taltal Earthquake on December 28, 1966 with the magnitude m of 6.9.[12),13),14)] Before that great event, there were really only three events

(a)

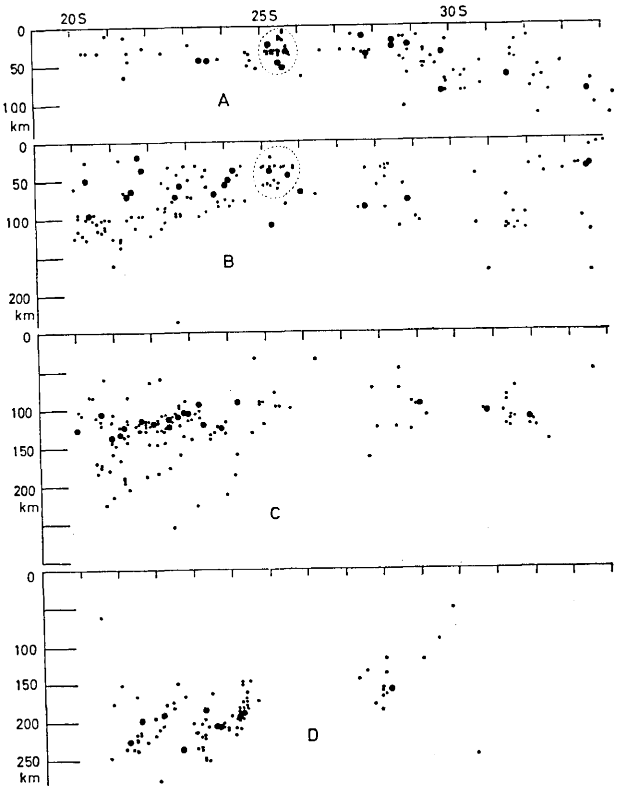


Fig. 13.(a) Foci distributions of earthquakes along the profiles which are presented in Fig. 12. Foci envelopped by dashed curves in the profiles A and B indicate those of aftershocks being associated with Taltal Earthquake.

12) W. J. Arabasz, "Geologic Structure of the Taltal Area, Northern Chile, in Relation to the Earthquake of December 28 1966", *Bull. Seism. Soc. Amer.*, **58** (1968), 835-842.

13) A. M. Pitt and J. O. Ellis, "Preliminary Report on some Aftershocks of the December 28, 1966 Earthquakes in Northern Chile," *Bull. Seism. Soc. Amer.*, **58** (1968), 843-850.

14) R. W. Lemke, E. Dobrovolne, L. Allarez S. and F. Ortiz O., "Geologic and Related Effect of the Taltal Earthquake, Chile of December 28, 1966", *Bull. Seism. Soc. Amer.*, **58** (1968), 851-860.

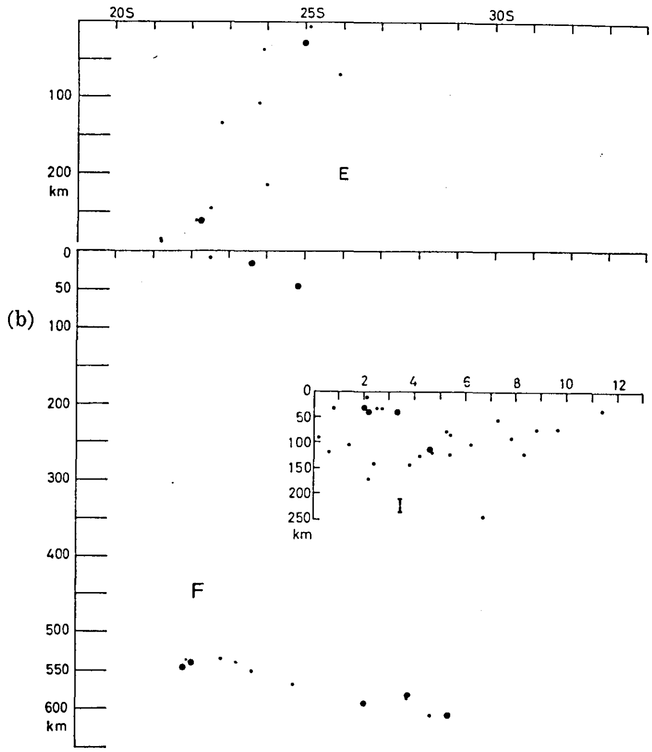


Fig. 13.(b) Foci distributions of earthquakes along the profiles which are presented in Fig. 12.

in the district during the period of almost one year since the beginning of 1966 at latest. Before that great event, therefore, the silent area now we are dealing with cut through even the shallower seismic zone. In any case, the active area of the upper mantle earthquakes is clearly cut by a wedge shaped area deeply entering near the shallower zones.

In Fig. 12, we can see a shallow earthquake zone which enters deeply inland and runs along a curve in the middle of the silent area above-mentioned. This zone encounters with a deep earthquake zone around 23°S. Quite interesting fact is that the depths of earthquakes along the deep seismic zone become remarkably shallower right in this encountering area. (See the foci distribution in profile *F* in Fig. 13(b). Refer also to the seismic zone D4 in Fig. 15.) Moreover, in general the foci distribution of upper mantle earthquakes in the northern part of the silent area shows upward tendency to the silent area. (See the foci distributions along the profiler *B*, *C* and *D* in Fig. 13. (a)) Generally speaking, the silent area seems to pull up all the foci. It is hard to advance any suggestions on the elucidation of this fact based on the present data only.

There might exist another nonseismic area of upper mantle earthquakes between 29°S and around 31°S, which is bounded on its eastern side by a narrow seismic zone which also runs on a curve starting from 34°S near the coast. Foci along this curve also become shallower towards the foci of a shallow event in the midst of the wedge shaped silent area (see foci distributions along the profile I in Fig. 13(b)).

4. Special distribution of deep earthquake foci

In Table 5, deep earthquakes having been originated in South America during the period from August 1960 down to September 1968 are listed being picked from the data in P.D.E. The distribution of epicenters shows again an interesting character. These epicenter distributions can be grouped into four zones **D1**, **D2**, **D3** and **D4**, which are remarked in the last column in Table 5. Earthquakes in zone **D1** distribute along a curve between 6.0°S and 11.5°S near the boundary of northern Peru and Brazil. An isolated great deep earthquake ($\lambda=$ 13.8°S, $\varphi=69.3°$W, m=7.2) on August 15, 1963 looks like lying on the extension of this active line (Fig. 14-(a)). If this earthquake is included in zone **D1**, depth distribution of foci along this line seems to fluctuate between approximately 550 km and 680 km (Fig. 14-(b)).

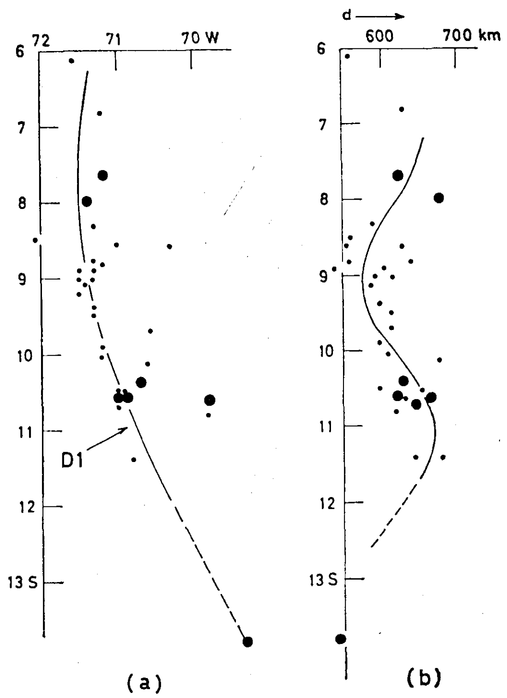


Fig. 14.(a) Epicenter distribution of deep earthquakes around curve **D1**. Large circles: m≧5.0. (b) Depth distribution along NS profile. Large circles: m≧5.0.

Table 5. Deep ($d>300$ km) earthquakes in South America (August 1960—September 1968). Groups of the events which are closely related with each other both in space and time are combined by brackets in the Epicenter column.

Year	Date	Origin Time (G.M.T.)	Epicenter λ	Epicenter φ	Mag. (m)	Depth (km)	Remark
1961	Feb. 8	08 : 04 : 13.8	10.6 S	71.0W	5.8	669	D1
	May 26	08 : 42 : 15.0	10.1 S	70.6W		678	D1
	July 25	02 : 48 : 13.5	8.8 S	71.3W		642	D1
	Aug. 19	05 : 09 : 49.5	10.7 S	71.0W	7	649	D1
		16 : 01 : 25.6	11.4 S	70.6W		645	D1
	20	00 : 07 : 24.5	10.5 S	70.9W		659	D1
		09 : 10 : 11.9	11.4 S	70.8W		678	D1
	31	01 : 48 : 31.5	10.6 S	70.9W	7	626	D1
		01 : 57 : 08.0	10.4 S	70.7W	7.5	629	D1
	Sept. 10	04 : 45 : 27.1	27.7 S	63.1W		519	D2
	12	11 : 18 : 26.3	10.8 S	69.8W		618	D1
	16	20 : 02 : 42.8	10.6 S	69.8W		629	D1
	19	02 : 25 : 49.2	20.3 S	63.2W	6.5	609	D2
1962	Sept. 29	15 : 17 : 47.6	27.1 S	63.5W	6.5	577	D2
	Dec. 8	21 : 27 : 22.2	25.8 S	63.4W	6.8	620	D2
	25	12 : 43 : 58.9	28.2 S	63.2W		589	D2
1963	Mar. 23	07 : 57 : 35.4	10.5 S	71.0W		600	D1
	Aug. 15	17 : 25 : 05.9	13.8 S	69.3W	7.2	543	D1
	Oct. 8	06 : 25 : 08	6.6 S	71.6W	3.7	557	D1
	Nov. 9	21 : 15 : 30.4	9.0 S	71.5W	6.5	600	D1
		23 : 14 : 12.6	8.5 S	72.1W	4.4	563	D1
	10	01 : 00 : 38.8	9.2 S	71.5W	6.3		D1
		01 : 36 : 41.3	9.4 S	71.3W	4.1	600	D1
	11	19 : 54 : 09.4	9.1 S	71.4W	4.9	585	D1
	13	04 : 17 : 59.9	8.9 S	71.5W	3.6	545	D1
		09 : 01 : 41	9.0 S	73.3W	4.0	328	
1964	Jan. 23	11 : 38 : 52	2.5 S	80.1W	3.6	418	
	Feb. 24	01 : 13 : 37	21.0 S	67.9W	4.1	326	D3
	25	09 : 44 : 36	22.2 S	62.6W	4.1	470	D3
	Mar. 8	06 : 20 : 12	22.3 S	67.1W	3.9	302	D3
	June 10	09 : 33 : 31	22.5 S	64.7W		480	D3
	25	11 : 47 : 02.2	22.8 S	63.5W	4.3	525	D4
	30	11 : 28 : 58	23.3 S	66.6W	4.5	345	D3
	Sept. 12	09 : 59 : 00	21.7 S	66.6W	3.8	309	D3
	Nov. 28	16 : 41 : 33.4	7.7 S	71.2W	5.4	626	D1
		49 : 30.3	8.0 S	71.4W	5.6	655	D1

(to be continued)

Table 5. (Continued)

Year	Date	Origin Time (G.M.T.)	Epicenter λ	Epicenter φ	Mag. (m)	Depth (km)	Remark
	Dec. 7	06 : 02 : 21.5	5.5 S	80.3W	3.5	345	
	9	13 : 35 : 42.4	27.5 S	63.2W	6.0	586	D2
	22	00 : 24 : 48.7	9.5 S	71.3W	5.3	614	D1
	23	06 : 30 : 38	27.4 S	63.1W	4.4	580	D2
1965	Feb. 18	03 : 52 : 54	22.9 S	63.7W	3.9	530	D4
		54 : 11	23.1 S	62.5W	4.7	468	D3
		22 : 32 : 19.6	9.9 S	71.2W	5.0	594	D1
	Apr. 20	21 : 31 : 38	25.9 S	63.1W	4.1	600	D2
	May. 13	02 : 23 : 23	19.3 S	63.8W	5.1	589	D2
	July 30	02 : 11 : 39.0	22.8 S	63.7W	4.5	526	D4
	Sept. 3	05 : 42 : 24.9	27.6 S	63.0W	4.5	581	D2
	Nov. 26	12 : 48 : 40	8.6 S	71.0W	3.5	553	D1
	Dec. 11	03 : 40 : 42	27.6 S	63.1W	4.1	571	D2
1966	Feb. 15	11 : 59 : 00	8.6 S	70.3W	3.4	629	D1
	June 5	19 : 03 : 10	9.7 S	70.6W	4.6	608	D1
	Aug. 8	01 : 24 : 28	28.7 S	62.5W	3.9	609	D2
	Oct. 14	22 : 42 : 51	6.8 S	71.2W	3.9	631	D1
	Dec. 20	12 : 26 : 55.0	26.1 S	63.2W	5.7	589	D2
1967	Jan. 17	01 : 07 : 54.3	27.4 S	63.3W	5.5	590	D2
	27	08 : 38 : 51.9	9.0 S	71.5W	4.6	613	D1
	Feb. 15	16 : 11 : 11.8	9.0 S	71.3W	6.2	597	D1
	19	21 : 09 : 01	24.7 S	63.5W	4.0	566	D2
	Mar. 25	20 : 32 : 02	8.3 S	71.3W	4.2	587	D1
	27	08 : 26 : 34	8.9 S	71.3W	5.3	603	D1
	Aug. 10	06 : 50 : 03	23.2 S	63.8W	3.9	538	D4
	28	00 : 56 : 51.0	10.0 S	71.2W	4.7	609	D1
	30	17 : 28 : 09	22.8 S	63.8W	4.1	534	D4
	Sept. 4	22 : 06 : 13	28.3 S	63.1W	4.6	604	D2
	9	10 : 06 : 44.1	27.7 S	63.1W	5.8	578	D2
1968	Jan. 1	19 : 07 : 23	27.1 S	62.8W	3.9	641	D2
	Feb. 8	22 : 50 : 04.6	9.1 S	71.4W	4.7	593	D1
	Apr. 1	02 : 17 : 09	23.6 S	63.6W	4.1	550	D4
	May. 11	13 : 30 : 05.9	28.8 S	63.1W	5.2	602	D2
	Aug. 5	04 : 20 : 44.4	8.8 S	71.2W	3.8	564	D1
	23	22 : 36 : 51.3	22.0 S	63.5W	5.8	537	D4
		23 : 14 : 52.7	21.8 S	63.5W	5.2	541	D4

There is another group of epicenters which are distributed around another curve **D2** extended also N–S direction between 19°S and 29°S (Fig. 15–(a)). This curve crosses perpendicularly the boundary of Bolivia and Argentine. (Refer also to Fig. 16.) Epicenters distributing along **D2** are more or less concentrated between 27°S and 29°S in the northern

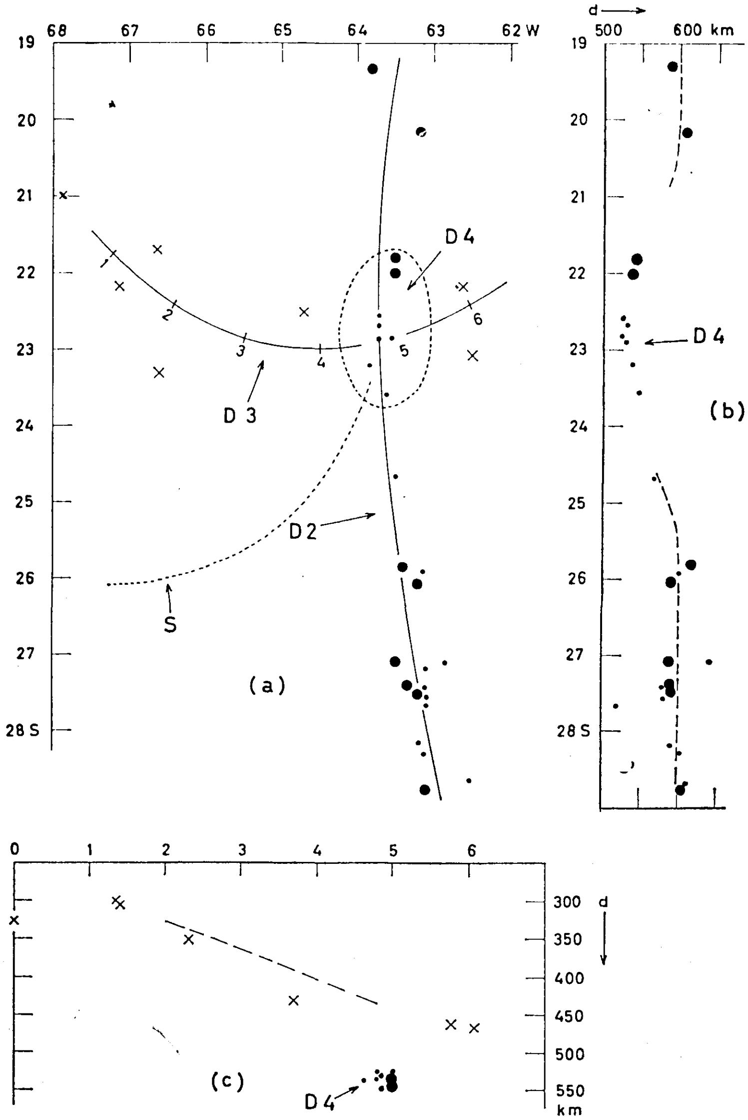


Fig. 15.(a) Epicenter distributions of deep earthquakes around two curves **D2** and **D3**, and in region **D4**. A dashed curves **S** shows the shallow earthquake zone which was presented in Fig. 12. (b) Depth distributions of the foci which belong to groups **D2** and **D4** along the NS profile. (c) Depth distributions of the foci which belong group **D3** ane **D4** along curved profile **D3**.

Argentine. As will be seen in Fig. 16, it is hard to connect line **D2** smoothly to the northern active line **D1**.

The third zone **D3** is composed of small number of earthquakes with rather shallower depths of 300 km – 480 km. The epicenter distribution forms also a curved band, and their foci distribute around a plane which slopes down to the east with the angle of around 24°. (Fig. 15-(b) and -(c)). As is seen in Table 5, the earthquakes in this zone took place mostly during only about eight months since February 1964, which draws our attention. It is also quite interesting that, around a crossing area of these two zones **D2** and **D3**, there is another group of foci the depth of which belongs neither to zone **D2** nor to **D3** (Fig. 15-(b) and -(c)). Moreover, this area exactly corresponds to the area which meets with another shallow earthquake zone running through a silent area of upper mantle earthquakes (see Fig. 12). Geophysical meaning of these aspects is not clear at this moment. We shall, for a moment, name this group (enclosed by dashed curve in Fig. 15-(b)) **D4**. Depths of foci belonging to this group are restricted between 525 km – 550 km.

It was reported in the previous section that among the intermediate earthquakes with the depth range of 100 km to 200 km there were many special events which accompanied one, two or sometimes three events closely related with each other both in space and time. Table 5 again shows that the group **D1** has several similar special events as given above in the range from 8°S to 12°S. Together with other data of the

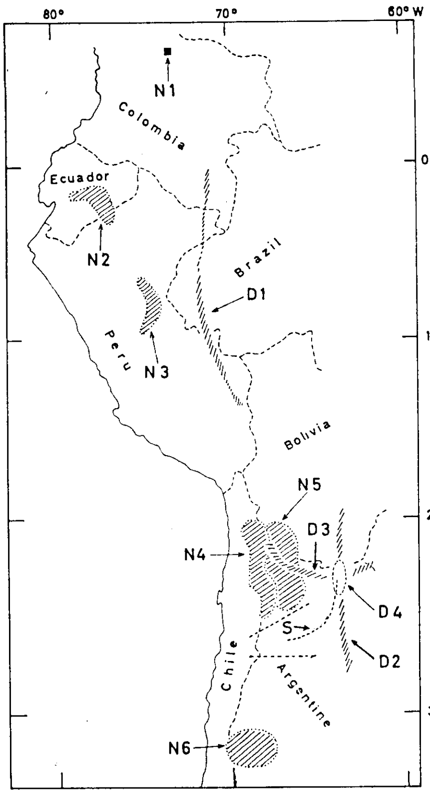


Fig. 16. Summarized map showing the characteristic distributions of intermediate earthquake nests **N1** to **N6**, active zone of deep earthquakes **D1** to **D4** and a special zone of shallow earthquakes **S** running deeply inland.

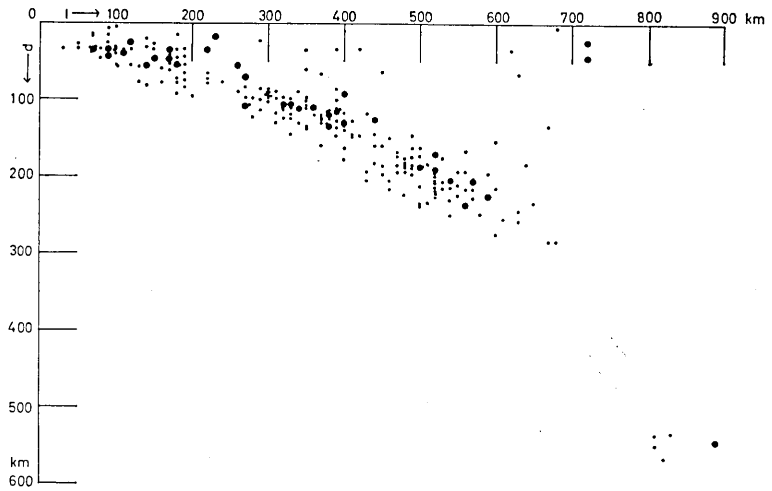


Fig. 17. Depth distribution of the earthquake foci along a EW profile from 20°S 25°S. Earthquake data from August 1965 were used.

deep multiplets in Fiji-Tonga-Kermadec region observed by B. L. Isacks et al[15], the data of the multiple events in intermediate and deep earthquakes explained in the present paper would be valuable to studying earthquake mechanism and the physical nature of materials in the upper mantle beneath the Andes.

In Fig. 16, the geographycal relations between deep seismic zones **D1** and **D4** are shown on a map together with the distributions of intermediate earthquakes in each nest from **N1** to **N6**. Also the figure shows that non-active seismic area of intermediate events contains a special shallow seismic zone S inside. Fig. 17 gives the depth distribution of the foci along a profile around 22°S perpendicular to the coast. The data used for making this figure were collected in the period (b), from August 1965 to September 1968, which gives more reliable data as was described with regard to the nests N4 and **N5**. The dip of foci plane was measured around 28°. Foci of deep earthquakes with the depth of around 600 km located below the extension of the foci zone which are formed by the foci shallower than 300 km. The present profile corresponds to a part of the wide profile along which H. Benioff studied on the depth distribution of earthquake foci.[16] H. Benioff divided the dip of the foci plane into two parts, one for intermediate earthquakes and

15) B. L. ISACKS, L. R. SYKES and J. OLIVER, "Spacial and Temporal Clustering of Deep and Shallow Earthquakes in the Fiji-Kermadec Region," *Bull. Seism. Soc. Amer.*, **57** (1967), 935-958.

16) H. BENIOFF, "Orogenesis and Deep Crustal Structure—Additional Evidence from Seismology", *Bull. Geol. Soc. Amer.*, **65** (1954), 389-400.

another for deep ones, with different dips with each other. The foci plane in the present result, however, is preferable to be taken as forming a gentle curved trend in all with an interruption of foci between the depth range from 300 km to 500 km.

5. Seismic activity in South America

Seismically active area from 10°N down to 46°S were divided into many meshes of $1° \times 1°$, and frequency of earthquakes in each mesh was

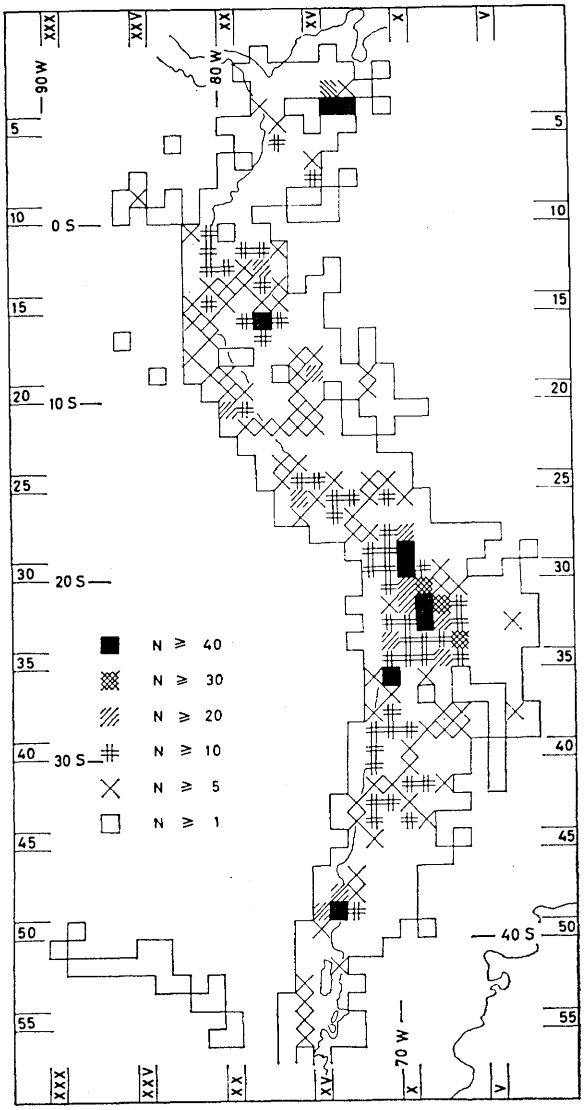


Fig. 18. Frequency distribution of earthquakes in $1° \times 1°$ meshes.

counted. The result is shematically presented in Fig. 18. Though it is not numerically shown in the figure, the mesh which had the largest number of events was 4-XIV due to the activity of intermediate earthquake nest N1, where the frequency of the events was as large as 116. There are several other meshes which showed a large number (N≧40) of frequencies due to the aftershocks. One of them is mesh 16-XVIII in which 45 out of 70 are the aftershocks of the main event (m=6.4) on June 19, 1968. Another mesh of this kind is mesh 36-XI which has the frequency of 40, 22 of which are aftershocks of a large (m=6.9, M=7.5~7.8 for Berkeley, and $7^3/_4$ for Pasadena) earthquake on December 28, 1966.[17] The frequency 40 in mesh 49-XIV also contains around 20 aftershocks of a great Chilean earthquake on May 22, 1960 which seems to retain its activity of aftershocks more or less until about June 1962. Almost all the earthquakes in mesh 21-XX were also aftershocks associated with the great earthquake of October 17, 1966 (M=7.5)[18].

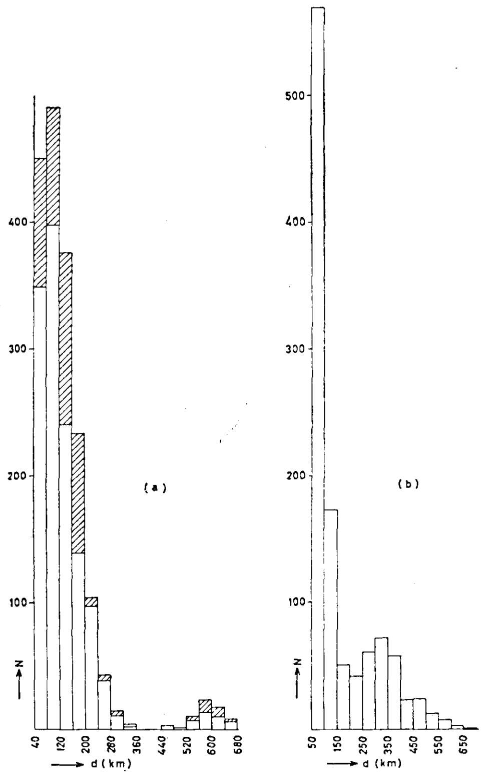


Fig. 19. Frequency distribution of mantle earthquakes (a) in South America and (b) in and near Japan (after A. Sugimura). Frequency columns in (a) are divided into nothern (10°N−10°S, hatched portion) and southern (10°S−46°S) regions.

17) *ibid.*, 11), 12) and 13).

18) C. LOMNITZ and R. CABRE, S. J., "The Peru Earthquake of October 17, 1966," *Bull. Seism. Soc. Amer.*, **58** (1968), 645-661.

Excluding these areas in which large frequency of events is clearly derived by the activity of aftershocks, the most active areas are distributed between 18°S and 23°S[19], where the seismic zone also extends widely inland. It must be noticed that large frequency of events in dense meshes in the region above-mentioned is due to the activity of intermediate earthquakes with the depths from 70 km down to 200 km or somewhat deeper. As is illustrated in Fig. 19-(a), the activity of upper mantle earthquake is quite predominant, which is one of the important fact in the seismicity of South America. In figure 19-(b), frequency distribution of mantle earthquake in and near Japan Islands[20] is presented for comparison.

Fig. 18, on the other hand, shows that the seismic zone along the oceanic ridge abruptly disappears near the coast around 45°S.

The pattern in Fig. 20 reflects the distributions of total energy which has been released from each mesh during the same period as in Fig. 18. In this figure, total energy E that has been released in each mesh is represented by the magnitude M' of an "equivalent earthquake", the monthly constant occurrence of which may release the total energy E in 98 months from August 1960 to September 1968. That is, M' in each mesh was found by:

$$E=98\times E'(M') ,$$

where E' is the energy released by an "equivalent earthquake" with the magnitude M'. In this calculation U.S.C.G.S. magnitude m in P.D.E. was tentatively changed into the magnitude M determined by surface waves using the formula $m=2.5+0.63M$[21], and E was found by $\log E=11.8+1.5M$[22].

P.D.E. before June 1963 lacks the m values for small earthquakes. It was found, however, that this lacking practically had no effect on the pattern of M' in Fig. 20.

By comparing Fig. 20 with Fig. 18, at least the following facts may be recognized.

i) The amount of energy released by deep earthquakes of around and/or deeper than 600 km is quite large although the frequency in low.

ii) The amount of energy released by shallow earthquakes in Colum-

19) E. Cajardo and C. Lomnitz, "Seismic Provinces of Chile", *Proc. World Conf. Earthq. Engin., 2nd Conf.*", **3** (1960), 1529-1540.

20) *ibid.*, 10)

21) C. F. Richter, *Elementary Seismology*, (W. H. Freeman and Company, London 1958), p. 348.

22) B. Gutenberg and C. F. Richter, "Magnitude and Energy of Earthquakes", *Ann. di Geof.*, **9** (1956), 1-15.

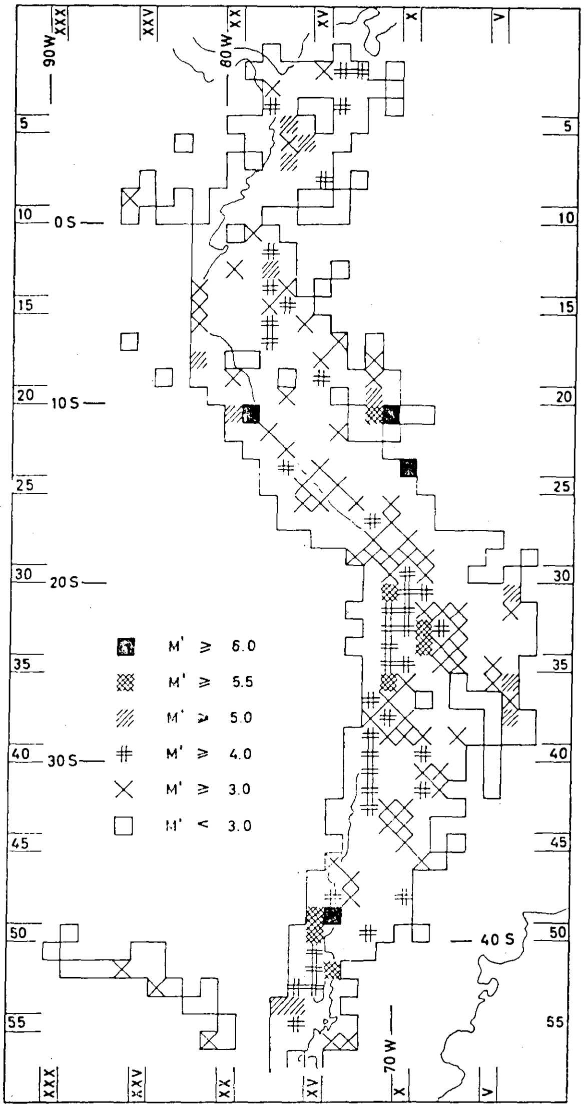


Fig. 20. Distribution of the magnitude M′ of "equivalent earthquakes".

bia (3°N–5°N) and in southern part of Chile (40°S–46°S) are also relatively large although their frequency are low.

iii) The most active area both in frequency and in released energy is located between 20°S and 26°S around the junction of three boundary lines between Bolivia, Argentine and Chile.

Item i) above given is more emphasized by Fig. 21 in which frequency (left) and released energy (right) distributions versus depth are presented by percentages. Energy released by deep earthquakes, especially by

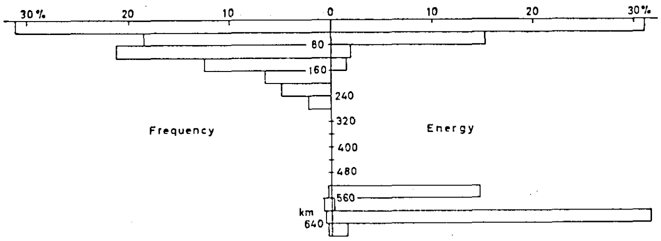


Fig. 21. Relative distributions of frequency (left) and energy (right) versus depth.

those with the depths of 600 km – 640 km, is so large as is equivalent to the energy released by crustal earthquakes ($d \leqq 40$ km). In the crust, 6.819×10^{23} ergs have been released by 872 events, while 6.972×10^{23} ergs were released by only 17 events in the deep place. Average energy of crustal events, therefore, is 7.84×10^{20} ergs (corresponds to the energy released by an event with $M = 6.05$), while that of deep events is 4.11×10^{22} ergs (corresponds to the energy released by an event with $M = 7.2$).

There are some other regions which are characterized by releasing a large amount of energy due to the deep earthquakes[23], for instance, New Britain-Solomon Islands, Philippine Islands and Tonga-Kermadec Islands. Deep earthquakes in South America, however, have the most predominant feature in this respect. Very few small events in these depths may mainly be caused for lack of swarms and aftershocks associated with the great earthquakes[24]. It might be said anyhow that the materials in such a deep region in South America have in general such property as to store a lot of strain energy without releasing a part of it intermittently.

Table 6 presents the data of great ($M \geqq 7.0$) deep ($d \geqq 550$ km) earthquakes which are collected from the table arranged by S. J. Duda[25]. The symbols of deep earthquake zones which were denoted previously are also given, in the last column "Rem.". It can be noticed that the activity of large deep earthquakes in South America had been quite predominant together with those in Tonga-Kermadec region throughout a long period before 1960 (see also Table 7). Especially, the active line **D1** in Bolivia-Argentine area looks like to have become more active recently. This fact may result in the predominant energy distribution

23) M. MIZOUE, "Variation of Earthquake Energy Release with Depth. Part I", *Bull. Earthq. Res. Inst.*, **45** (1967), 679-709.

24) S. SUYEHIRO, "A Search for Small, Deep Earthquake Using Quadripartite Stations in the Andes", *Bull. Seism. Soc. Amer.*, **57** (1967), 447-461.

25) S. J. DUDA, "Secular Seismic Energy Release in the Circum-Pacific Belt", *Tectonophysics*, **2** (1965), 409-452.

Table 6. Large ($M \geqq 7.0$), deep (around 600 km) earthquakes in the world (1901–1964).

Year	Date	Epicenter λ	Epicenter φ	Depth (km.)	M	Region	N	Rem.
1907	May 25	51.5N	147.0E	600	7.9	Okhotsk Sea	41	
1909	Feb. 22	18 S	179.0W	550	7.9	Fiji Is.	12	
1910	Aug. 21	19 S	179.0W	600	7.25	Fiji Is.	12	
	Dec. 14	21.0S	198.0W	600	7.0	Fiji Is.	12	
1911	Apr. 28	0.0	71.0W	600	7.1	Colombia	8	(D1)
1912	Dec. 7	29.0S	62.5W	620	7.5	Argentine	8	D2
1914	Aug. 6	6.0S	123.0E	600	7.0	Indonesia	24	
1915	Feb. 25	20.0S	180.0	600	7.15	Fiji Is.	12	
	Apr. 23	8.0S	68.0W	650	7.25	Brazil	8	D1
1916	June 21	28.5S	63.0W	600	7.5	Argentine	8	D2
	July 8	18.0S	180.0	600	7.0	Fiji Is.	12	
1918	Apr. 10	43.5N	130.5E	590	7.2	Sea of Japan	41	
1921	Dec. 18	2.5S	71.0W	650	7.9	Colombia	8	(D1)
1922	Jan. 17	2.5S	71.0W	650	7.6	Colombia	8	(D1)
1924	May 4	21.0S	178.0W	560	7.3	Fiji Is.	12	
1932	May 26	25.5S	179.3W	600	7.9	Fiji Is.	12	
	Sept. 6	21.5S	179.8W	600	7.1	Fiji Is.	12	
1937	Aug. 11	6.3S	116.5E	610	7.2	Indonesia	24	
1939	July 20	22.0S	179.5W	650	7.0	Fiji Is.	12	
1940	July 10	44.0N	131.0E	580	7.3	Sea of Japan	41	
1944	May 25	21.5S	179.5E	640	7.2	Fiji Is.	12	
1945	Nov. 26	21.0S	180.0	600	7.0	Fiji Is.	12	
1946	Jan. 11	44.0N	129.5E	580	7.2	Northern Korea	41	
	Aug. 28	26.0S	63.0W	580	7.2	Argentine	8	D2
	Sept. 26	25.0S	179.0E	600	7.0	Fiji Is.	12	
1947	Jan. 29	26.0S	63.0W	580	7.25	Argentine	8	D2
1948	Jan. 4	20.8S	179.0W	600	7.0	Fiji Is.	12	
	27	20.5S	178.0W	650	7.2	Fiji Is.	12	
1950	July 9	8.0S	70.8W	650	7.0	Brazil	8	D1
		8.0S	70.8W	600	7.0	Brazil	8*	D1
	Aug. 14	27.3S	62.5W	630	7.25	Argentine	8	D2
1954	Feb. 20	6.8S	124.5E	580	7.0	Indonesia	24	
	Mar. 29	39.0N	3.6W	640	7.1			
1955	May 30	24.0N	142.8E	580	7.3	Volcanic Is.	18	
1957	Jan. 3	44.0N	130.0E	600	7.0	Sea of Japan	41	
	Apr. 16	4.5S	107.5E	600	7.5	Indonesia	24	
	Sept. 28	20.5S	178.0W	600	7.5	Fiji Is.	12	
	July 26	13.5S	69.0W	620	7.5	Peru	8	D1
1961	Aug. 19	10.8S	71.0W	649	7.0	Peru	8	D1
	Aug. 31	10.7S	70.9W	626	7.2	Peru	8	D1
		10.5S	70.7W	629	7.5	Peru	8**	D1
1962	Mar. 7	19.2N	145.1E	685	7.0	Mariana Ridge	18	
1963	Aug. 15	13.8S	69.3W	543	7.75	Peru	8	D1
	Nov. 9	9.0S	71.5W	600	7.0	Brazil	8	D1
	Dec. 15	4.8S	108.0W	650	7.1	Indonesia	24	

N: Region number after B. Gutenberg and C. Richter.
*: occurred 10m 01s after the previous one.
**: occurred 08m 30s after the previous one.
D1 and D2 are the symbols of the active zones corresponding to those in Table 4.
(D1): Earthquakes in a part of zone D1 which is not active recently.

due to deep earthquakes in Fig. 20.

Table 6 presents three great earthquakes in Colombia. One of them occurred in 1911 and the rest occurred at one and the same spot between

Table 7. Seismicity of great ($M \geqq 7.0$), deep ($d \geqq 550$ km) earthquakes of the world (1901–1964).

Region	Frequency	Energy ($\times 10^{24}$ erg.)
South America	17	1.656
Tonga-Kermadec-Fijí	15	1.459
Sea of Japan	5	0.693
Indonesia	5	0.220
Mariana Ridge	2	0.076

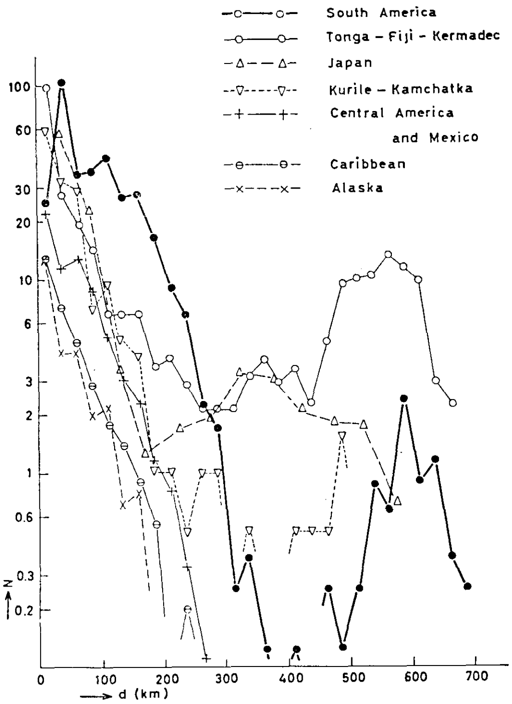


Fig. 22. Annual frequencies N of earthquakes versus depth d for several island-arc system. Data excepting those for South America (filled circles) were collected from the figures compliled by B. Isacks et al.

1921 and 1922, the interoccurrence interval of which was about one month. These epicenters also are located on the northward extension of the seismic line **D1** (see Fig. 16.). The activity in this part, however, seems to have come to the end recently. No deep earthquake, even a small one, was reported in these regions in P.D.E. during the period which are presently dealing with. Together with another great recent event in August 15, 1963, it can be said that the seismic zone **D1** has two separate ends having special capability of storing a large amount

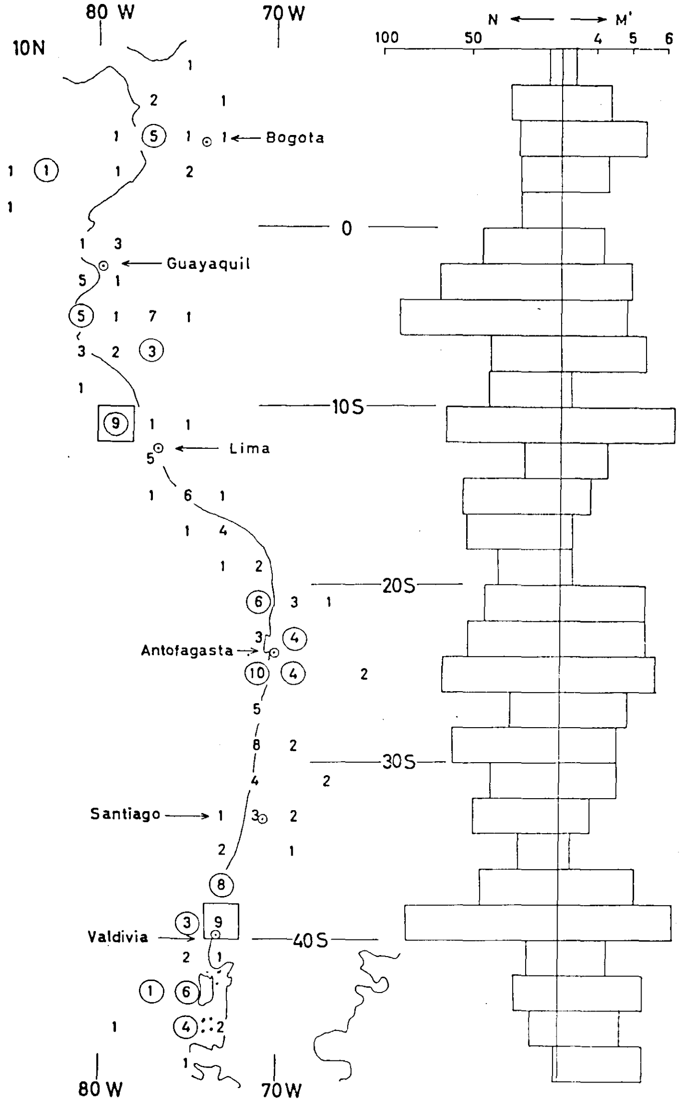


Fig. 23. Map: Frequency distribution of shallow earthquakes (d≦70 km, m≧5.0) in the meshes of 2°×2°. One circle and rectangle indicates the meshes where one of dangerous events of m ≧ 6.5 and of m≧7.0 occurred respectively between August 1960 and September 1968. Figure: Total frequency (N) and energy (M') distributions of shallow earthquakes along the latitude. M' in the energy scale means the magnitude of the "equivallent earthquake" monthly occurrence of which releases the energy equal to the total energy.

of strain energy without releasing any part of it intermittently.

Table 6 also gives two group of double events which are closely related with each other in time and space in the southern part of **D1** zone (see remarks below the Table).

Remarkably low seismic activity in the depth range of 320km – 520km, on the other hand, is another noticeable characteristic of the seismicity of South America. Really, in this depth range, only four small events took place in 320 km – 360 km and five in 480 km – 520 km. (See also Fig. 19).

B. Isacks and others[26] compiled the frequencies of earthquakes versus depth for several island arcs; in this compilation the data for South America were lacking. Now we can add our data to their figure, which are shown by filled circles in Fig. 22. Comparing these several curves with one another it is again made clear that the frequency distribution against depth for South America is characterized by the high seismic activity of intermediate earthquakes and by the remarkable low activity in the depths between 300 km – 500 km, both of which were mentioned previously.

From the view-point of earthquake engineering, seismic activity of conspicuous events shallower than 70 km may be a special matter to be cleared. Fig. 23 was illustrated for this purpose. From this figure, the followings may be recognized.

i) Although the frequency is low, large earthquakes occurred in the northernmost (4°N – 8°N) and southermost (42°S – 48°S) parts of the continent.

ii) Energy distribution shows minimums around 1°N, between 12°S and 20°S and between 32°S and 36°S.

iii) Southern area of Guayaquil (Ecuador), northern part of Lima (Peru), around Antofagasta (Chile) and northern part of Valdivia (Chile) have been active shallow seismic areas both in their frequency and energy released.

The data of shallow and large earthquakes in South America, being listed in Table 4, tells another fact that there was a calm period for about three years from November 1963 to January 1967.

6. Conclusion

Characteristics of seismicity in South America are possessed mainly by intermediate and deep earthquakes. They may be summarized as follows:

a) Seismic activity of shallow earthquakes running down along the coast and activity of those associating with oceanic ridge are mutually interrupted off the coast of around 46°S (Figs. 1-(a) and 18).

26) B. Isacks, J. Oliver and L. R. Sykes, "Seismology and the New Global Techtonics," *J. Geophys. Res.*, **73** (1968), 5855-5899.

b) There is a wedge shaped non-seismic area of intermediate earthquakes between 25°S and 28°S. Interesting facts are that this area contains a shallow earthquake zone running along a curve, which enter deeply into the land until it meets with a deep seismic zone, and moreover, this meeting makes the depths of deep earthquakes along the latter zone remarkable shallower (Figs. 12 and 13(b)).

c) Seismic activity of upper mantle earthquakes shallower than 200 km is quite predominant in frequency (Figs. 19 and 22). They have six "nests" at least (Fig. 16). Density of the foci is especially high in the northernmost nest **N1**, in which around 80 events have taken place in such a limited volume as 10 km × 10 km × 10 km (Fig. 2). This nest looks like dispersing into NW-SE direction with the length of about 100 km and with the inclination of around 39°.

d) Upper mantle earthquakes (100 km – 200 km) are fairly often (about three in one hundred) followed by a few events which are closely related to each other both in space and time (Table 3).

e) Two neighboring nests **N4** and **N5**, locating around a junction of three border lines of Chile, Argentine and Bolivia, lie on a certain dip inclined landward. The activities of these two nests have more or less reversal correlation (Figs. 6(b) and 16).

f) Earthquakes deeper than 550 km originate along two seperate arcs with the length of approximately 1000 km in each (Fig. 16). They are especially characterized by releasing a large amount of energy in spite of their few occurrence. The energy released by the deep earthquakes of 600 km – 640 km, for instance, accounts for a little over 30% of the total energy, which is equivalent to the energy released by crustal earthquakes (Fig. 21).

g) Separate ends of the deep seismic zone **D1** have low seismicity in frequency but have capacities of storing large amounts of strain energy. In the southern part from 8°S to 11°S, on the other hand, **D1** has a tendency to produce some events which are closely related with each other both in space and time (Tables 5 and 6).

h) Most of the foci in the depth range of 300 km – 480 km distribute around curve **D3** which perpendicularly crosses another active zone **D2** with deep foci (580 km – 620 km) around 23°S, 63.5°W. Depths of foci in this crossing area are restrictly limited at the depths belonging neither to the zone **D2** nor to **D3** (Fig. 15).

i) Seismic activity in the depth range from 320 km down to 520 km is extremely low, and most of the earthquakes occurred in the period of only eight months in 1964. (Table 5 and Fig. 19).

Through the present work, capability of U.S.A. stations in detecting earthquakes was made clear. Their observations always took important part in the epicenter determination even of such small events as $m \fallingdotseq 4.0$ which took place in southern part of South America as far as over 9000 km (Fig. 10). The services of the stations in eastern part of South America, on the other hand, were found to be quite poor.

Acknowledgement

The present research work was performed as one of the activities of the Technical Cooperation Plan by the Government of Japan during the period of October 1, 1968 to March 31, 1969, with the research facilities offered by the Department of Geophysics and Geodesy, University of Chile.

The writer wishes to express his sincere thanks to Dr. E. Kausel for discussions and helps throughout the research work.

---

28. 南米大陸における地震活動の特徴

地震研究所
国際地震
地震工学研究所
三東哲夫

1960年8月から1968年9月までの8年2ヶ月間における南米大陸の地震活動を USCGS の資料で調べ，その特徴をさぐつた．

最も著しい特徴は，深さ 100 km～200 km のマントル上層部における地震活動が盛んなことで，この点は同じく島弧系の地震地帯といわれてはいても日本列島周辺のそれとは正に対照的であるし，他のどの島弧系にも見られないことである．この深さの地震はさらに，

1. 少なくとも6つの地震の巣をもつている．このうちで，Colombia 北部にある地震の巣 **N1** は，最も密度の高いもので，深さ 155 km を中心として 10 km^3 の小さな体積中で毎月1回平均の地震を起こしている．この巣を中心として，付近の震源は約 100 km の長さでほぼ NW-SE 方向に約 39° の傾斜で尾を引いている（第2図）．また，Chile, Argentine, Bolivia 三国の国境が相交わる周辺には2つの地震の巣 **N4**, **N5** が相隣り合つている．これらの巣の深さは，**N4** では 100 km から，150 km, **N5** では 150 km から 250 km の範囲を占め，震源は両者相つづいて NW-SE 方向に 21° 前後の傾斜をもつ面の周辺に分布している（第5，6図）．

2. 約3％の地震が，空間的，時間的に誘発性をもつている．（第3表），150 km 前後の深さで，こんなにも誘発性地震が起こつていることはたいへん注目される．

深さ 550 km 以上の深発地震の活動もまた次に述べるような注目すべき特徴をもつている．

1. 小さな地震に比べて大きな地震が圧倒的に起こり易く，そのためたとえば 600km～640km の深さの地震が放出したエネルギーは，すべての深さの地震全体によるそれの 30％ 以上にもなり，地殻内の地震によるエネルギーに匹敵している（第21図）．

2. 北部深発地震帯 **D1** 中の一部では，空間的・時間的に誘発性の地震が起こつている（第5表）．

同じ深発地震でも，深さ 320 km から 520 km の間の地震となると，数が急に減つて，調査期間の8年2ヶ月中にわずか9ヶしか起こつていないことも特筆される．このうちの大部分（7ヶ）の震源は，Argentine と Bolivia の国境線のやや南部を，ほぼ東西方向に，約 24° の傾斜面に沿つて分布し（第15図），しかも 1964 年の2月から10月までの9ヶ月間に限つてしか起こつていない（第5表）．

浅い地震に関しては，Andes にそう地震帯と，東太平洋海嶺から枝分れして 46°S あたりで西から大陸に近づく海嶺下で起こる海嶺性の浅発地震帯とが交わりそうなあたりから先で，両者の活動が急に消滅してしまう（第1図）のも興味をひかれる事実であるが，もつと面白いのは，26°S から 28°S にかけて，上部マントル地震が，くさび形に西に入りこんだ区域できれいになくなつているのだが，その真中を，細い浅発地震帯が大陸の奥深くまで円弧状に走つて，その先端が深発地震帯 **D2** に入りこむ（第12図），その場所で，**D2** に属する地震の深さがめだつて浅くなつている．それだけでなく，途中のやや深発地震の深さもまた，この浅発地震帯に吸いあげられているかのように，次第に浅くなる傾向を見せている（第13図）．これが何を意味するかに関して，このあたりでこんご綜合的な地学的調査の行われることが望まれる．