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MICROSEISMIC STUDY OF THE INTERANDINE VALLEY BETWEEN LATACUNGA AND CUAYLLABAMBA

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16. Abstract

The article describes a study which investigated the present state of two active volcanoes and the principal active seismic faults in a 100 km area from Quito to Toacaso, Ecuador. A brief seismic history of the region is reviewed.

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MICROSEISMIC STUDY OF THE INTERANDINE VALLEY BETWEEN LATACUNGA AND GUAYLLABAMBA[*]

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[*] Study carried out for the National Civil Defence Board.

I. Introduction

1.1. Preliminary remarks

At the time of the resumption of the Cotopaxi volcano at the end of 1975, scientists of the Geological Service of the United States (Miller et al., 1976) and of the Quito Polytechnic School (Hall, 1976) published two reports in which they recommended the installation of three portable seismographs for the monitoring of the volcano. /1*

The National Civil Defense Board therefore acquired three portable Sprengnether short-period seismographs to be used both in volcanological studies and tectonic studies, and which were used during the present study.

On the other hand, the Minitrack satellite tracking station operated by NASA and located in the immediate vicinity of the volcano, which would be threatened in case of an eruption, installed a monitoring station for the volcano in May 1977. This station consisted of a short-period seismograph and two inclinometers; the information obtained with this seisomgraph was also used for this study.

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*Numbers in the margin indicate pagination in the original foreign text.

1.2. Geographic and geologic characteristics of the region

Geographically this study includes part of the Interandine Valley in the provinces of Pichincha and Cotopaxi. Toward the north, this region extends to the vicinity of the city of Guayallabamba and in the south, close to the city of Latacunga. This portion of the Interandine Valley contains large areas of high population density, which makes it a dangerous region in case of the occurrence nearby of a possible seismic event of any magnitude.

In this region, the Interandine Valley is surrounded by volcanoes, some of them active like those of Cotopaxi and Guagua Pichincha. The latter furnished all the volcanic material filling the valley at present and consisting chiefly of thick sequences of the Gangahua Formation distributed widely all over the valley and covered in some cases by pyroclastic material from the adjacent volcanoes, lava streams which came down the valley, very extensive mudstreams like those originating in the 1877 Cotopaxi eruption, alluvial sediments and landslides, and lacustrian sediments like those north of the city of Quito.

/2 All these materials have a common characteristic which is that they are not well consolidated, which makes them dangerous in case of the occurrence of a seismic event as will be explained further on.

1.3. Seismic history of the region

This region has suffered from a long history of seismic activity: those mainly affected were the areas of Pastocalle, Toacazo, Tanicuchi, Aloasi, Mulalo, etc., along with the cities of Quito, Latacunga, Ambato. Some of them were totally destroyed, and even several times, as in the case of Latacunga and Pastocalle.

In December 1736 at the time of the Latacunga earthquake, serious damage occurred, including the destruction of the Toacazo Church.

In February 1923, a strong earthquake devastated the region, causing serious damage, especially at Machachi, Tambillo, Aloag, and Aloasi. There were several deaths.

One of the strongest earthquakes occurred on October 15, 1944, forcing the founders of Pastocalle to change the location of the town, since most of the buildings were totally destroyed.

Finally, in October 1976, violent tremors occurred in the region of Pastocalle and approximately one month later another violent shock occurred in the Machachi sector, whose consequences are well known.

The history of the seismic activity of the region may be found in greater detail in the map of the historic epicenters (Map No. 3).

1.4. Purpose

The general purpose of this study is to locate and study the principal active faults of the region with the object of warning the National Civil Defense Board about the areas which will most probably be affected by future seismic events. The object of this study is also to investigate and know the present state of the active volcanoes Pichincha Gaugua and Totopaxi, through the seismological network which was set up in the region.

II. Study and Map of the Tectonic Faults in the Area

The importance of the studies of microseismicity becomes much more significant if it is possible to determine which faults or systems of faults are active. Faults known to be active in the last hundred thousand years may affect the region in the future. To this end, a map of the principal faults was established to improve our knowledge of the faults (location, displacement, longitude, etc....) and to support the results of seismological research.

2.1. Methodology

The study of mapping of the faults were carried out on the basis of different sources of information.

The use of aerial photos proved to be the fastest and most useful method for this type of map. It has been tested throughout the world; it is the most acceptable method of studying the tectonics of an area. Fortunately, the study area is totally covered by aerial photographs on an approximate scale of 1 : 60,000. The photos were studied by means of a pocket stereoscope and the tectonic features were plotted on the topographic maps of scale 1 : 50,000. The latter, with Xerox reduction, gave the final map on the scale 1 : 100,000 (original).

Many morphological features are useful for identifying the faults on the aerial photos. We list below the most important characteristics for identification used in this study.

1. Straight features (generally defined by the drainage).
2. Slopes which cut and end in a triangle.
3. Large valleys which are straight.
4. A long series of depressions.
5. Large rectangular blocks which were raised or collapsed (horst and graben structures).

6. Areas of landslides.
7. Lines of small volcanoes and cones.

The area of interest for the study was the Interandine Valley from Latacunga to Guayllabamba, which is totally covered by cangahua: a thick sequence of volcanic calcareous tufas. This deposit of cangahua had the favorable effect of softening the topography of the valley. This became very useful for recognizing the faults, since it is very easy to identify irregularities in the topography due to dislocation. It should also be noted that the faults cutting the cangahua must be young and will probably move again. Although these faults are recognizable in the areial photos, their identification in the field is very difficult. Generally, the cangahua, fracturated by faulting, crumbles, hiding the trace of the fault and making it difficult to recognize on the terrain.

Other regions, expecially the western side of the Western Cordillera, raise many problems with respect to recognition of the faults. The topography which is steep and the dense vegetation are two aspects concealing the tectonic features. It was therefore impossible to locate the faults of this flank, although there is no doubt of their existence.

Certain information about the regional faults was also found in the studies by Torres (1975), in certain maps published by the General Board of Geology and Mines, and the Geological Mission of Great Britain.

2.2. Fault systems found

The tectonic map presented (Map No. 1) shows most of the faults and main features of the Interandine Valley from Latacunga to Guayllabamba, including Quito. It is the first map of this nature established in the country. All the faults are tectonic; none of them are of purely volcanic origin. All appear to be young, since they are cut and displace the cangahua. They should therefore be considered as potentially active faults. The faults are grouped into three main systems: the system of the Interandine Valley, the northeast system, and the northwest system.

2.2.1. System of the Interandine Valley

This first so-called system consists of faults which have north-south directions, especially near Latacunga, and north-northeast directions in the valley of Los Chillos and Guayllabamba. They are generally restricted to the flanks of the valley and the displacement seems to be mainly vertical (normal faults). The valleys are depressed with respect to the adjacent chain of mountains and are called graben; the valleys of Los Chillos and Guayllabamba are examples of this structure.

To the east of Latacunga is a series of faults with north-south direction, probably continuing northward up to Machachi; unfortunately, they are covered and concealed by recent volcanic materials
from the Cotopaxi volcano. The western border of the same valley is /5
also distinguished by faults; the best known one passes through Pujili. Two large faults, known here as Saquisili faults, run parallel to each other from Salcedo to Saquisili and then turn northeast. In this range, several active faults of the northeast system combine with the Saquisili faults. The latter also modified the morphology of the valley to a considerable extent, forming great slopes and deflecting many drainages. It seems that they have been active for a long time.

The Machachi valley is also bordered by faults of this system. It is noted that these faults are curved, probably affected by the volcanic structures. The most notable aspect of this valley is the convergence of the large active faults; the Saquisili faults converge with those of the northeast system coming from the Iliniza mountain. In November 1976, a violent tremor caused much damage in the region around Machachi, which show there is no doubt that greater seismic activity may be expected in that sector.

From Tambillo to San Antonio de Pichincha, the tectonic structure is complicated. Starting from Tampillo and Amaguana, a series of parallel faults continue up to the north, forming the long triangle of Puengasi, that of Las Monjas, and also the valley of the Machangara River. Many indications of landslides may be found in this area, probably induced by tremors along these faults. Although some faults of this series pass through the southern suburbs of Quito, it seems that the more active faults pass through the eastern side of the Puengasi triangle, specifically from Amaguana to Conocoto and Cumbaya; among them, the best known include the Ilumbisi and Machangara faults. It is certain some faults of this series pass through Quito; nevertheless, the density of the constructions makes it difficult to identify them.

Another prominent fault: the Pichincha fault separates the city from the Pichincha volcano and seems to continue to the north, cutting through the extinct volcanoes of Calacali and Pululagua. One branch of this series — the Ilumbisi fault — extends to the north passing a little to the east of Nayon and Zambiza and then continuing through the structural valley of Pomasqui and San Antonio de Pichincha. The town of Calderon is located on a plateau bordered by these faults and by those of the valley of Guayllabamba, of which the most outstanding is called the Calderon fault. From Cumbaya, the principal branch passes in a north-northeast direction to Guayllabamba and Cayambe. The latter, called the Guayllabamba fault, was active during the past months.

The eastern border of the valleys of Los Chillos and Guayllabamba is also bordered by many faults in a north-south direction, running from the Sincholagua mountain to the town of El Quinche. /6
The map shows only the best known of these faults. Some of them cut the lava stream of Antisanilla, near Pintag, proving that there was seismic activity of considerable magnitude after 1760.

Although superficial signs of faulting were not detected in the aerial photos in the central portion of the valley of Los Chillos, faults certainly exist. An earthquake with epicenter close to

Alangasi occurred in August 1938, producing much damage. Furthermore, two tremors were recorded in May 1978, a little south of Sangolqui. The extension toward the north of these faults is probably connected with those of the Guayllabamba River. The fact that tremors were registered both in the faults of the Guayllabamba River and in those of Los Chillos indicates that this series of central faults are also active.

2.2.2. Northeast system

The discovery of the northeast system of active faults is one of the most interesting aspects and one whose existence was not suspected until now. This system comes from the area of Quilotoa and enters the Interandine Valley between the Iliniza mountain and the town of Saquilisi. A series of important faults called the Iliniza faults continues to the northeast, passing through the southeast flank of the Corazon ridge and joining with the Saquisili faults near Aloag. Although it is impossible to see directly the intersection of these faults because of the agricultural cultivation, the extension of the faults and their subsequent intersection cannot be doubted. A second series of faults, called the Toacazo faults, parallel to the previous ones pass directly below the town of Toacazo, joining with the Saquisili faults and then passing a little to the northeast of Pastocalle. This was probably the fault causing the strong tremor which affected Pastocalle and its suburbs in October 1976. Other faults in the northeast direction join with the Saquisili faults, directly to the east of the same town.

Once they have joined together, these faults follow the Machachi Valley, passing close to Tambillo and Amaguana, and continue thereafter along the western border of the Los Chillos Valley, approaching the faults of the Interandine Valley. From there they continue northward, some of them separating subsequently to the northeast. One is deflected at Conocoto and passes northwest of the Ilalo ridge. The others turn a little north of Cumbaya, follow the San Pedro River, and at the end pass through the Guayllabamba region. From /7
the latter onward, they probably extend to Cayambe and Olmedo.

Many recently recorded tremors belong to this northeast system. Many epicenters are located in the Iliniza fault near the mountain itself, others near Cumbaya, and still others in the region of Guayllabamba. The conclusion should therefore be drawn that this system is very active at present.

It seems that, on the whole, this system has a length of at least ninety kilometers within the studied area. It is probable that this system is much larger and passes through a great portion of the country. The faults of this system present certain indications giving rise to the assumption that they are directional faults.

2.2.3. Northwest system

Although it is not as important as the previous systems, the northwest system is more recognizable on the western flank of the Cordillera Ral, in front of the Los Chillos Valley and also the valley of Guayllabamba between Tumbaco and Guayllabamba.

These faults have typically a north-northeastern direction and cut through the cangahua, from which it is deduced that they are young. The direction of movement of these faults is unknown.

2.3. Summary

A map was established of the principal faults of the Interandine Valley between Guayllabamba and Latacunga, including Quito, through the study of aerial photographs. This tectonic map is the first of its kind to be established in the country. Three main systems of faults are identified: the faults of the Interandine Valley with approximate north-south directions, which are young and probably active; those of the northeast direction, passing through the Interandine Valley from the Iliniza peak to Cayambe. This last system of faults had not been previously discovered nor studied. The third system which is characterized by lines of northwest direction is found chiefly in the valley of Guayllabamba; it seems that it is not as active as the other two systems.

Thus, the three systems pass almost completely through the Interandine Valley, in such a manner that there exists almost no sector or area which is far from a potentially active fault.

III. The Microseismic Activity

Three portable Sprengnether short period (1 Hz) seismographs /8 were installed within the area of study, forming a seismological network for the purpose of determining the seismicity in the region concerned. Information was also available from the seismograph installed by NASA on the slopes of the Cotopaxi volcano.

The purpose of the compilation and interpretation of the seismic data is to determine the main areas which are systematically active and which will probably be affected by future events. The precise location of the epicenters of the events detected is also of vital importance in the determination of the tectonic fualts which are active at present.

3.1. Methodology

Obtaining and interpreting seismic data requires a series of stages and processes which are interconnected and which take place in the following sequence.

3.1.1. Installation and maintenance of the instruments

At the beginning of October 1977, the instruments were delivered and we proceeded immediately to check and test them before installing them in the field.

After laying out a tentative seismological network, the first weeks of October 1977 were devoted to seeking the appropriate sites for the installation of the instruments. Finally, the stations of the network were laid out as may be seen in Figure 1. We considered this layout as the most suitable for carrying out the microseismic studies and for monitoring the active volcanoes Guagua Pichincha and Cotopaxi.

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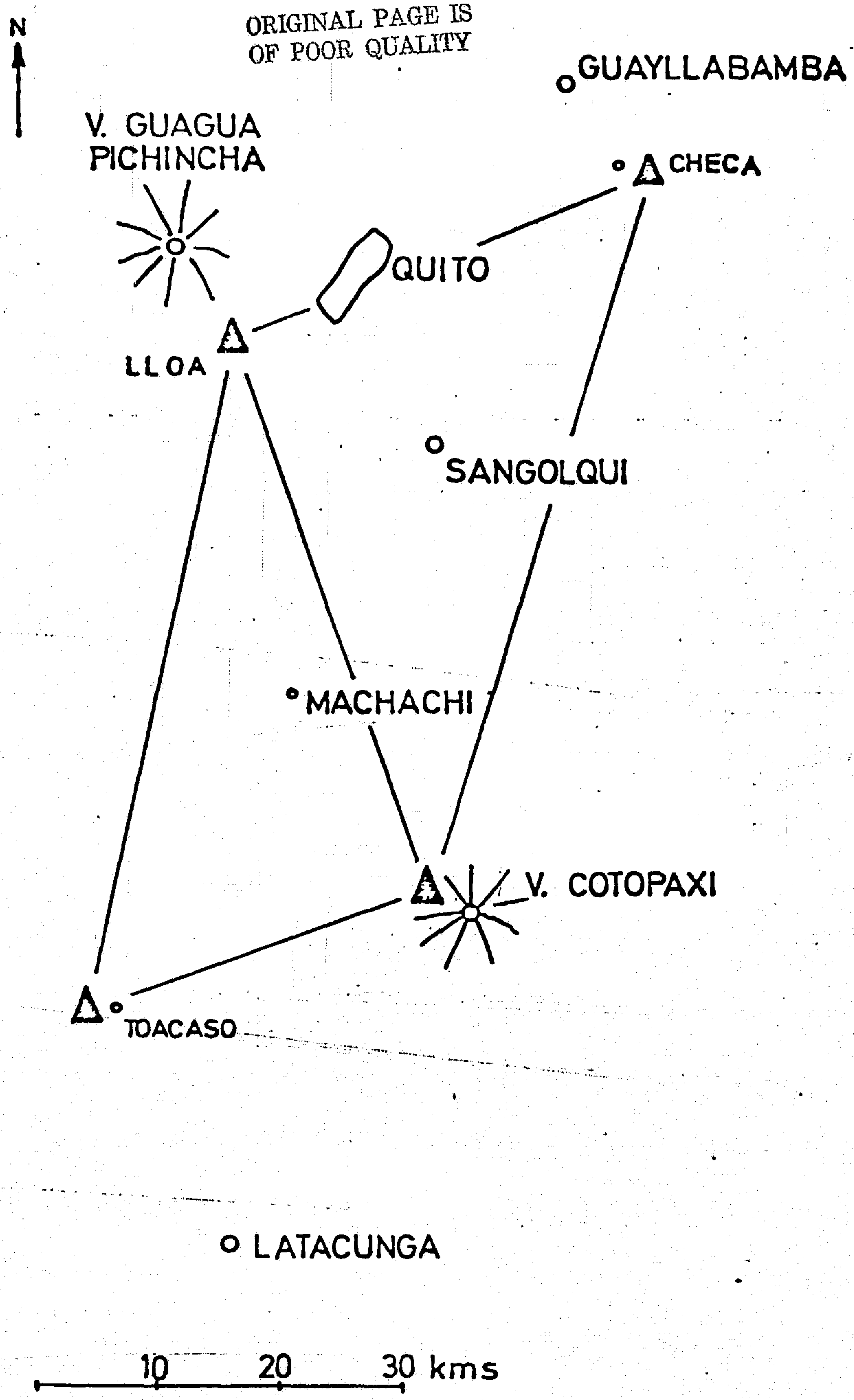

Figure 1

The first instrument (#494) was installed at the Rasuyacu station near the town of Toacazo (Cotopaxi Province) on Nobember 20, 1977, and until the day it completed its operation with a total of 3228 working hours there were no serious drawbacks.

One week later, on November 27, the second instrument (#495) was installed at the Cuscungo Camp of the Empresa de Agua Potable near the town of Lloa, west of Quito. This instrument operated altogether for 3655 hours. /9

On December 18, 1977, the third instrument (#493) was installed at the San Augustin station near the town of Checa. It had completed altogether 1692 hours of operation by the time it was removed on April 1, 1978, and it was re-installed in the San Jose district of the town of Yaruqui on April 12, 1978, where it operated for 840 hours, thus giving a total of 2532 hours.

Figure 2* shows a summary of the operating schedule of all the instruments and the number of seismograms obtained during the period of operation of the instruments.

Once a week an inspection was carried out of the sites of the instruments, with servicing of the latter. This included: overall checking of the instrument, adjustment and calibration, checking and correction of the clock and preparation of the instrument to be operated by the respective agent during the following week.

Finally, all the instruments stopped operating and were removed from their sites on May 27, 1978, after having worked excellently and without problems during the entire period of operation.

3.1.2. Interpretation of the seismograms

The seismograms obtained weekly were classified and numbered, they were all read, and each seismic event was measured and included in a long list containing all the events registered.

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*Translator's note. Figure 2 does not appear in the foreign text.

These events are 904 in number altogether, of which at least 413 (45%) occurred within the studied area. The other events correspond to teleseisms or remote tremors of regional nature, in all cases outside the studied region.

The reading of the seismograms was carried out by us with a group of three persons by means of several reading instruments, such as a binocular microscope, several magnifying glasses and measurement gauges.

3.1.3. Data processing

To locate the epicenters more precisely and in view of the large amount of data obtained, the authors decided to use for the first time in this country a computer program to calculate the various seismic parameters of each event. The program used was called HYPOELLIPSE (Lahr, Ward, 1973). This program had to be adapted to the local conditions for its application, i.e., to condition the program to the type of computer used, the number of seismic stations constituting the network, and the type of information assigned to the program and the results expected from it. The authors established a model of the seismic velocities of the Earth's crust for the region studied, and also calculated the seismic corrections for each station. This model of seismic velocities of the crust used in the present study is based on a summary of the model presented in the Narino Project (Ocola et al., 1977), data from the theses by Robaline (1975) and Torres (1975), and in various models set up and tested previously by the authors. /10

We give below a synthesis of the model used in this study.

Synthesis of the Model of the Earth's Crust for the Studied Area

Stratum	Velocity (km/sec)	Depth (km)	Density
1	2.60	0.00	0.50
2	5.50	0.50	5.70
3	6.13	6.20	23.00
4	7.54	29.20	79.00
5	8.10	108.20	1000.00

From the long list of events registered, we proceeded to select the tremors which would be processed considering several aspects in this connection. These are — for each seismic event — as follows:

a) its recording by at least 3 of the 4 stations, which means that probably only tremors of magnitude more than 2 were processed;
b) the probability of being located inside the studied area;
c) clearness in the reading of the occurrence of the different phases;
d) presenting a constant seismic velocity ratio Vp/Vs.

All these conditions reduce drastically the number of tremors to be processed; thus only 11% of the tremors registered inside the area were processed. Figure 3 represents a list of all the events processed by computer.

3.2. Maps of epicenters /11

Starting from the data obtained and other sources, we proceeded to the establishment of the different epicenter maps. A more detailed description will be made of each of them.

Date	Time	Latitude	Longitude	Depth
January				
10	1015	00 14.42	78 53.09	6.3
10	1016	00 14.07	78 56.02	6.3
17	1008	00 13.95	78 20.73	18.0
25	0142	00 41.77	78 48.32	8.4
25	0021	00 46.24	79 14.03	105.0
26	0203	00 08.97	78 24.42	48.0
February				
02	0721	00 36.44	78 52.29	1.6
04	0335	00 41.77	78 46.35	9.2
07	1601	00 21.92	78 57.46	11.0
15	0236	00 09.00	78 32.56	0.4
15	0920	00 44.94	78 45.30	3.1*
21	0702	00 29.43	78 39.46	6.6*
25	0515	00 01.47	79 19.72	5.0*
28	0840	00 20.21	78 42.15	0.6
March				
09	0542	00 19.06	78 39.92	12.0
09	1042	00 03.08	78 24.46	5.3*
17	0900	00 43.48	78 44.63	4.6*
17	0905	00 44.14	78 48.33	10.0
17	1841	00 42.17	78 44.46	4.6
22	0531	00 12.76	78 06.08	2.3
27	1251	00 12.05	78 13.59	4.4
28	1750	00 25.83	78 35.44	26.5
29	0748	00 29.20	78 30.01	35.0
29	1810	00 46.04	78 51.96	1.0*
30	1936	00 27.50	78 41.50	8.3
April				
05	2227	00 48.58	78 42.76	5.9
07	1549	00 42.13	78 44.90	7.8
17	0533	00 50.35	78 57.00	6.0*
19	0746	00 41.52	78 55.42	9.4

Figure 3. (continued on following page)

Date	Time	Latitude	Longitude	Depth
May				
01	0917	00N10.08	79 07.34	4.2*
08	0930	00 41.82	78 43.77	1.7
11	0213	00 44.66	78 48.28	6.4
11	1424	00 13.26	78 27.56	3.3.
11	1429	00 10.99	78 27.45	10.0
13	0132	00 20.87	78 27.58	13,0
15	1651	00 13.92	78 11.95	5.8
18	0423	00 07.60	78 22.87	0.9*
18	0454	00 05.18	78 22.14	3.6
19	0141	00N00.23	78 34.16	24.0
26	0325	00 22.08	78 25.85	32.0
26	0421	00 44.52	78 43.96	11.0
26	0427	00 43.61	78 46.28	16.0
26	0453	00 41.56	78 43.06	7.6*
26	0459	00 42.47	78 41.51	6.5*

Figure 3. (continued). List of computer-processed events
*Approximate depth.
Latitude: south (if not specified)
Longitude: west

3.2.1. Tectonic map of the Interandine Valley
(Map No. 1)

The epicenters calculated by computer and occurring within the region covered by the tectonic map concerned were plotted in it. It contains, furthermore, some past epicenters which were located precisely and are important for this study.

The purpose of plotting the epicenters on this map of faults is to obtain a direct correlation between the detected tremors and the active faults inducing them. More generally, we may define the active seismic regions, which are described in the next section (section 3.3).

3.2.2. Map of regional epicenters (Map No. 2)

This map, based on the Geographic Map of Ecuador, scale 1 : 500,000 (1957), presents the events listed in Figure 3. That is, all the recorded and processed events occurring both inside and outside the Interandine Valley.

On the basis of the concentration of the epicenters on this map, the seismic areas active at present were defined. These active seismic areas are described in section 3.3.

3.2.3. Map of historic epicenters (Map No. 3)

This map is also based on the Map of Ecuador of scale 1 : 500,000. It contains the information on the epicenters located since 1587 to the present of magnitude more than 4, corresponding to the region between Quito and Ambato.

It is noted in it that regions now seismically active were also active in the past. The best known are the large number of epicenters close to the town of Toacazo; this area is also active at present and some catastrophic earthquakes have accurred in it (1736, 1944, 1976). Considerable activity was also noted in the past in the vicinity of the cities of Ambato and Latacunga. Parallel to the upper course of the Toachi River and following its extension to the /12 north, we noted the presence of several past epicenters coinciding with an area which is also active at present and which defines a system of faults: or north-south direction which probably produced these epicenters (see section 3.3.2).

Apart from these important characteristics, other past epicenters are also found in the Interandine Valley which were certainly produced by the system of faults passing through this valley and which was active in the past.

3.2.4. Frequency diagrams

Frequency diagrams (Figure 4) were established from the long list containing all the events recorded in the seismic network. They were plotted by comparing the number of tremors (frequency) with the difference in the arrivals of S and P waves for each (S-P) event, from which we obtain the distances between the epicenter and the seismological station. These diagrams were established for each month. As has previously been mentioned, of the total number of events recorded in the area, only 11% were processed. This does not mean that the rest of the information was rejected. On the contrary, it was used to establish the seismic and volcanic frequency diagrams. These diagrams give more information that that given by the computer, and confirm it in many cases.

The best known of these diagrams is the greatest frequency of seismic occurrence in the neighborhood of the Rasuyacu station. This confirms the fact that the Toacazo area is the most active region found by us. This is also indicated in the diagrams corresponding to the Cotopaxi station, where a seismic activity is registered at a distance of 30 km; this probably corresponds to the Toacazo region.

The activity in the Toachi area is also confirmed in the frequency diagrams. At a distance of 30 - 40 km from the Lloa station, a constant activity is found in the diagrams, reaching maximum in the month of January.

With regard to the other seismic areas, it is more difficult to treat them by this method with frequency diagrams.

These diagrams also give us an idea of the present state of the active volcanoes Cotopaxi and Guagua Pichincha; the details will be given in a better form in section IV.

December 1977

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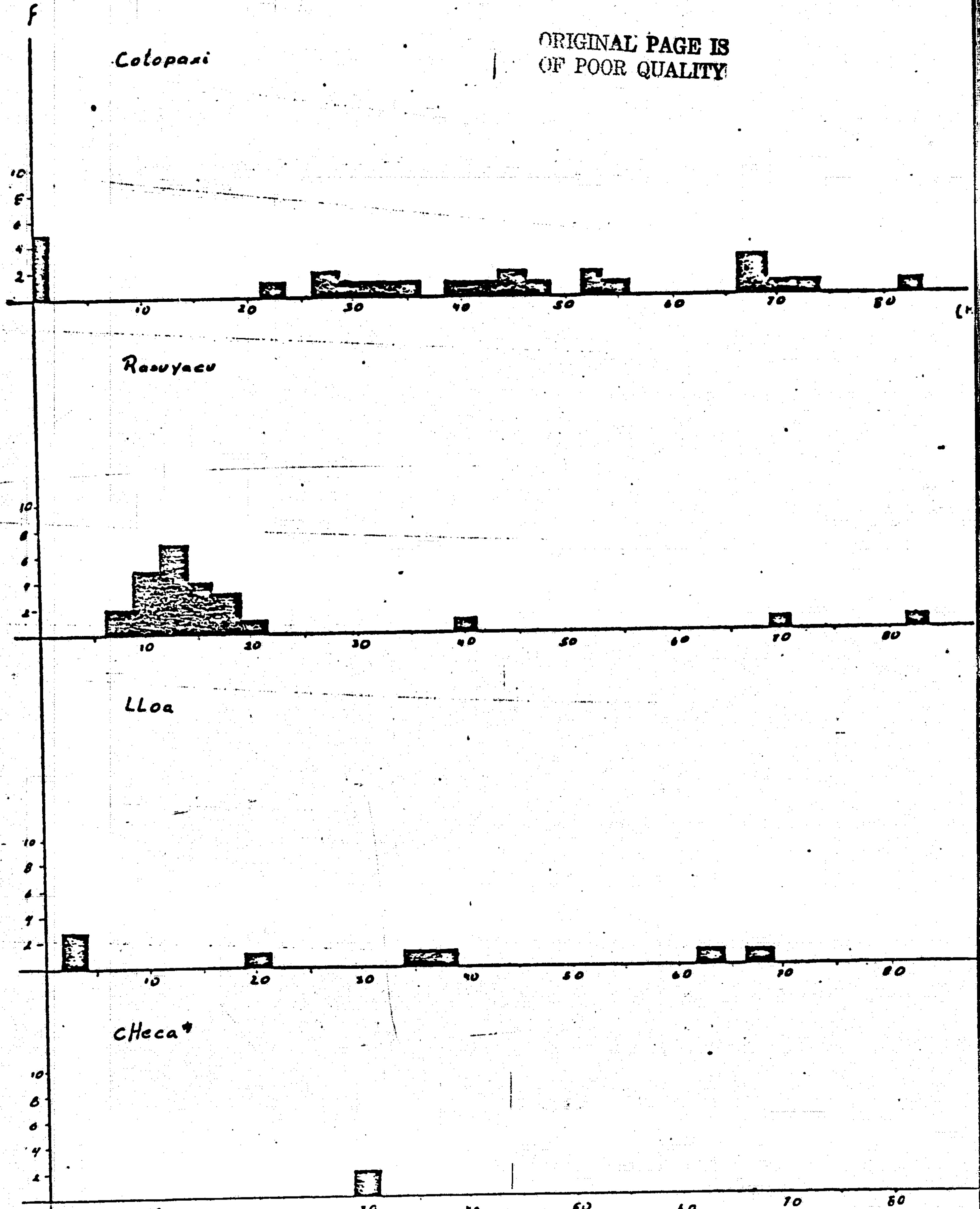
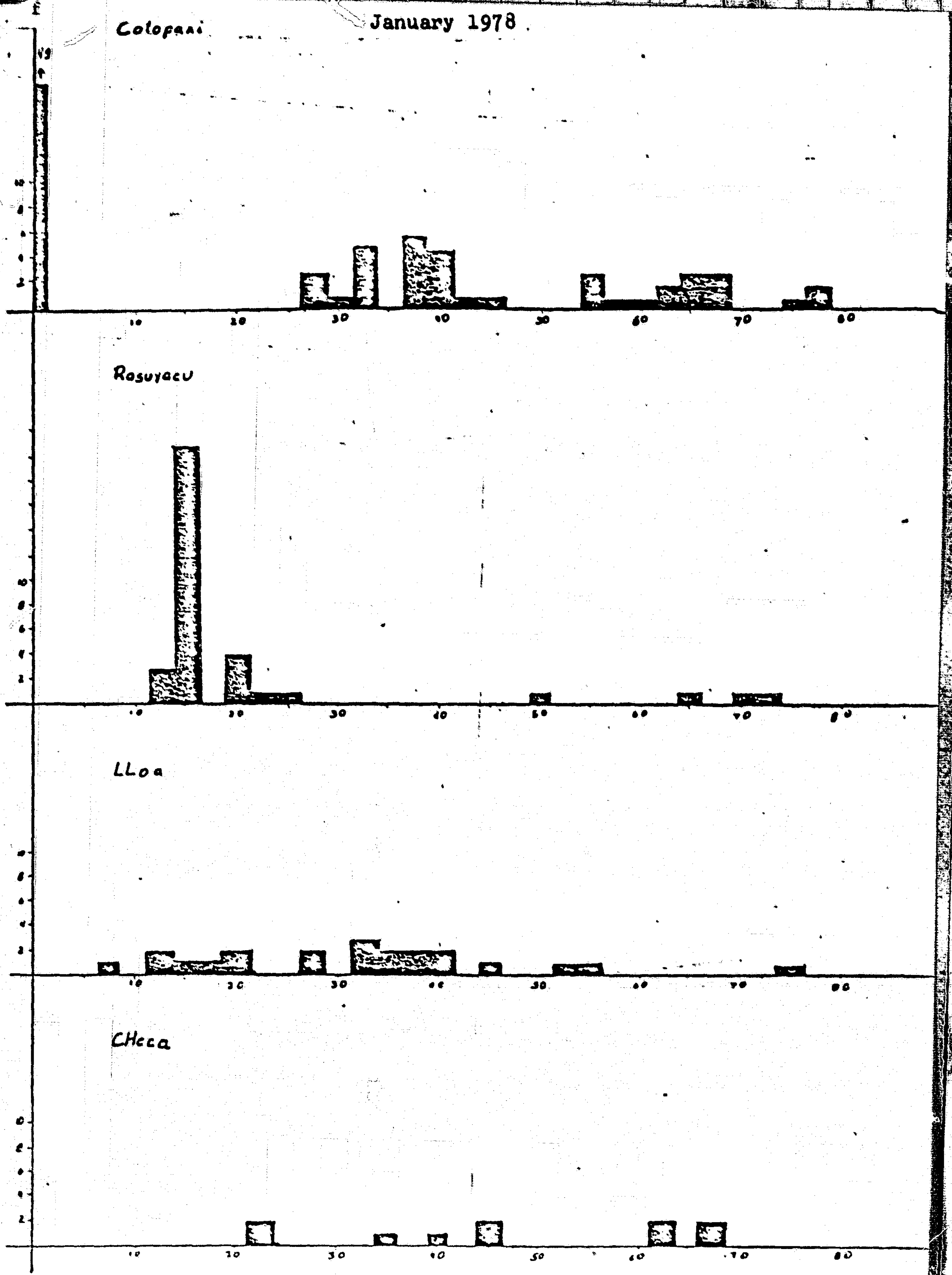


* Instrument operated for only 2 days

Figure 4. (continued on following page)



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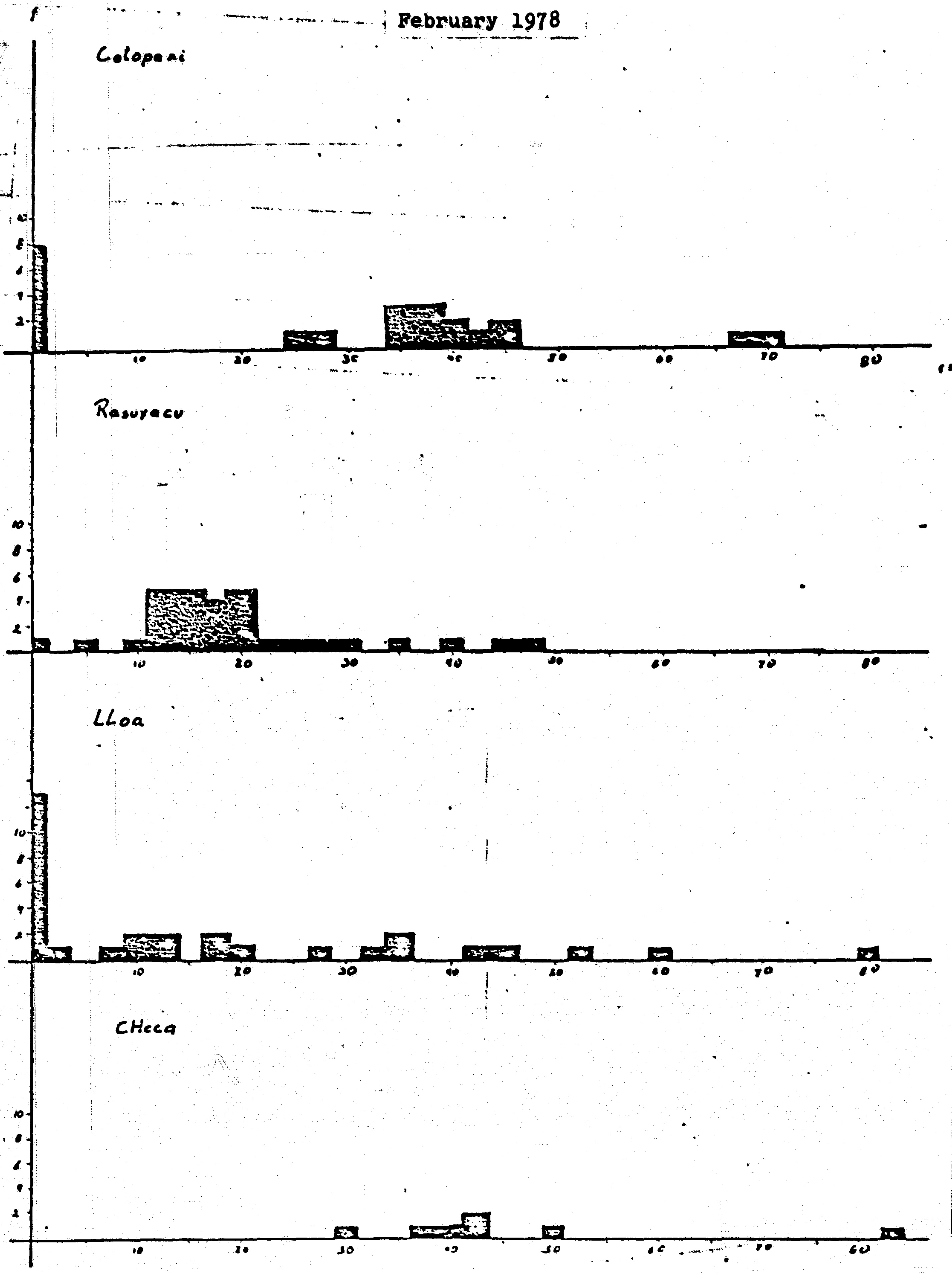

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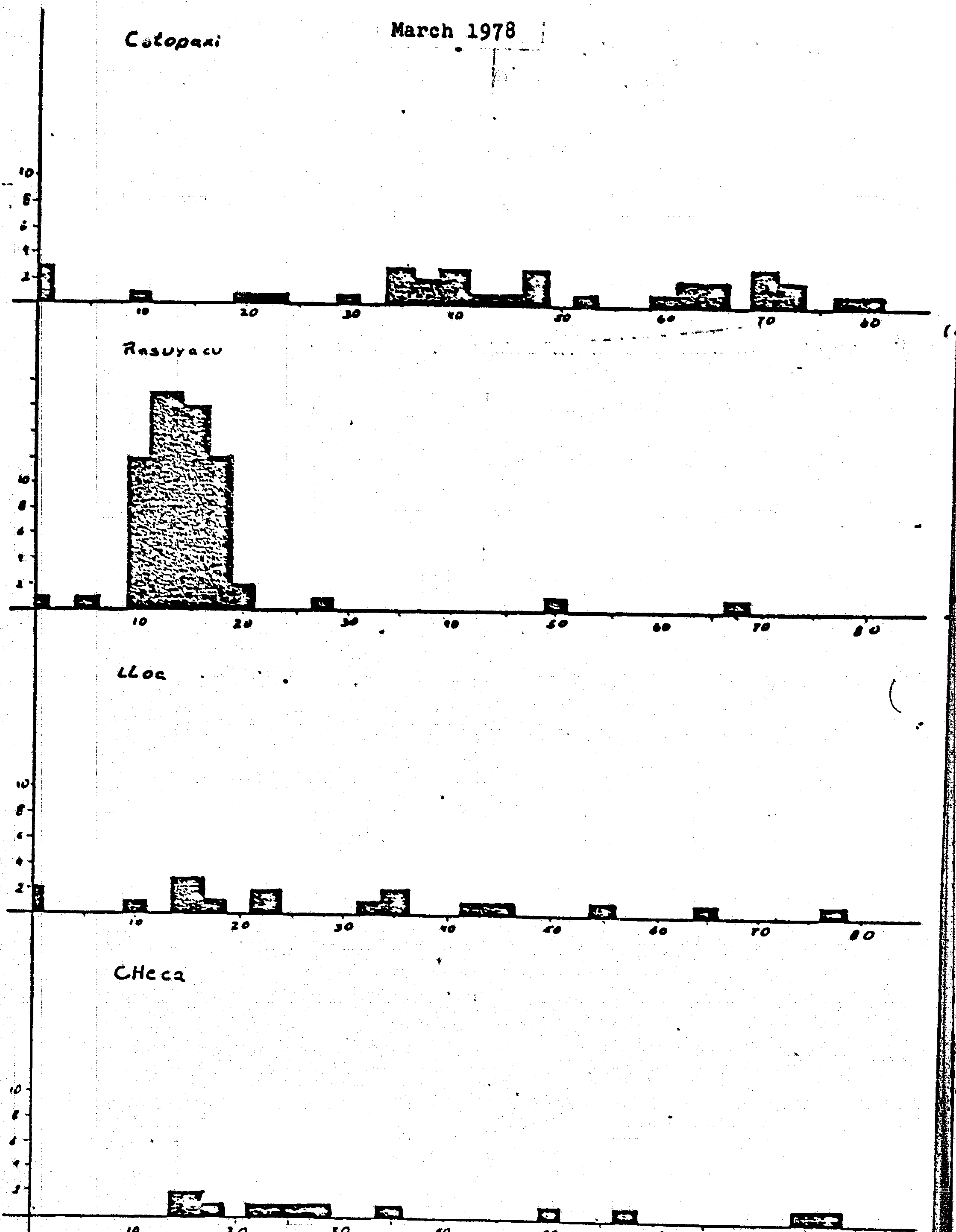
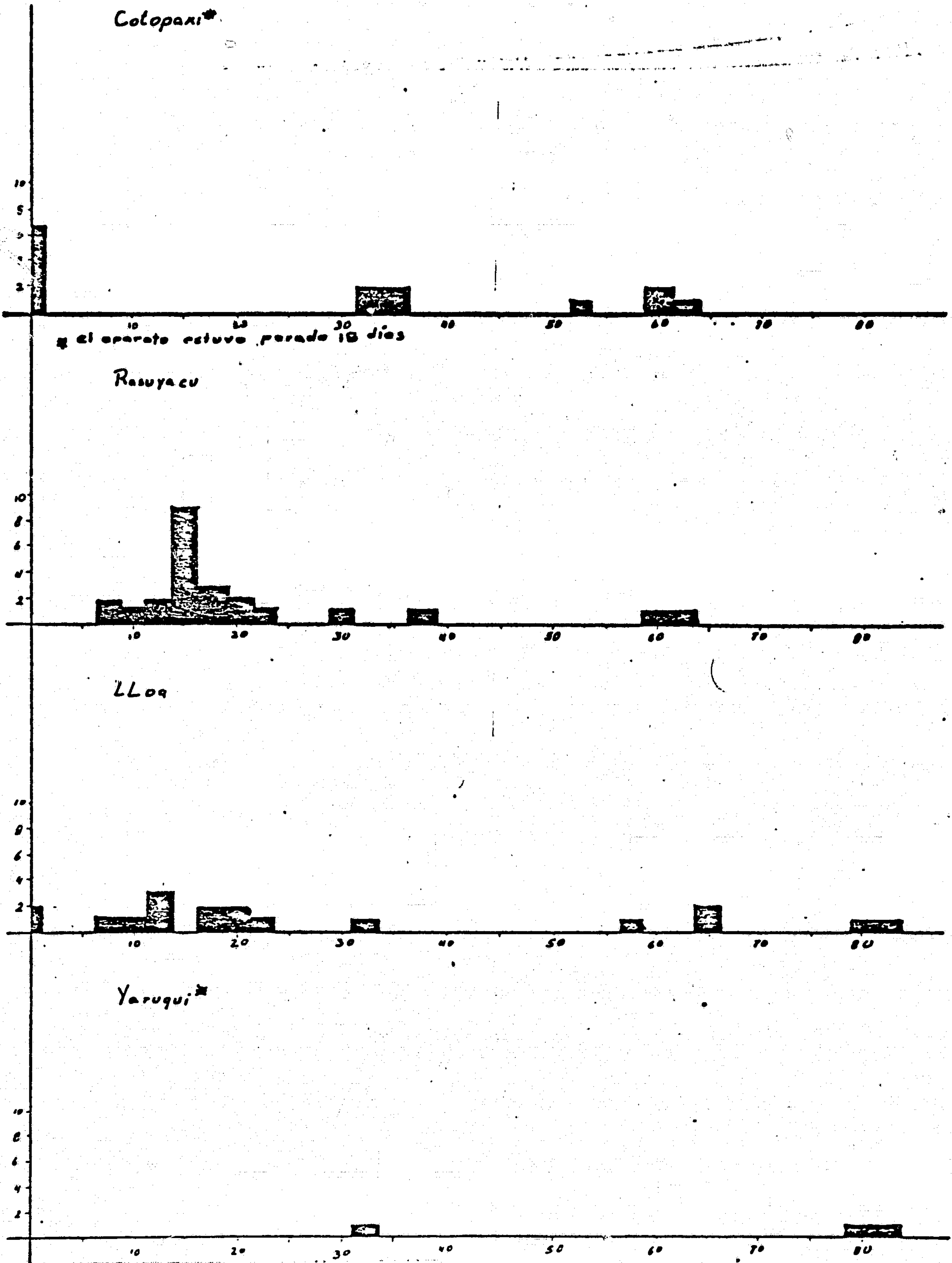


Figure 4. (continued on following page)

April 1978



* Instrument was stopped for 18 days

Figure 4. (continued on following page)

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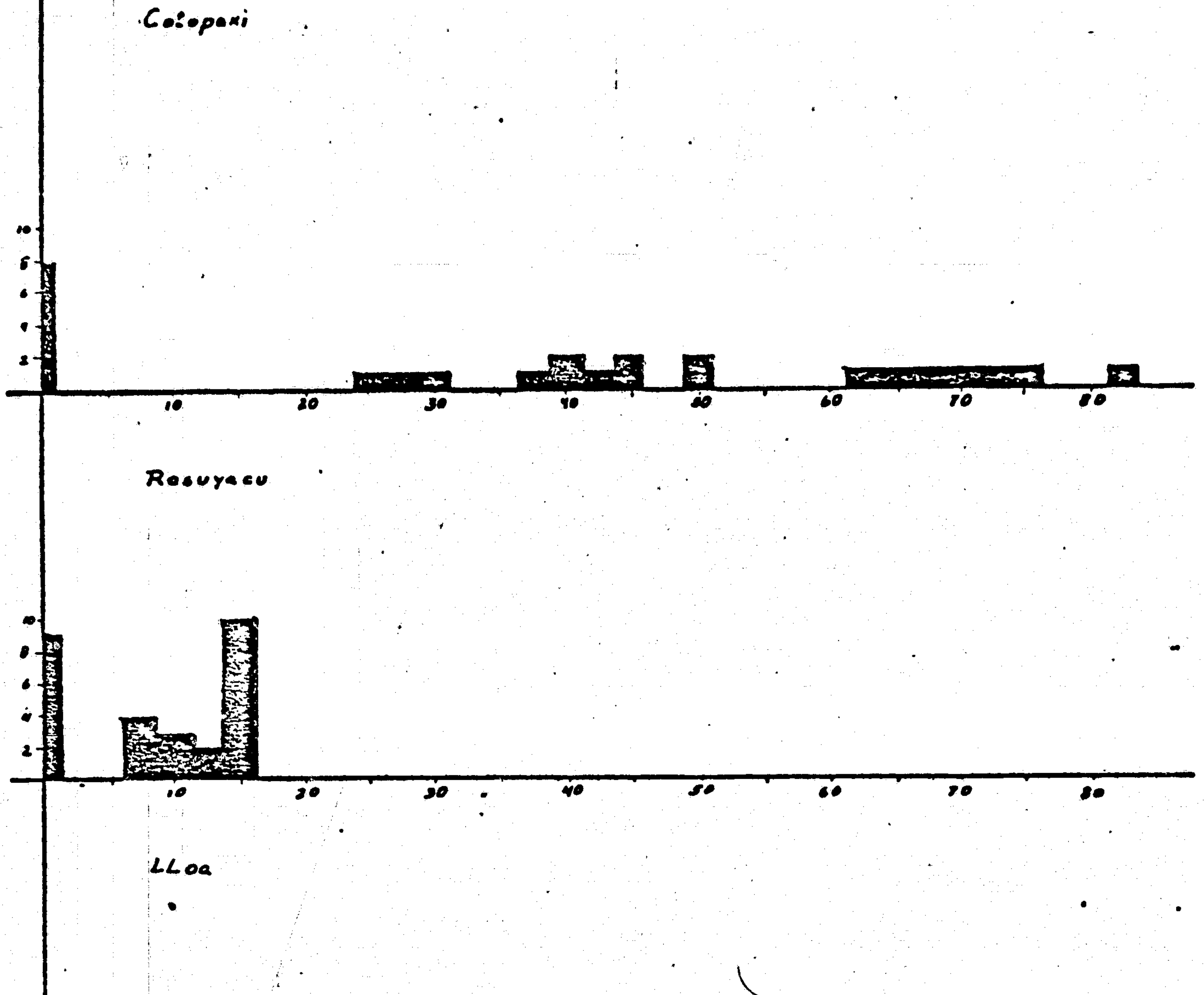

Figure 4. Frequency diagrams (continued)

3.3. Active seismic regions

On the basis of the maps already presented, four regions of greater seismic activity are distinguished, which are discussed in greater detail in this section.

3.3.1. Toaczao area

This is the region of greatest concentration of epicenters, and it is located approximately to the northwest of Toacazo and east of Sigchos (see Maps Nos. 1 and 2). Most of the seismic activity recorded in this study belongs to this region. Many of the tremors of this area were so strong that they could be felt at Quito, and must have had orders of magnitude between 4 and 5 on the Richter scale. It is worth noting that the tremors occurring on March 17 and May 26 were felt at Quite.

These events obviously originate in a displacement region which is very active at present. On the basis of the frequency diagrams (see Figure 4), it may be seen that during the 6 months of operation 165 tremors were recorded within a radius of 17 km around Toacazo, the maximum of 59 tremors occurring in the month of March.

Most of the epicenters occur on the system of fault of northeastern direction, especially the Iliniza faults and on a smaller scale the Toacazo fault, belonging to this system. The tremor was probably responsible for the earthquakes of October and November 1976, which affected the area.

The epicenters of the days January 25, February 4, February 15, April 7, March 17, May 8, May 11, and May 26 are related to the Iliniza fault. The event of April 5 occurs precisely on the Toacazo fault.

3.3.2. Toachi area

This area is defined by a series of epicenters located on either side of the upper course of the Toachi River, starting from Quilota Lake northward (see Map No. 2). To this group correspond the epicenters of January 10, February 7, March 29, April 17 and 19. The event of January 10 was felt in the city of Quito, and its magnitude corresponds probably to a value of 3 or 4 on the Richter scale.

The tremors of this area were produced by a system of faults of approximately north-south direction and running along the Western Cordillera parallel to the upper course of the Toachi river. This system of faults was not described in the tectonic map since it was outside the studied area, but its existence cannot be doubted and the authors proved it in the field in the neighborhood of Sigchos. This system extends probably toward the north to the sector of Pacto and Nanegal and southward to the Cordillera of Angamarca. /14

It should be mentioned that the plotted events represent a small percentage of the total seismic activity of this region. On the basis of the frequency diagrams (see Figure 4) it is noted that several dozen tremors were registered corresponding probably to the region of Toachi or its extension to the north. On the other hand, the layout of the seismological network does not permit a good detection level for the events of less magnitude, only the stronger ones.

Obviously, this area represents one of the regions most active from the seismic point of view existing at present in our country, and which was unknown before the present study. The north-south fault system producing this seismic region is not well known and the active nature presented by these faults was not known.

3.3.3. Quite-Gauyllabamba region

Another area of concentration of epicenters is located east and northeast of Quito (see Maps Nos. 1 and 2). To this area correspond the epicenters of January 26, March 9, May 11, 18 and 19. These events were produced by dislocation along the two principal fault systems: the northeastern fault system with the Guayllabamba fault as one of the main ones and the fault system of the Interandine Valley with the Calderon faults, with the typical representatives Ilumbisi and Pomasqui.

The events of January 26 and May 18 occur on the Guayllabamba fault. On March 9 we have an event on the Calderon fault intersecting with the Guayllabamba fault. The event of January 26 occurs on the intersection of these two faults. On May 11, two events occurred on the Ilumbisi fault near its intersection with the Guayllabamba fault. These two events were followed on May 18 by events along the Guayllabamba fault, suggesting that these two faults are active branches of a set of faults which at present are releasing tension in this region.

The event of January 17 belongs probably to the northwest system. /15
The two events of May 13 and 26 in the valley of Los Chillos indicates that active faults belonging probably to the system of the Interandine Valley lie under this important valley. This very valley suffered a big earthquake in 1938.

Three events on March 22 and 27 and on May 15 occurred to the east and outside the studied areas, belonging probably to a fault system of the Eastern Cordilleras.

3.3.4. Machachi region

This area contains the epicenters located in the neighborhood of Machachi, southwest of Quito. It includes the events of March 9, 28, 29, and 30, February 28 and 21. The latter were greatly scattered on the flanks of the extinct volcanoes: Atacazo, Corazon, and Pasochoa.

They probably form part of the two dominant fault systems in the area: specifically, faults of the northeast and faults of the Interandine Valley.

IV. Present State of the Active Volcanoes Cotopaxi and Guagua Pichincha

The volcanoes of Ecuador have a long history of activity. During the last four centuries, at least 8 volcanoes have shown considerable volcanic activity. These volcanoes, active and dormant, include: Reventador, Sumaco, Antisana, Cotopaxi, Tungurahura, Sangay, Quilotoa, and Guagua Pichincha. The eruptions of these volcanoes produced great disasters on a regional scale and on many occasions, with great loss of life and destruction of property, factories, and valuable agricultural land. More specifically, the volcano Cotopaxi has a long series of eruptions during the decades from 1900 to 1950, in which many townswere destroyed, including the city of Latacunga. Although it did not have such a destructive history, the Guagua Pichincha had a great eruption in 1660 which deposited a layer of ashes 40 cm thick over Quito; slight signs of the resumption of its activity were also noted in the years 1868, 1869, and 1881. /16

During the last decade, volcanologists have observed that before an eruption microseismic activity under a volcano often increases little by little, culminating in the eruption itself. Probably this occurrs through the rise of the magma from a great depth to the volcanic edifice. Seismographs of high magnification are able to detect these volcanic microseismisms, and with their continuing operation over a long period it is possible to register changes in this activity preceding a possible eruption. A warning period before the eruption would obviously be very useful for the development of contingency plans, evacuation, etc. These seismographs operate continuously in some volcanoes of Central America, the United States, Japan, and Italy.

Because of the indications of the resumption of the activity of Cotopaxi in 1975, NASA, collaborating with the National Polytechnic School, installed a seismograph and two inclinometers on the western flank of the volcano in May 1977, which are recording continuously

the activity of the volcano (Allenby, 1977; Ramon, 1978). The seismological project of the Latácunga-Quito region, set up by the National Civil Defense Board, offered the opportunity for studying briefly the Guagua Pichincha volcano. The layout and location of the seismological network were set up in such a manner that it permitted us to monitor this volcano. For this purpose, an instrument was installed near Lloa, at about 7 km from the crater of the volcano, which at the time the volcano was being monitored, was part of the seismological network. Almost 6 months of continuous operation were carried out, through which we are much better acquainted /17
with the present state of the volcano, and a normal level of its seismic activity was established.

4.1. Results

On the basis of the result obtained from the seismographs installed in Cotopaxi and Lloa, the frequency graphs were plotted of the microseismic activity of volcanic origin (see Figure 5). The number of microseismisms detected in Totopaxi varied from 3 to 49 per month during the studied period. Without taking into consideration the month of January in which an abnormal number of local tremors were registered, the number varied between only 3 and 9 microseimisms per month, with an average of 6.3. This level of seismic activity was accepted as normal, and with it it will be possible to compare the future seismic activity of the volcano. We will thus be able to obtain a possible prognosis for the resumption of the activity of the volcano.

The abnormal number of tremors detected in January may be due to a number of causes. No doubt many are of volcanic origin; nevertheless, many are perhaps due to the movement of the glaciers of the mountain, which constitutes a common phenomenon observed in other volcanoes. Recent communications with Dr. John Latter, volcanoligist of the Government of New Zealand, are furnishing new criteria for this type of tremors.

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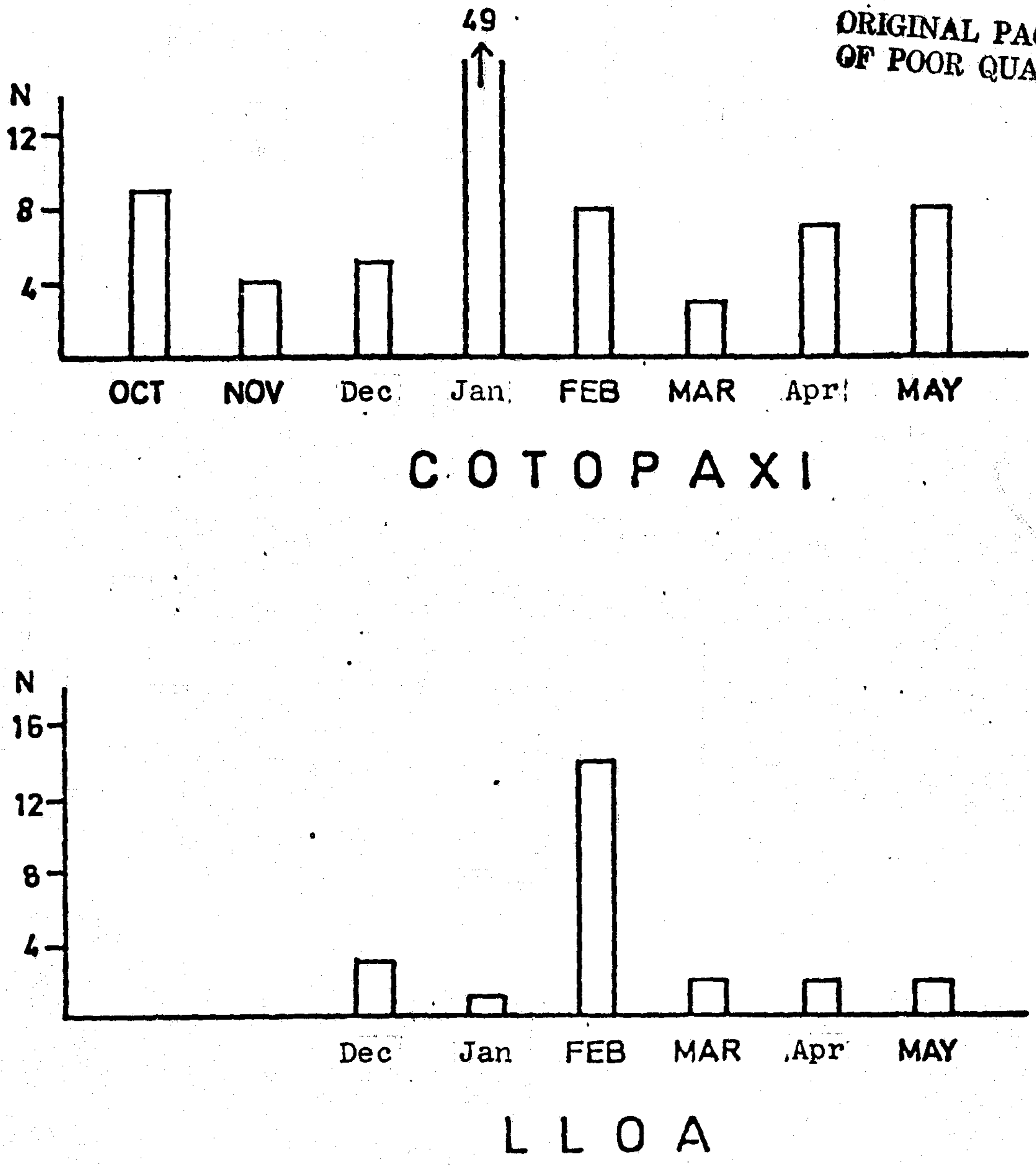

Figure 5. Frequency of volcanic microseimism

With respect to Guagua Pichincha, it may be seen on the graph that the number of microseismisms of volcanic origin varies between 1 and 14 per month during the period studied. Without considering the month of February in which a relatively abnormal number of tremors were registered, the normal level of seismic activity seems to be about 2 tremors per month. This level will be used as the standard for future comparisons.

4.2. Other data

Sporadic visual observations were also carried out, in which no considerable change was detected in the state of these two volcanoes in the last twelve months.

4.3. Conclusion

To sum up, the conclusion may be drawn that for neither of the two volcanoes did one detect an extraordinary number of volcanic tremors which would imply that the state of the volcanoes changed. /18
This coincides with the visual observations which did not detect any considerable change either. The important thing is that the normal activity levels were established for each of the volcanoes, which is necessary to obtain a prognosis of the resumption of the activity.

V. Conclusions and Discussion

5.1. Conclusions. Summary /19

For the first time a detailed map was established in the country of the faults which might affect the Interandine Valley between Laracunga and Quito. These faults were grouped into three main systems. The faults of the system of the Interandine Valley, with mainly north-south directions, control the shape of the valley. The active faults of the northeastern system which pass through the Interandine Valley with northeast direction from Saquisili and the Iliniza peak to Guayllabamba and probably Cayambe. The third system, the northwest system, consists in faults of northwest direction which are noted in the valley of Guayllabamba. All these systems of faults cut through the cangahua, proving their youth.

The best known of these fault systems is that of northeastern direction, which had never before been identified in the Sierra. It crosses through the entire region under study, with a length of at least 90 km, and certainly extends toward the southwest and northeast to Cayambe and Ibarra. It seems that its motion is of the type of direction fault, with mainly horizontal displacements, although this needs to be confirmed. According to Allen (1975), the long and continuous direction faults are the most dangerous potentially. But there is no way of knowing whether these faults are going to produce a strong tremor in the near future.

A network of 4 seismographs was maintained in operation for 6 months to determine the seismic activity of the region. From the seismological data, the epicenters were calculated by computer, this being the first time this technology has been used in this country. The results reveal that there have been microseismisms in the faults of the three systems during the last months, specifically, that the three fault systems should be considered active. Furthermore, most of the calculated epicenters have a superficial focus, i.e., the seismic events occurred at depths of less than 30 km below the ground surface. Thus the seismic activity along the northeast system is distinguished, as well as in the sector of the Toachi River outside the project area.

It appears that these three fault systems and the system of the Toachi River form a complex set of faults producing the seismic activity which is now affecting the northern part of the Ecuadorian /20 Andes. The conclusion should be drawn that this region is under tectonic tension, which is indicated by the abnormal seismic activity of the region. If these systems participate in this complex set of faults, one should expect that the faulting and displacement in a sector may cause subsequent faulting in other sectors. According to this concept, the occurrence of apparent migration of tremors could be explained, from the Ilumbisi fault to the Guayllabamba fault during May. Other apparent migrations of dislocations have also been observed.

5.2. Discussion

5.2.1. Faults and faulting

The faults are ruptures of the Earth's crust, generally long, produced by the breaking of the rocks during the release of tension. The breaking process is called faulting.

Bolt et al. (1975) explain this process as follows. The tension which is gradually accumulated in the crust represents a reserve of elastic energy, in the same way as when a spring is compressed. At some point called the focal point (focus) within this region under tension, rupture starts suddenly and extends rapidly in all directions along the surface of the fault. This occurs as a series of erratic movement or jumps caused by the irregular resistance of the rocks. The irregular propagation of the displacement along the fault causes "explosions" of high frequency waves which travel through the Earth, producing the seismic shock, which causes most of the damage and destruction. The propagation of the rupture travels intermittently in jumps measured in fractions of seconds with a typical velocity of 2 to 3 km/sec. The shock outside the fault consists of all types of (vibrating) waves of different frequency and amplitudes.

5.2.2. Risks inherent in faulting

The risks induced by faulting are divided into three groups.

a) Rupture of the Earth's surface. This refers to the rupture, opening, and displacement of the Earth's surface by faulting. The damage is therefore limited to the structures built precisely over the track of the fault. /21

b) Seismic shock. The waves generated by the faulting spread in all direction. Generally at a greater distance from the focus of the faulting, the frequencies and amplitues of these waves decrease. Damage is caused to any structure when the frequency of the seismic waves is similar to the natural frequency of the structure. Unfortunately, many structures or buildings have frequencies of the same range as those generated during the faulting.

The seismic shock will generally affect a considerable area, occasionally up to hundreds of kilometers from the focus. Consequently, destruction occurs over an enormous region. It is known, moreover, that the rocks of the subsoil may modify greatly the nature of the seismic waves; thus when they travel through nonconsolidated materials such as alluvia, filling, and pyroclastic material from a volcano the waves are attenuated and lose part of their velocity. Unfortunately, this causes an increase in the amplitude of the waves and of the duration of the strong shock, which is the main cause of destruction over a wide range. Dobry et al. (1978) noted during certain earthquakes and in poorly consolidated materials the presence of superficial phases following the strong phase (S), which had a high content of long periods and were probably responsible for the selective damage and the collapse of the foundations of high buildings. Hence the structures built over these materials incur greater risk. Unfortunately, comparatively loose geological material lies under a considerable part of the Interandine Valley (cangahua, pyroclastic materials, etc.), and it may therefore be expected that the seismic shock will be responsible for much damage in the future.

c) Secondary effects. There are many secondary effects which are caused by faulting and therefore rapidly become dangerous:

Floods: They are caused by the collapse of dams due to shock.

Landslides: They are produced by the shock in unstable soils of low slope, especially soils saturated with water.

Avalanches: They may originate on the upper flanks of mountains causing danger to the towns on the slopes.

Tsunamis: These are great tidal waves produced through violent undersea faulting. They are dangerous on the coasts.

Overflow: This is the overflow of water from a lake or dam, caused by the shock. /22

Sinking: In rare cases, the shock or faulting itself causes a sinking of the ground.

Fires: The main risk in the cities is the starting of great fires caused by the rupture of polyducts, oil tanks, electric plants and substations, etc. Sometimes fires are hard to fight because of the rupture of aqueducts and of communication lines.

Liquefaction of the subsoil: When sand and clay materials are saturated with water, the water occurring in the mineralogical structure separates, forming a clay of low resistance. Buildings cemented with these materials may suffer from this phenomenon, causing the loss of equilibrium in their suport, and therefore of the buildings themselves.

It is obvious that tremors and earthquakes produced by faulting may cause many dangers, both direct and secondary. According to the local situation, one or several of these disastrous phenomena will predominate; although the seismic shock is the main one, the other phenomena which might occur in each region or district should also be taken into consideration. It is proper to present here a discussion of how the Interandine Valley would be affected by these risks.

5.2.3. Risks in the Interandine Valley

Faults which might potentially induce strong tremors pass through almost all the studied region. The conclusion was previously drawn that most of these faults are active and that the region is under tectonic tension. It is well known that this region has had a long history of tremors. Although the main concern is caused by the northeast fault system, the faults of the other systems might also induce strong tremors. The faults of the northeast system follow a great portion of the Interandine Valley, and therefore tremors of magnitudes of more than 5 produced by this system may affect an enormous populated industrial and agricultural sector. Most of the populated and industrial sectors, infrastructure works, and agricultural sectors in the Machachi-Guayllabamba system are located at about 6 km or less from the faults of this system.

Another cause of anxiety is that much of the area in question lies over cangahua or other unconsolidated materials. Consequently, in case of a strong tremor, a great shock may be expected over a wide range for reasons already discusssed in section 5.2.1. Moreover, the past tremors as well as those registered in this study are of shallow origin, which aggravates the situation. A brief evaluation of the earthquakes of Pastocalle 1976, Machachi 1976, and Pelileo 1949, regions lying over not very consolidated materials, suggests that tremors of force greater than 5 will have intensities (modified Mercalli) greater than VII, an intensity for which the adobe houses suffer great damage. Obviously this damage would be multiplied at higher intensities. /23

The two factors mentioned above suggest the existence of a potentially dangerous situation in this region.

It is worth listing the buildings and installations which might be affected by tremors along the faults of the northeast system. These include:

1. the satellite-tracking station (NASA);
2. the town of Machachi;
3. the town of Aloag. Its position is critical since the main roads leading to Quito and the north of the country converge here. Furthermore, the polyduct, the railroad, and the high tension lines of Pisayambo pass through it;
4. the nuclear reactor which will probably be built at Aloag;
5. Quito drinking water supply. The aqueduct of the Pita-Tambo Project may be cut off by the faults;
6. oil duct. Conocoto sector;
7. Terrena station. IETEL communications center;
8. express highway: Quito-Los Chillos Valley;
9. electric power stations of Guangopolo and Nayon;
10. Quito;
11. many road, factories, and industries.

It is known and attention has been drawn to the fact that many vital works for the well-being of Quito and of the country have been built a few kilometers from active faults.

6. Recommendations

6.1. Microseismic studies importance

The studies of microseismicity, along with the geological, geophysical, and tectonic studies, constitute a source of information which is important for the identification of sources of future significant events, to define the seismological environment, and to evaluate the seismic risk (Savage, 1978). /24

We recommend studies similar to this one to be carried out along the Interandine Valley, especially in seismically active areas with high population density.

The region between Guayllabamba and Machachi requires the continuation of the studies of microseismicity to improve the knowledge of the seismic risks they present. Also, toward the northeast of Guayllabamba in the sectors of Cayambe and Ibarra, being a densely populated area and in view of the probable presence of active faults in it, adequate investigation is needed. The region of Ambato and its surroundings have already been affected strongly by tremors in the last decades (see Map No. 3), and we are ignorant of the present tectonic situation in this area.

Future studies of this type should give more importance to the study of the type of faulting and its different parameters. These include: the type of faults found, the length of the faults, and their activity. To satisfy these requirements, one should increase the number and quality of the instruments for seismic observation and registration.

This study proved that microseismic studies may be carried out by national technicians and with instruments easily obtainable on the world market, and with a technology similar to the one used at present in the highly developed countries. This is of great advantage, since it will reduce the costs of these studies which we believe should be undertaken with the highest priority, since their importance is indisputable.

6.2. Instrumentation

In the continental part of Ecuador, there is at present not a single complete seismic station operating whose information is satisfactory. The VELA station of the Astronomy Observatory at present is not operating because there is no adequate place to install it. The VELA station of Galapagos is operating permanently, but with many breakdowns. /25

We recommend that an impetus be given to the creation of seismic stations in the country, which will be of definite assistance in research similar to this one. The microseismic network used in this study would have had better results if we have been able to rely on a larger number of instruments of the same type. We therefore recommend that the National Civil Defense Board acquire a larger number of instruments similar to those it already possesses, since the latter have proved to be very reliable and their operation does not pose major problems.

An urgent need is the purchase and installation of several accelerographs in the principal cities of the country for the purpose of determining the characteristics of the movements of the soil during strong earthquakes. This will be of great help and will furnish better criteria in designing and building new edifices in the cities, and will represent a great step toward the future establishment of a building code which takes seismicity into account.

6.3. Monitoring the active volcanoes

It is obvious that it is necessary to continue monitoring the most dangerous volcanoes, especially Cotopaxi, Guagua Pichincha, and Tungurahua, which are active and represent a direct threat to the nearby cities and towns.

The geophysical station of Cotopaxi operated by NASA and the Polytechnic School was planned to continue operating indefinitely, so that we are confident the volcano will be well monitored.

The Guagua Pichincha is in a dormant state, but it can in no way be considered extinct. According to Dr. H. Tazieff, the world-famous French volcanologist, this volcano is the most dangerous in the country, since a very explosive activity is expected in its next eruption. Consequently, it is critical that the study of the volcano should continue. The following is recommended:

1. Establish a map of the volcanic risks of this volcano, similar to the one obtained for Cotopaxi (see Miller et al., 1978).

2. Monitor this volcano with a high-magnification seismograph. This may be obtained by installing an instrument of the Civil Defense Board in a well selected site. Another possibility which is of great interest is that the Astronomical Observatory Station located at present in the Alameda Park, because of which it does not /26 operate satisfactorily, should be shifted to a site on the Picnincha flank, from which it may monitor the volcano with its instruments. Unfortunately, this change of site for the station has already been postponed for years.

It is also necessary to study the Tungurahua volcano to determine its average level of seismic activity, as was done in Cotopaxi and Guagua Pichincha in the course of this study. It is recommended that if a seismic study is carried out in the Ambato region, one of the instruments included in this network be installed on the Tungurahua volcano. This will make it possible to investigate both the seismic and tectonic seismicity.

6.4. Operations and projects of national importance

One of our important preoccupations is the planning and probable construction of several projects of great importance for the development of the country, and whose location coincides with sites identified by us as seismically active.

The INECEL Project on the Toachi River is located within the seismic area of the same name (see Map No. 2) in which there are active faults passing through the area of the project and in which several epicenters were detected.

The Ecuadorian Atomic Energy Commission is planing the installation of a nuclear reactor in the immediate vicinity of the town of Aloag. The tectonic map (see Map No. 1) shows that through this area pass systems of faults which are active, and it is also noted that the epicenter of the Machachi earthquake (November 1976) is very close to this region.

We recommend that the location of these projects should be reconsidered, taking into account the above described criteria, since in their present location in case of a strong earthquake they might produce serious catastrophes.

6.5. Contingency plans

Finally, we recommend that, on the basis of the results obtained in this study, the National Civil Defense Board should prepare contingency plans for this region, if this has not already been done, /27 in the case of occurrence of a great natural catastrophe, such as an earthquake or a volcanic eruption affecting the population.

The National Civil Defense Board should consider that in the region studied there are large populated centers, infrastructure establishments of national importance, lines of communication and means of supply on which the population of this region depends. In view of what was described above, we believe that in case of disaster it is vital to have established contingency and emergency plans which would help to save lives and property of the population affected by a disaster.

Acknowledgements

The authors express their gratitude to all those who participated in one way or the other in the development of this study. We express our gratitude especially to the personnel of the Woodward-Clyde Company, who lent us valuable assistance in the calculation of the epicenters, and the members of the National Civil Defense Board, who gave us their support in all directions during the entire duration of this study. /28

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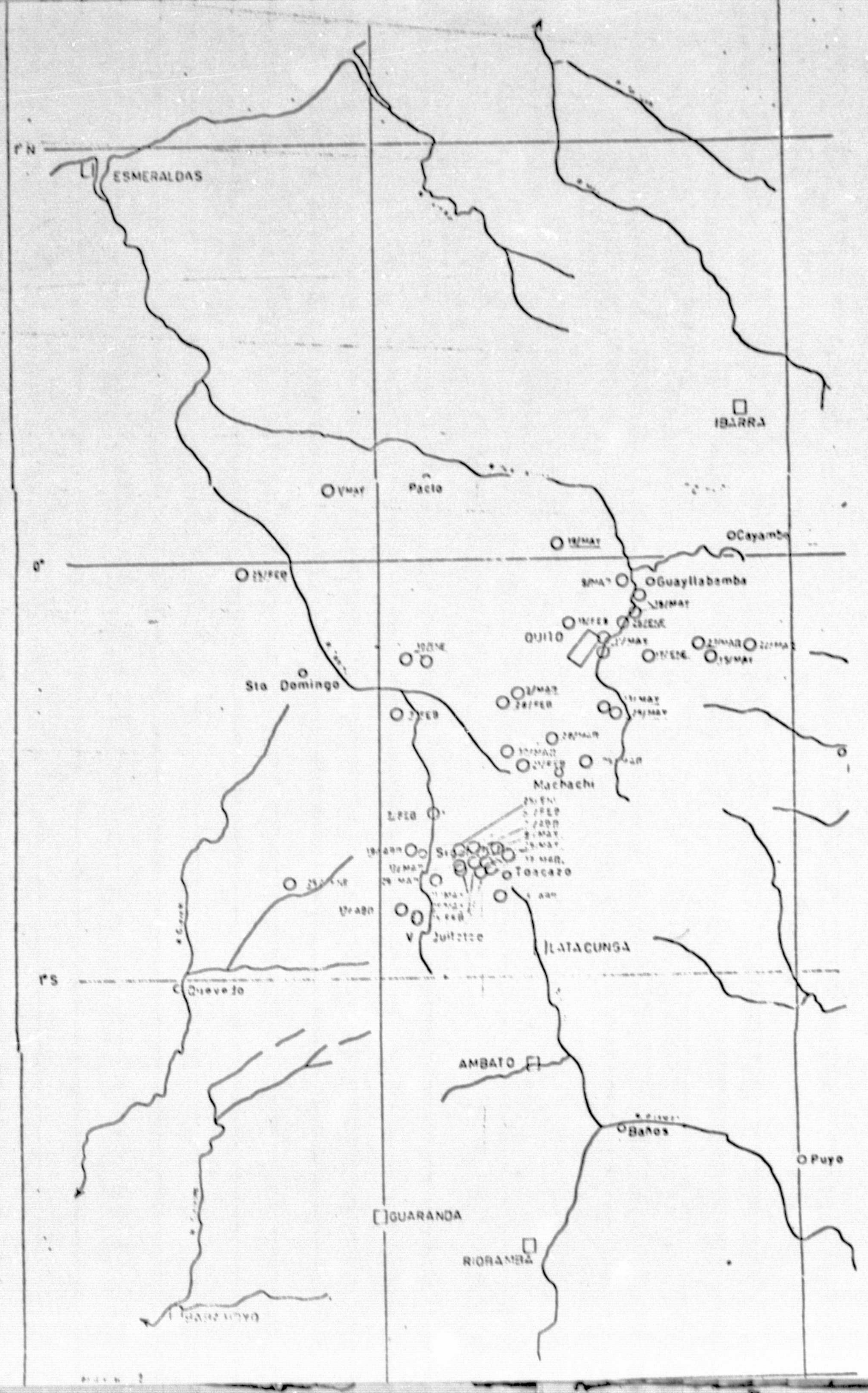

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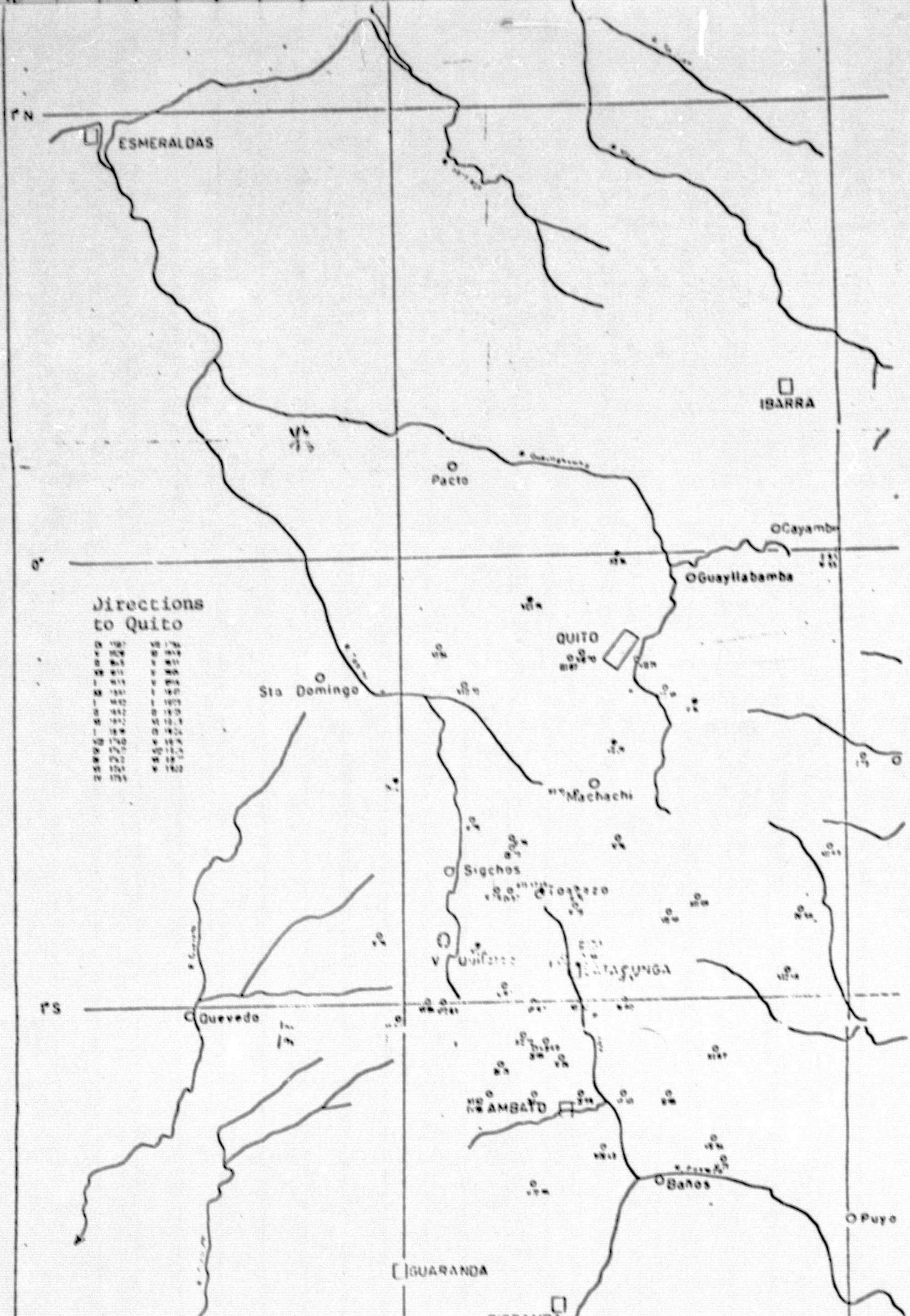
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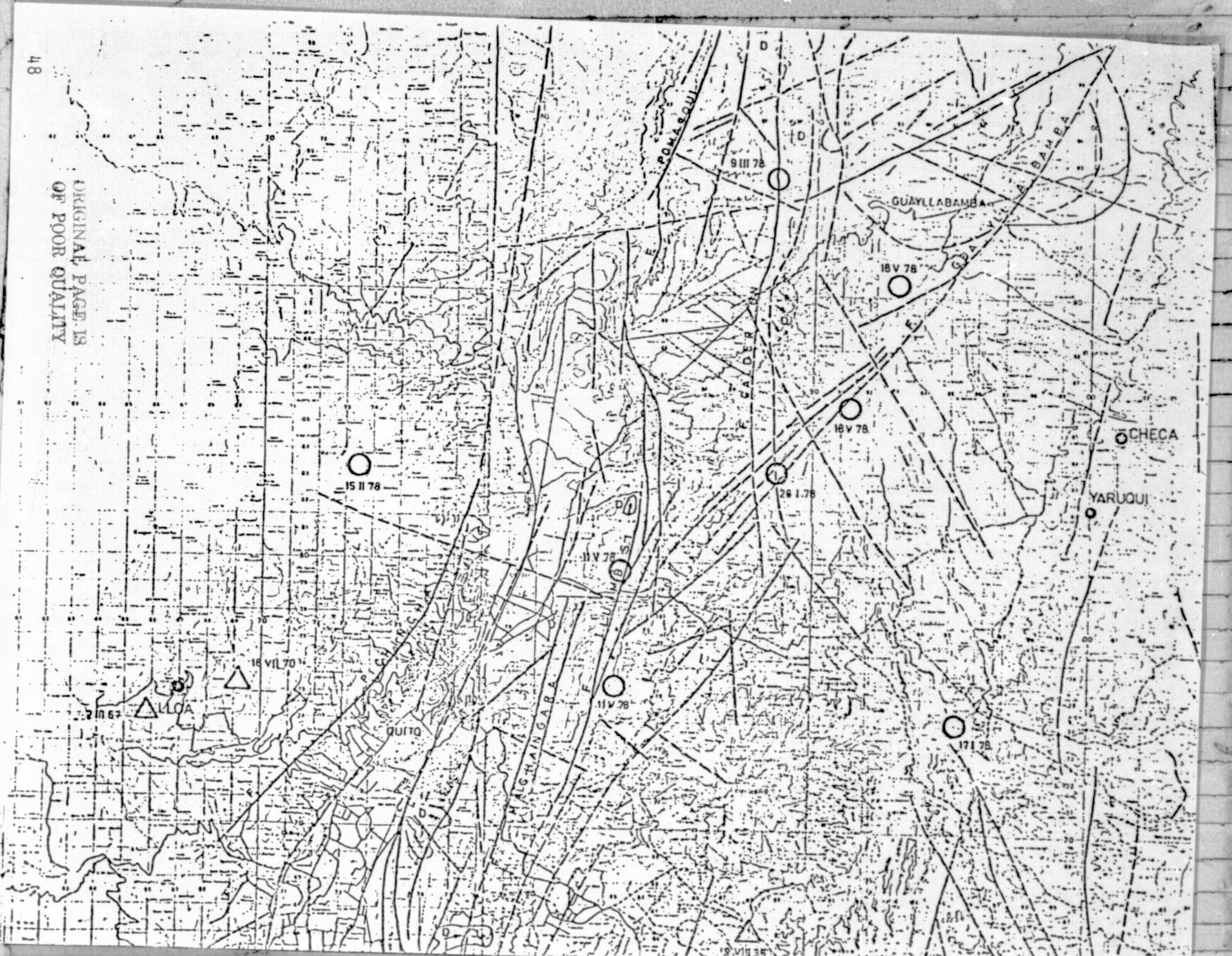
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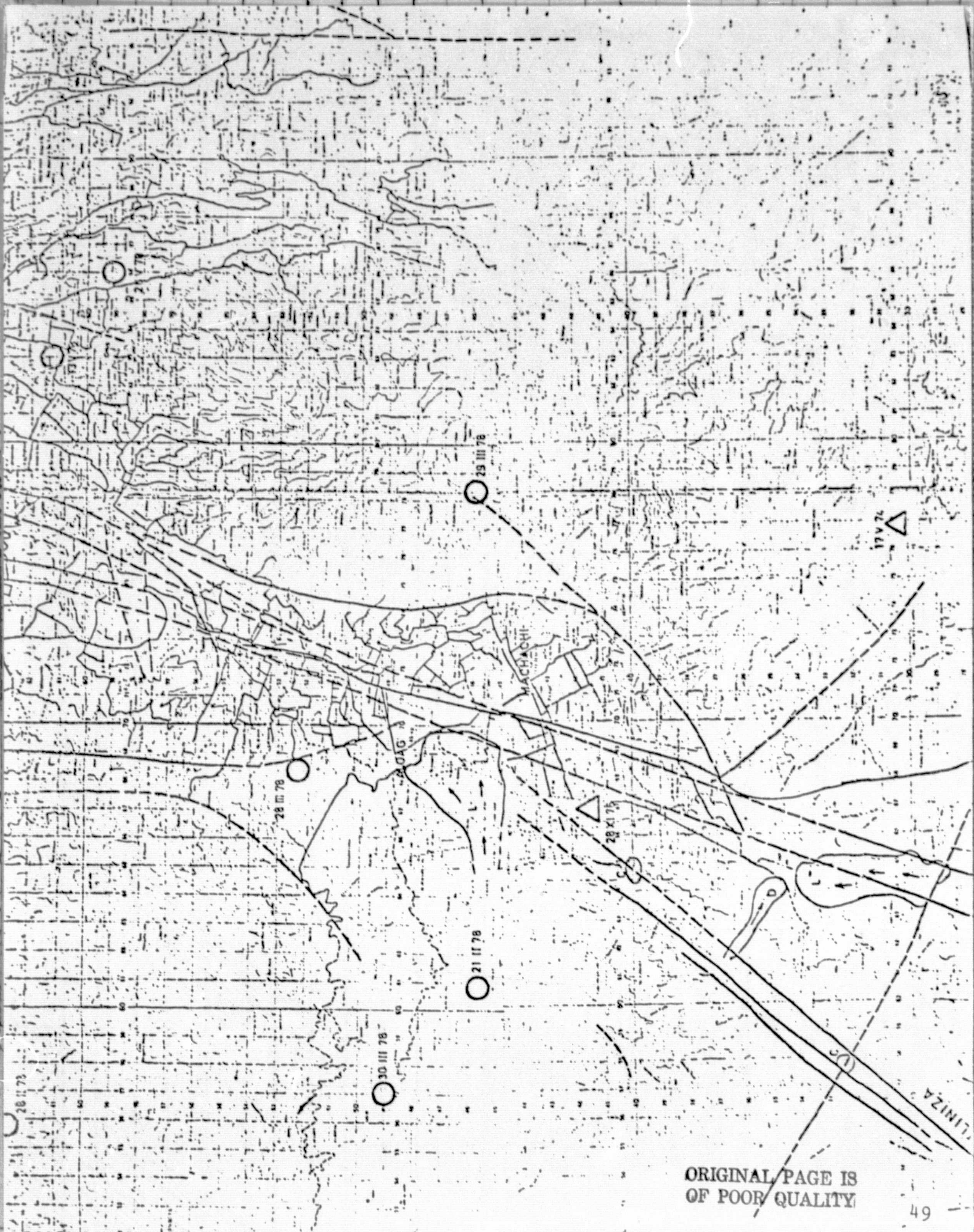

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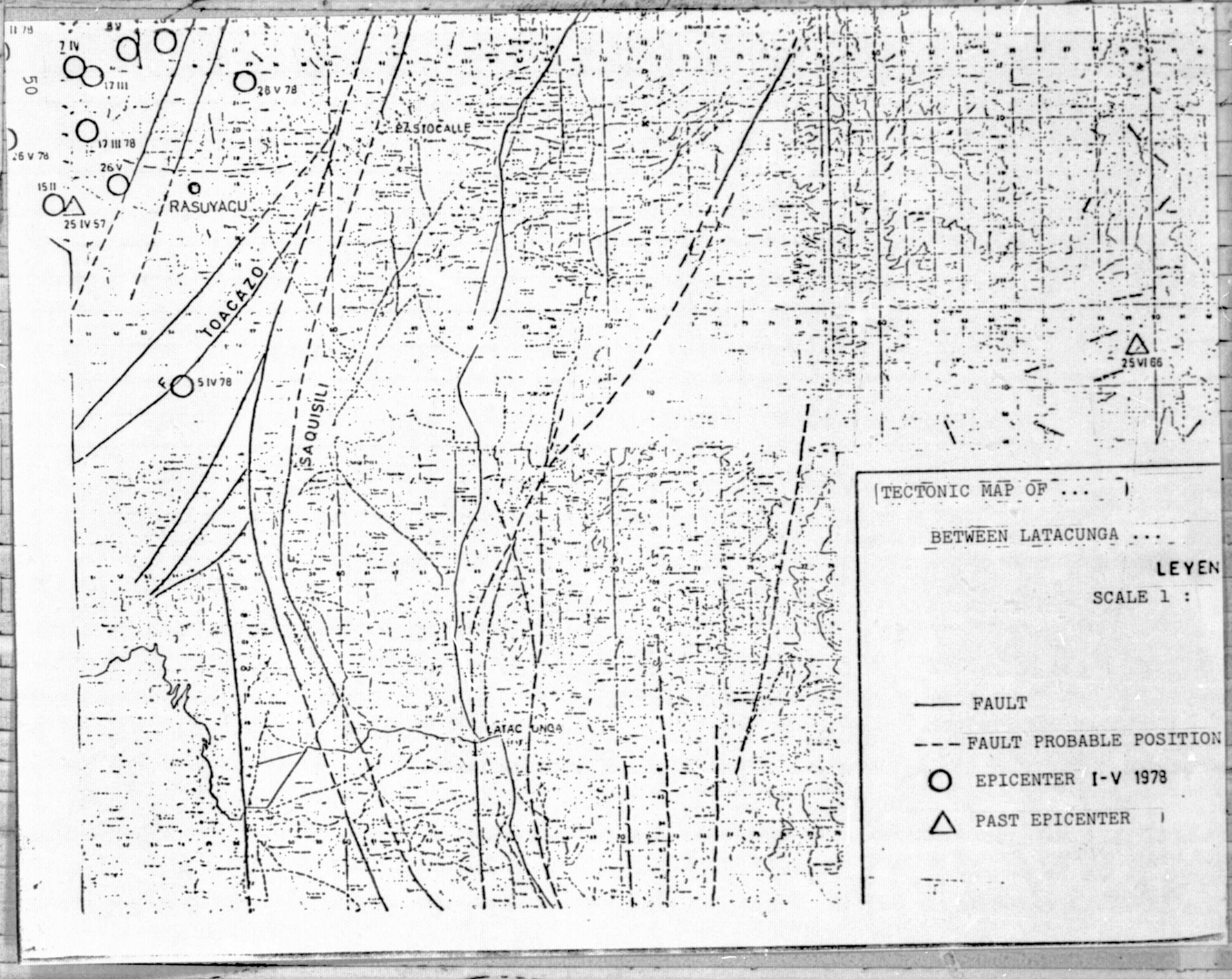

TECTONIC MAP OF ...

BETWEEN LATACUNGA ...

LEYEN

SCALE 1 :

OPERATING SCHEDULE — SEISMOMETERS

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

November 1977 1

COTOPAXI Continuous operation

RASUYACU 1 2 M 3 4

LLOA 1 2

CHECA

December 1977

COTOPAXI Continuous operation

RASUYACU 5 M 6 7 8 M 9 10 11 M 12 F 13 14 M 15 16 F 17

LLOA 3 M 4 5 6 M 7 8 9 M 10 11 12 M 13 14 15

CHECA 1 2 M 3 F

ORIGINAL PAGE IS OF POOR QUALITY

January 1978

COTOPAXI Continuous operation

RASUYACU M 18 F 19 M 20 21 F 22 M 23 24 25 M 26 27 28 F M 29 F

LLOA 16 17 18 M 19 20 21 M 22 23 24 M 25 26 27 M 28

HECA F 4 5 M 6 7 8 M 9 10 11 M F 12 13 14 FM 15

1

February 1973

C OPAXI Continuous operation

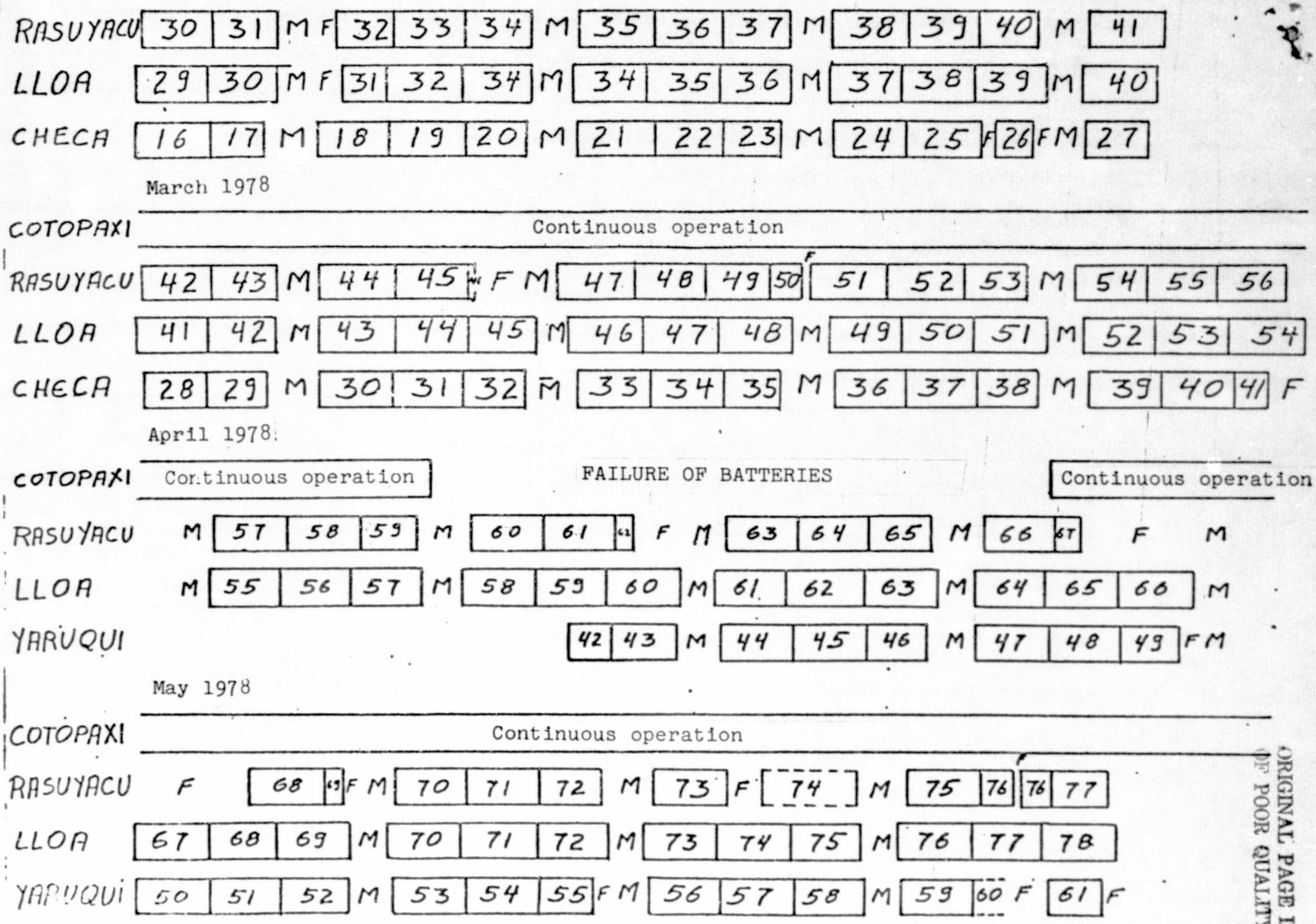
RASUYACU 30 31 M F 32 33 34 M 35 36 37 M 38 39 40 M 41
LLOA 29 30 M F 31 32 34 M 34 35 36 M 37 38 39 M 40
CHECA 16 17 M 18 19 20 M 21 22 23 M 24 25 F 26 F M 27
March 1978
COTOPAXI
Continuous operation
RASUYACU 42 43 M 44 45 F M 47 48 49 50 F 51 52 53 M 54 55 56
LLOA 41 42 M 43 44 45 M 46 47 48 M 49 50 51 M 52 53 54
CHECA 28 29 M 30 31 32 M 33 34 35 M 36 37 38 M 39 40 41 F
April 1978
COTOPAXI
Continuous operation
FAILURE OF BATTERIES
Continuous operation
RASUYACU M 57 58 59 M 60 61 62 F M 63 64 65 M 66 67 F M
LLOA M 55 56 57 M 58 59 60 M 61 62 63 M 64 65 66 M
YARUQUI 42 43 M 44 45 46 M 47 48 49 F M
May 1978
COTOPAXI
Continuous operation
RASUYACU F 68 69 F M 70 71 72 M 73 F 74 M 75 76 76 77
LLOA 67 68 69 M 70 71 72 M 73 74 75 M 76 77 78
YARUQUI 50 51 52 M 53 54 55 F M 56 57 58 M 59 60 F 61 F

Fig. 2