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1943

U. S. DEPARTMENT OF COMMERCE
JESSE H. JONES, Secretary

COAST AND GEODETIC SURVEY
LEO OTIS COLBERT, Director

Special Publication No. 233

# GRAVITY OBSERVATIONS IN PERU AND COLOMBIA

by
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and
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WASHINGTON : 1943

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# GRAVITY OBSERVATIONS IN PERU AND COLOMBIA

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## INTRODUCTION

Early in 1939, in accordance with a policy of cooperation with the other American Republics, the U. S. Coast and Geodetic Survey, through the Department of State, began correspondence with several of the American countries concerning determinations of the intensity of gravity. It was found that isolated surveys from assumed bases had been made in the process of geophysical exploration but there were no well established bases on the International Datum.

The Governments of Peru and Colombia indicated a desire to have a number of basic gravity stations established throughout their respective territories. In both countries the importance of gravity surveys was recognized not only for their geophysical value and their contribution to the determination of the figure of the earth but also in connection with studies of the relationship between intensities of gravity and deflections of the vertical. Large variations of the deflection in comparatively short distances occur in both countries, making them ideal locations for a study of this relationship.

Owing to the large amount of work required in preparing for the observations, including the design and construction of several instruments, the project was not initiated until early in 1941. In February

1941, Lt. Carl I. Aslakson of the U. S. Coast and Geodetic Survey, accompanied by Philip T. Hansen, Principal Scientific Aid, arrived in Lima, Peru, with the shipment of instruments.

## INSTRUMENTS

The gravity instruments used were the standard Brown pendulum apparatus of the U. S. Coast and Geodetic Survey. Two separate

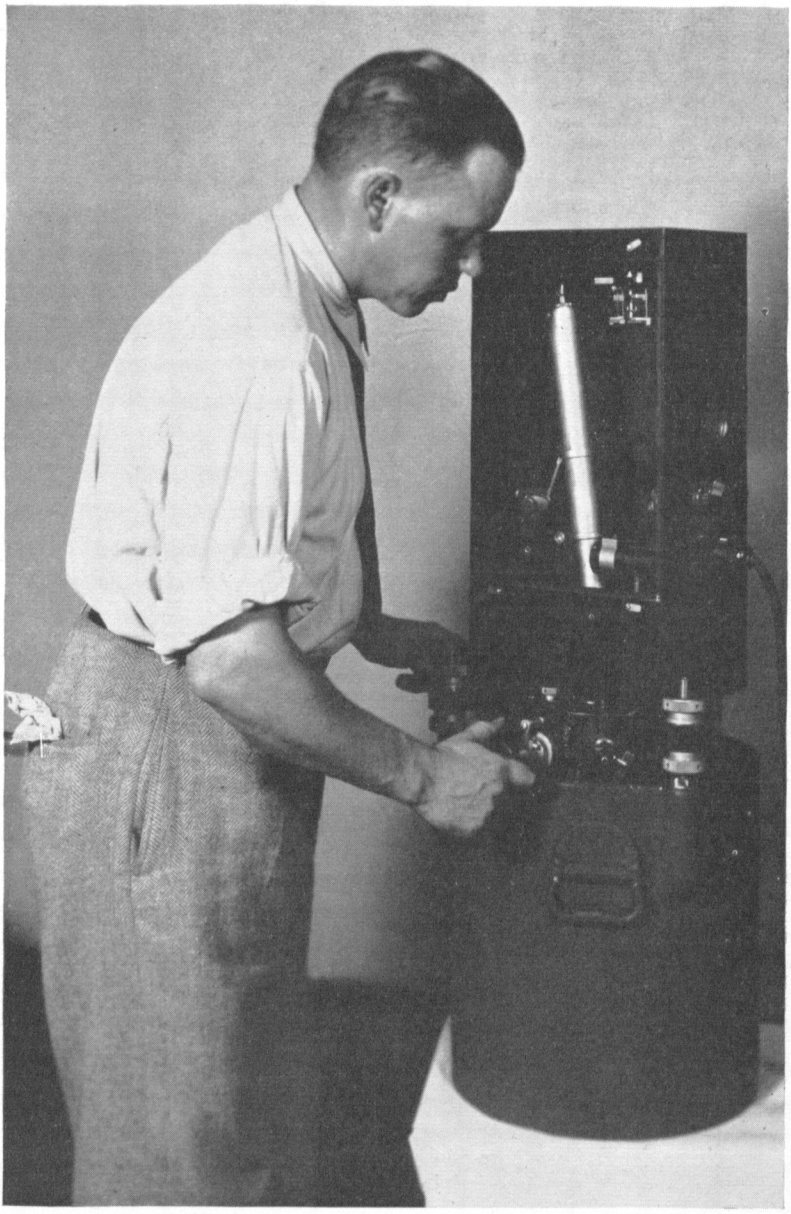

FIGURE 1.—Brown gravity apparatus.

instruments were used for simultaneous observations at each station in order to insure the integrity of the results.

The Brown pendulum apparatus makes use of the standard invar quarter-meter pendulum of the U. S. Coast and Geodetic Survey which

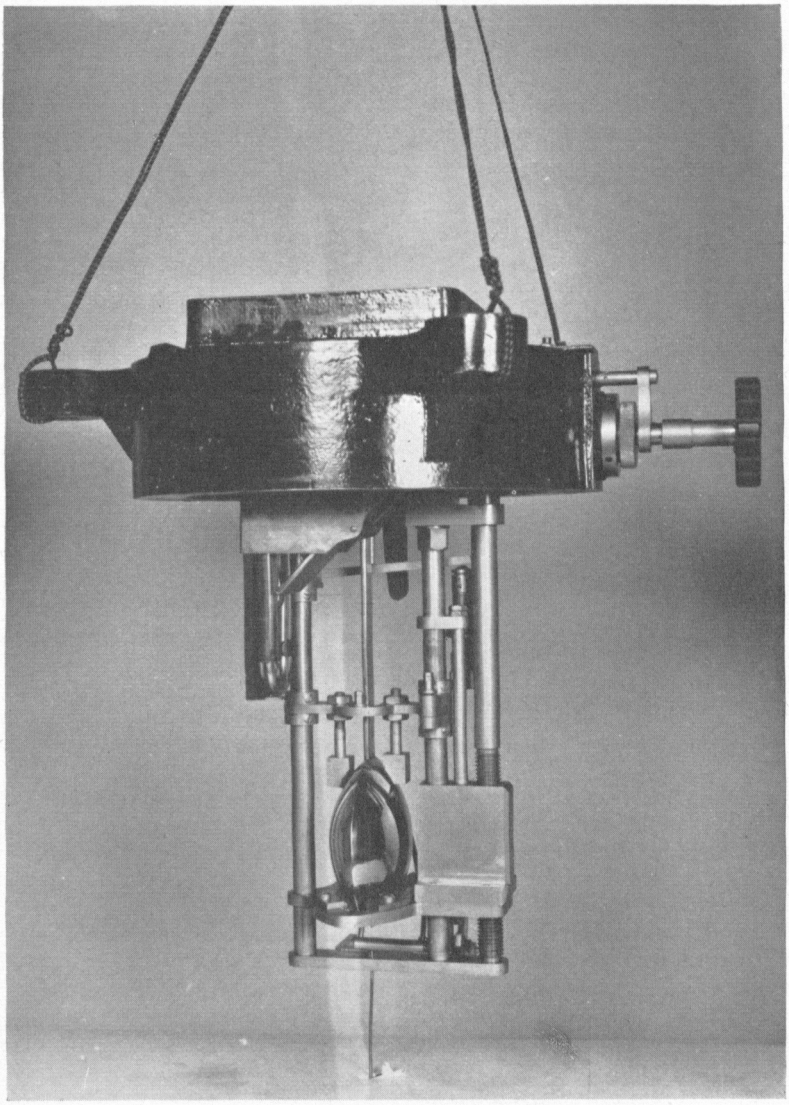

FIGURE 2.—Inside of pendulum case.

is swung in an evacuated chamber. The pendulums have knife edges of agate and they swing on agate planes. The essential pieces of equipment required with this apparatus are the following:

Pendulum apparatus.
Photoelectric amplifier.
Power amplifier.
Chronograph.
Radio receiver.

The apparatus functions by registering the pendulum beats and the mean-time seconds of the U. S. Naval Observatory time signals simultaneously on the same chronograph record. The pendulum beats are picked up by a photoelectric cell and amplified sufficiently to operate a chronograph pen through a relay, and the time signals are received by the radio and amplified sufficiently to operate a second chronograph pen. The two pens are adjusted to follow the same track when not recording, and one makes jogs to the left and the other to the right when recording the impulses through the relays. By means of a micrometer-microscope system the chronograph records can be scaled to 1/1000 of a second.

The duration of the observations is 6 hours. An exact determination of the number of beats during this interval of time is obtained, and the time interval is determined with an error probably well under 0.005 second. The time signals of the U. S. Naval Observatory as transmitted by the Annapolis naval radio station are used as time control for this interval.

Corrections for temperature, pressure, and amplitude of oscillation are applied to the periods of the pendulums as thus derived. A correction for the elastic yielding of the support caused by the movement of the pendulum is also applied. The amount of this movement is read in units of the wave length of monochromatic light by means of a specially designed interferometer.

Because of the lack of uniformity of voltages in the power supplies of the different cities concerned, it was necessary to design the instruments to operate from batteries. The battery drain was fairly heavy, and it was found necessary to use a charging unit driven by gasoline motor to charge the batteries in the field rather than to rely on charging them at commercial establishments.

## GRAVITY OBSERVATIONS IN PERU

### PERSONNEL

In Peru the Servicio Geográfico del Ejército, a division of the Ministerio de Guerra, was designated by the Peruvian Government to cooperate in the determination of the gravity stations and a commission was appointed. Col. B. Vallenas, Director of the Servicio, was appointed President of the Commission. The other Peruvian representatives were Dr. Alfred Rosenblatt, Professor of Geodesy and Geophysics, San Marcos University, Lima, and Dr. Carlos Basadre, Professor of Geodesy in the Engineer's School in Lima.

In addition, Dr. J. A. Broggi, Director of Mines and Petroleum of the Ministerio de Fomento, although not a member of the Commission, naturally had great interest in the work and assisted the Commission in many ways.

Colonel Vallenas appointed two officers, Capt. José San Miguel and Capt. Manuel Llanos, to accompany and work with the party while in the vicinity of Lima. When the party left Lima, Captain Llanos was detached but Captain San Miguel remained with the party during the entire project in Peru.

### ORGANIZATION OF THE SURVEYS

During the latter part of February 1941, the organizational work was completed in Lima. In addition to Captain San Miguel and Captain Llanos as aides, five soldiers were detailed to assist with the work. One 1½-ton truck was furnished for transportation of the instruments and a new station wagon (camioneta) was purchased for the transportation of the officers and members of the Commission.

### ESTABLISHMENT OF BASE STATION

The first site selected for the principal base station in Peru was at Conchan, the site of a base triangulation station about 35 kilometers south of Lima. The equipment was set up at that site, and observations were attempted. However, much difficulty was experienced here which finally caused the abandonment of this location. The instruments had been handled roughly during shipment, and this necessitated extensive repairs which were difficult to make at Conchan because of dusty conditions and the presence of many mosquitoes. High humidity had also caused a number of short circuits in transformers and coils. Furthermore, radio reception was very poor at Conchan.

The necessary repairs and adjustments were completed at the Servicio de Trasmisiones, an Army post in the northern edge of Lima, and the base gravity station was established at that point. The repairs, occupation of the station, transportation difficulties, and preparation of the plans for the expedition into other parts of the country required a month's time and it was not until the early part of April that the party finally left Lima. By that time the numerous roads blocked by landslides in February and March had for the most part been reopened and the roads were in fair condition.

### ITINERARY OF THE GRAVITY COMMISSION

During April, May, and the early part of June, 10 additional gravity stations were established in Peru. These stations were located near the following cities and towns, except the last 2 which are at triangulation stations:

| | |
|---|---|
| Piura. | Tacna. |
| Trujillo. | Juliaca. |
| Huarás. | Anta. |
| Ica. | San Jerónimo north base. |
| Chala. | San Jerónimo south base. |

An excellent geographic distribution of stations was secured, ranging over 13° of latitude and 10° of longitude.

All travel was by road. Considering the tremendous difficulties of road building in this region, the roads were excellent. Grades were necessarily steep in the mountains, but in general the construction had been well engineered. The incomparable scenery of the Andes and the historical background of many of the cities were greatly enjoyed by the North American members of the Commission.

The sites of the stations were usually in public buildings, such as cuartels, or municipal or government buildings. This assured greater

permanency and care of the station site. All public officials were extremely kind and helpful in the selection of the station sites and in providing the necessary amount of space, electric current, and assistance in installing the equipment. Captain San Miguel was very efficient in making the necessary contacts in selecting the station locations, and the excellent progress of the party was largely due to his efforts.

While at station Anta, near Cuzco, mechanical difficulties were encountered, requiring a return to Lima for repairs. After completion of repairs, several reobservations were made at Lima, and the party then returned to the field and established the two San Jerónimo base stations. Early in June the party returned to Lima and the final reobservations were made at the Lima base.

During the latter part of June, the party packed and shipped the instruments and left for Colombia.

The full and complete cooperation of the Peruvian War Ministry, of Col. B. Vallenas, Director of the Servicio Geográfico de Ejército, and of the officials of the United States Embassy was of prime importance in the successful completion of the observations.

## GRAVITY OBSERVATIONS IN COLOMBIA

### PERSONNEL

The gravity work in Colombia was executed in cooperation with the Instituto Geográfico Militar y Catastral, a division of the Ministerio de Hacienda. The Director of the Instituto Geográfico, Dr. Hernando Posada Cuellar, designated a commission composed of the following scientists and engineers to collaborate with the North American members:

Dr. Darío Rozo M., Chief of the Section of Geophysics of the Instituto Geográfico
Dr. Thomas Aparicio V., Engineer, Instituto Geográfico
Captain Gerardo Cabrera A., Engineer, attached to the Instituto Geográfico as a geodesist.

The efficient manner in which all preliminary arrangements had been made by Dr. Posada Cuellar and the members of the Colombian Commission greatly expedited the observations. Lieutenant Aslakson arrived at Bogotá by airplane on June 21, 1941, and found that all arrangements for free custom entry of the instruments had been completed, and that Dr. Rozo, Dr. Aparicio, and Captain Cabrera had departed for Buenaventura to meet the S. S. *Santa Elena* on which Mr. Hansen and the shipment of instruments were arriving. A tentative schedule of stations was discussed with Dr. Posada Cuellar, and Lieutenant Aslakson then proceeded to Buenaventura.

The instruments arrived at Buenaventura in the afternoon of June 23, and the first observation was begun there on the morning of June 28, as the customs entry, unpacking and assembling of instruments, and the selection of the station site required only 4 days.

### COLOMBIAN BASE STATIONS

It was planned to establish two primary base stations in Colombia. One was desired at Bogotá, the capital city, and another at the port

of entry, Buenaventura, in order that standardization observations could be made immediately after disembarking and just before reembarking. Later, however, it was found advantageous to reobserve also at Cali, thus furnishing a third primary base in Colombia.

### ITINERARY OF THE GRAVITY COMMISSION

At the outset, plans were made for the party to leave Colombia about the first of September. The tentative selection of stations most desired included the following cities:

Buenaventura.
Cali.
Popayán.
Bogotá.
Bucaramanga.
Barranquilla.

It was decided to establish stations at these points and later, if more time were available, to improve the distribution by intermediate stations. Since the methods of transportation in Colombia included trucks and automobiles, railroads, busses, and river boats, it was impossible to make definite fixed schedules. For instance, the time of the river-boat trip to Barranquilla depended to a large extent on the amount of water in the river at the time, because at low stages of the river these vessels require many more days to negotiate the journey than when there is an abundance of water.

The varying methods of transportation presented further difficulties in the handling of the instruments. To dismantle, box, and address all instruments after the completion of each station would have required more than half the allowable time available for the work. However, Dr. Rozo and Captain Cabrera made arrangements with the railroads, trucking companies, and river steamers to load the equipment without boxing or tagging and under the personal supervision of the Commission members, and never to unload the equipment without the same supervision. In all cases, all companies concerned carefully complied with these requests. This arrangement proved very valuable in that it enabled the party to establish many more stations than were originally planned.

By August 20, 16 observations had been made at 9 stations. The order in which these stations were observed and the number of observations at each station are shown below:

| | *Observations* |
|---|---|
| Buenaventura | 4 |
| Popayán | 1 |
| Cali | 1 |
| Bogotá | 3 |
| Bucaramanga | 1 |
| Barranquilla | 1 |
| Medellin | 1 |
| Bogotá (reobservation) | 1 |
| Ibagué | 1 |
| Armenia | 1 |
| Cali (reobservation) | 1 |

At Cali, a cablegram from the U. S. Coast and Geodetic Survey was received authorizing the party to remain an additional month in Colombia to establish additional stations requested by the Colombian Commission.

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By September 25, the following stations were established or reoccupied:

| | *Observations* |
|---|---|
| Pasto | 1 |
| Ipiales | 1 |
| Villavicencio | 1 |
| Puerto Lopez | 1 |
| Bogotá (reobservation) | 2 |
| Buenaventura (reobservation) | 3 |

The complete Colombian program, therefore, included 13 stations, with principal bases at Buenaventura and Bogotá and a secondary base at Cali. This was exceptional progress considering the fact that the establishment of one station, that at Barranquilla, required 15 days owing to the length of time needed for the voyages up and down the Magdalena River by steamer. This fine progress can be attributed to the rapid and efficient manner in which either Captain Cabrera or Dr. Rozo always completed the travel arrangements for each station and the rapidity with which the station sites were selected. Officials of the United States Embassy were also of great assistance to the Commission.

Stations were located in public buildings such as cuartels, universities, post offices, or other government buildings. Invariably the authorities were exceedingly courteous and cooperative. For example, in two instances where stations were located in post offices, the telegraph instruments were stopped during the radio reception of the time signal to prevent interference.

The beautiful and varied scenery, the kindness and courtesy of the Colombian people, and the pleasant association with the members of the Colombian Gravity Commission and of the Instituto Geográfico Militar y Catastral made a lasting impression upon the North American members of the Commission.

On September 29, the boxing of the instruments was completed and the party embarked on the S. S. *Santa Elena* for New York on October 1, 1941.

## GRAVITY RESULTS

The results obtained at the 24 gravity stations in Peru and Colombia which were determined during the expedition are given in the following table of "Principal facts for gravity stations." Included in the table are the various corrections which were derived to take account of the elevation of each station and to allow for the gravimetric effect of mountain masses, isostatic compensation, and other irregularities in the attraction of the earth. In the last 6 columns of the table are various kinds of anomalies based on different theoretical assumptions regarding equilibrium conditions in the so-called crust of the earth. A brief explanation of the anomalies will be found on page 13.

## *Principal facts for gravity stations (Potsdam system)* [1] [2]

[Base value at Washington, Commerce Building, 1933 determination, is 980.118] International formula, $\gamma_o = 978.049\,[1 + 0.0052884 \sin^2\phi - 0.0000059 \sin^2 2\phi]$ gals

| Station | Latitude $\phi$ | Longitude $\lambda$ | Elevation $h$ | Observed gravity $g$ | Theoretical gravity $\gamma_o$ | Correction to theoretical gravity for— Elevation | Topography to Zone O | Indirect effect | Topography and Compensation: Depth 56.9 km. | Depth 96 km. | Depth 113.7 km. | Anomaly: Free-air $g-\gamma$ | Bouguer $g-\gamma'$ | Isostatic (Pratt-Hayford): Indirect $g-\gamma_{ci}$ | Depth 56.9 km. $g-\gamma_c$ | Depth 96 km. $g-\gamma_c$ | Depth 113.7 km. $g-\gamma_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ° ′ | ° ′ | *Meters* | *Gals* | *Gals* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* | *Gal* |
| ***Peru*** | | | | | | | | | | | | | | | | | |
| Lima, Servicio de Transmissiones | −12 01.1 | 77 02.3 | 143.6 | 978.289 | 978.2723 | −.0443 | +.0109 | −.0036 | −.0429 | −.0420 | −.0398 | +.061 | +.050 | +.107 | +.104 | +.103 | +.101 |
| Piura | −5 11.9 | 80 38.1 | 35.3 | 978.084 | 978.0913 | −.0109 | +.0040 | −.0028 | +.0057 | +.0145 | +.0186 | +.004 | .000 | −.008 | −.002 | −.011 | −.015 |
| Trujillo | −8 07.0 | 79 02.3 | 29.4 | 978.095 | 978.1517 | −.0091 | +.0007 | −.0035 | −.0494 | −.0475 | −.0447 | −.048 | −.048 | +.003 | +.002 | .000 | −.003 |
| Huarás | −9 31.9 | 77 32.1 | 3071 | 977.228 | 978.1902 | −.9476 | +.3320 | −.0072 | +.0141 | +.0691 | +.0889 | −.015 | −.347 | −.076 | −.029 | −.084 | −1.04 |
| Ica | −14 04.6 | 75 30.2 | 405.9 | 978.238 | 978.3537 | −.1253 | +.0442 | −.0040 | −.0297 | −.0264 | −.0234 | +.010 | −.035 | +.040 | +.039 | +.036 | +.033 |
| Chala | −15 49.0 | 74 18.5 | 14.0 | 978.452 | 978.4317 | −.0043 | −.0024 | −.0032 | −.0203 | −.0143 | −.0119 | +.025 | +.027 | +.042 | +.045 | +.039 | +.036 |
| Tacna | −18 01.0 | 70 15.0 | 557.1 | 978.298 | 978.5418 | −.1720 | +.0567 | −.0050 | −.0791 | −.0842 | −.0835 | −.072 | −.128 | +.017 | +.007 | +.012 | +.012 |
| Juliaca | −15 30.0 | 70 06.9 | 3825.2 | 977.325 | 978.4169 | −1.1800 | +.4286 | −.0083 | +.0229 | +.0522 | +.0656 | +.088 | −.340 | +.044 | +.065 | +.036 | +.022 |
| Anta | −13 28.6 | 72 09.1 | 3421.9 | 977.339 | 978.3237 | −1.0556 | +.3790 | −.0077 | +.0152 | +.0526 | +.0668 | +.066 | −.313 | +.021 | +.051 | +.013 | −.001 |
| San Jerónimo, north base | −11 56.6 | 75 18.7 | 3245 | 977.285 | 978.2696 | −1.0011 | +.3593 | −.0076 | +.0204 | +.0648 | +.0819 | +.016 | −.343 | −.041 | −.004 | −.048 | −.065 |
| San Jerónimo, south base | −12 00.6 | 75 14.3 | 3248 | 977.288 | 978.2720 | −1.0021 | +.3594 | −.0076 | +.0257 | +.0686 | +.0849 | +.018 | −.341 | −.043 | −.008 | −.050 | −.067 |
| ***Colombia*** | | | | | | | | | | | | | | | | | |
| Buenaventura | 3 53.9 | 77 04.7 | 5.1 | 977.998 | 978.0728 | −.0016 | +.0003 | −.0033 | −.0245 | −.0234 | −.0220 | −.073 | −.074 | −.046 | −.049 | −.050 | −.051 |
| Popayán | 2 26.5 | 76 36.0 | 1757.7 | 977.602 | 978.0584 | −.5425 | +.1950 | −.0055 | +.0040 | +.0313 | +.0413 | +.086 | −.109 | +.060 | +.082 | +.055 | +.045 |
| Cali | 3 27.5 | 76 31.1 | 996 | 977.861 | 978.0677 | −.3074 | +.1104 | −.0046 | −.0107 | +.0027 | +.0085 | +.101 | −.010 | +.103 | +.111 | +.098 | +.092 |
| Bogotá | 4 38.5 | 74 03.9 | 2591.8 | 977.404 | 978.0827 | −.7998 | +.2853 | −.0058 | +.0604 | +.0954 | +.1075 | +.121 | −.164 | +.032 | +.061 | +.026 | +.014 |
| Bucaramanga | 7 08.5 | 73 07.8 | 1117 | 977.820 | 978.1286 | −.3448 | +.1214 | −.0045 | −.0077 | +.0062 | +.0119 | +.036 | −.085 | +.034 | +.044 | +.030 | +.024 |
| Barranquilla | 11 01.0 | 74 47.8 | 28.5 | 978.245 | 978.2371 | −.0088 | +.0033 | −.0023 | +.0384 | +.0511 | +.0554 | +.017 | +.013 | −.032 | −.022 | −.034 | −.039 |
| Medellín | 6 14.9 | 75 33.6 | 1497.5 | 977.753 | 978.1100 | −.4623 | +.1658 | −.0049 | +.0072 | +.0336 | +.0432 | +.105 | −.060 | +.077 | +.098 | +.072 | +.062 |
| Ibagué | 4 26.4 | 75 14.0 | 1252 | 977.715 | 978.0799 | −.3865 | +.1280 | −.0052 | −.0493 | −.0286 | −.0208 | +.022 | −.106 | +.055 | +.071 | +.050 | +.042 |
| Armenia | 4 31.9 | 75 41.0 | 1514 | 977.732 | 978.0812 | −.4673 | +.1668 | −.0052 | −.0099 | +.0122 | +.0208 | +.118 | −.049 | +.111 | +.128 | +.106 | +.097 |
| Pasto | 1 13.2 | 77 16.9 | 2592 | 977.386 | 978.0513 | −.7998 | +.2863 | −.0058 | +.0750 | +.1135 | +.1267 | +.134 | −.152 | +.027 | +.060 | +.021 | +.008 |
| Ipiales | 0 49.5 | 77 38.3 | 2890 | 977.252 | 978.0500 | −.8917 | +.3207 | −.0063 | +.0822 | +.1267 | +.1418 | +.094 | −.227 | −.027 | +.012 | −.033 | −.048 |
| Villavicencio | 4 08.8 | 73 37.3 | 495 | 977.860 | 978.0760 | −.1528 | +.0519 | −.0042 | −.0516 | −.0483 | −.0457 | −.063 | −.115 | −.011 | −.012 | −.015 | −.018 |
| Puerto Lopez | 4 05.2 | 72 56.9 | 216 | 978.002 | 978.0751 | −.0667 | +.0244 | −.0033 | −.0201 | −.0250 | −.0259 | −.006 | −.031 | +.022 | +.014 | +.019 | +.020 |
| Mean with regard to sign | | | | | | | | | | | | +.035 | −.124 | +.021 | +.036 | +.016 | +.008 |
| Mean without regard to sign | | | | | | | | | | | | .058 | .132 | .045 | .047 | .043 | .042 |
| Maximum anomaly | | | | | | | | | | | | +.134 | −.347 | +.111 | +.128 | +.106 | −.104 |

[1] Chief of party—C. I. Aslakson.

[2] Year—1941.

## EXPLANATION OF TABLE OF PRINCIPAL FACTS FOR GRAVITY STATIONS

The first three columns of the table are self-explanatory. The elevations in the fourth column are given to tenths of meters wherever the available data seemed to justify this degree of accuracy. Those given in meters only are more uncertain and may be in error from one to several meters in some cases.

The observed values in the fifth column are on the Potsdam Datum. They are referred to the Washington base station located in the basement of the Department of Commerce Building, Washington, D. C., where the gravity value is 980.118 gals as determined in 1933 by connection with Potsdam, Germany, the world base station.

The theoretical values of gravity in the sixth column are based on the International formula, which is as follows:

$$\gamma_0 = 978.049\ [1 + 0.0052884 \sin^2 \phi - 0.0000059 \sin^2 2\phi]$$

in which $\phi$ is the latitude of the station. A table of gravity values for different latitudes computed by this formula will be found in Bulletin Géodésique No. 32.[1]

The next six columns, Nos. 7 to 12, contain the various corrections, one or more of which are applied to the theoretical value of gravity at sea level to obtain the computed value of gravity at the location of the station under various assumptions regarding the effects of topography and compensation.

The elevation correction in the seventh column is obtained by means of the following formula:

$$\text{Elevation correction} = -(0.00030855 + 0.00000022 \cos 2\phi)h + 0.000072\left(\frac{h}{1000}\right)^2$$

where $\phi$ is the latitude of the station and $h$ its elevation in meters. The second-order terms in this formula are appreciable only for stations in high altitudes. Where needed, they are readily computed by means of a special nomogram. Copies of this nomogram can be obtained by addressing the Director, Coast and Geodetic Survey, Washington, D. C.

The correction for topography to Zone O, given in the eighth column, is used in computing the Bouguer anomaly. The computation of this correction is part of the computations involved in deriving the isostatic anomaly and therefore requires no additional work after the isostatic reductions have been made. Very briefly, the Bouguer topography effect is obtained by computing first the effect of a slab of average surface rock (density 2.67) equal in thickness to the elevation of the station and extending out to the outer limit of Zone O (radius=166.7 km) of the Hayford reduction tables. A small correction is applied to the value thus derived to take account of the curvature of the sea level surface of the earth and another correction, considerably larger in rugged topography, to take account of the departure of the actual topography from the plane through the station.[2]

---

[1] Walter D. Lambert and F. W. Darling. Tables for theoretical gravity according to the new international formula. Bull. Géodésique No. 32, 1931, pp. 327–340.

[2] This method is a modification of the Hayford isostatic reduction method, first used by Dr. E. C. Bullard of Cambridge, England. See Gravity determinations in East Africa by E. C. Bullard, Phil. Trans., R. Soc. of London, Series A, No. 757, vol. 235, pp. 487–491. Convenient tables for computing the topographic effect to Zone O are given in Spec. Pub. No. 232 of the U. S. Coast and Geodetic Survey, pp. 67 and 68.

The correction for "indirect effect" in the ninth column is a small correction to take account of the attraction of the material included between the geoid and spheroid.[3] It forms a part of the isostatic reductions of gravity results. It may be explained briefly as follows: All elevations of the surface of the earth, as determined by leveling or other means, are necessarily referred to the geoid or sea-level surface. All topographic effects computed for the isostatic reduction of gravity determinations, therefore, include topographic masses between the geoid and the surface of the earth. The formula for theoretical gravity, however, is based on a mathematical spheroid. It must therefore be corrected for the effect of masses included between spheroid and geoid, as well as for topography and compensation, to obtain a computed value of gravity comparable with the actual observed value.

The next three columns, the tenth to the twelfth, contain the corrections for topography and compensation on the Pratt-Hayford hypothesis for three different depths of isostatic compensation.[4] The correction for the depth of 113.7 km is the one first derived by direct computation. Factors are then used to obtain the corrections for the other depths.[5]

The accuracy with which the corrections for topography and for compensation are derived for each station, especially for the zones within 100 or 150 km of the station, depend upon the availability of detailed topographic (contoured) maps and upon their accuracy. For a large part of the stations included in this publication, fairly adequate maps were available. For the remaining stations, new computations should be made as soon as better detailed maps are published.

## ANOMALIES

The last six columns of the table contain the anomalies derived by the different methods of computation or by using different depths of isostatic compensation. The free-air anomaly given in column 13 is the one most easily obtained. The theoretical value of gravity at sea level is simply corrected for the elevation of the station, and then the difference is taken between the observed value of gravity and this corrected theoretical value. No correction is applied for topography or for isostatic compensation. The free-air method may therefore be considered as based on the assumption that the effects of topography and compensation exactly balance each other. In low flat topography, it will give anomalies practically as small as the isostatic method but, in high topography, free-air anomalies are larger than the isostatic, and are ordinarily positive if the station is above the general level of the surrounding topography and have a tendency to be negative if the station is below the general level. Six of the stations in the preceding table have positive free-air anomalies greater than 100 milligals.

The Bouguer anomaly in column 14 is obtained by applying two corrections to the theoretical value of gravity at sea level before comparing it with the observed value. One is the correction for elevation

[3] See Tables for determining the form of the geoid and its indirect effect on gravity, by Walter D. Lambert and Frederic W. Darling, U. S. Coast and Geodetic Survey Spec. Pub. No. 199.

[4] The methods used for these reductions are fundamentally those explained in U. S. Coast and Geodetic Survey Spec. Pub. No. 10, The effect of topography and isostatic compensation upon the intensity of gravity, by John F. Hayford and William Bowie. For a slight modification of this method, see footnote on p. 10.

[5] See U. S. Coast and Geodetic Survey Spec. Pub. No. 40, Investigations of gravity and isostasy, by William Bowie, pp. 97–99.

of station already explained and the other is the correction for the effect of topography included within the outer radius of Zone O (166.7 km). The method used for computing the topographic effect is explained briefly on page 10. Bouguer anomalies are used quite extensively in geophysical prospecting to find variations in underground structure over comparatively small local areas if the topography is not too rugged. One reason for their use in this class of work is that they can be computed rather easily if a high degree of precision is not needed. Over extended areas the Bouguer anomalies are quite closely related to the height of the topography and are ordinarily strongly negative for mountain stations. It will be noted that four of the high stations in Peru have negative anomalies of 340 milligals or greater.

The last four columns of the preceding table contain isostatic anomalies. The first one of the four columns includes the indirect effect or the effect of the material between geoid and spheroid. The other three do not. The anomalies in this column are based on a depth of compensation of 96 kilometers, since this is considered the best depth of compensation for isostatic reductions in the United States.

The remaining three columns contain the isostatic anomalies based on three different depths of compensation. The methods used in computing these anomalies are explained in U. S. Coast and Geodetic Survey Special Publication No. 10 except for minor changes and short cuts that have been devised from time to time since No. 10 was published. These changes are explained in Special Publication No. 232. In computing the anomalies, two corrections are applied to the theoretical value of gravity at sea level before comparing the theoretical value with the observed value. One is a correction for elevation of station (the same correction as used in computing the free-air and Bouguer anomalies) and the other is a correction for the effect of the topography of the whole world and of the isostatic compensation of that topography.

Too much space would be required to explain the isostatic method in detail in this publication. Some of the basic assumptions underlying the method should be kept in mind, however. The topography above sea level is assumed to have an average density of 2.67, and the negative topography of the ocean basins is taken as the difference between this and the density of sea water which is about 1.03. The compensation is assumed to be uniformly distributed vertically, down to the specified depth of compensation. The density of the material below sea level is taken simply as normal (without specification of actual density) except as this normal density is affected by the assumed compensation. In other words, the compensation is computed by itself as a positive or negative mass superimposed on the normal mass, and no attempt is made to evaluate the normal mass. The effects of all topography and compensation from the station to its antipodes are derived for each station although the distant effects, beyond 150 or 300 kilometers, can ordinarily be interpolated. For the stations here considered, interpolations could not be used until the map readings had been carried out to a much greater radius than 300 kilometers.

No attempt is made in computing the correction for topography and isostatic compensation to evaluate the effect of abnormal structure

in the topography immediately surrounding and underlying the station. At many stations the density of this material differs several percent from the value of 2.67 assumed in the computations. There are two principal reasons why these differences in density are not included in the computations. First is the lack of accurate information regarding the form and extent of the abnormal structure, and second is the difficulty of making the computations with adequate accuracy even when the extent and density of the structure is well enough known. It has seemed more logical to make the computations on a uniform basis throughout and assume that the resulting anomalies are indications of the structural conditions in the vicinity of the station except as these conditions may be partly caused in certain areas by a lack of complete isostatic adjustment.

## DISCUSSION OF ANOMALIES

The mean anomalies, with and without regard to sign, given at the foot of the table, are smallest for the isostatic method based on a depth of 113.7 km and largest for the Bouguer method. Except for the Bouguer anomalies, the average anomaly is positive in every case. If the density of the topography near the stations is reasonably close to the normal density of 2.67 used in the computations, the average positive anomaly in the last four columns could indicate that the area is somewhat under compensated, or else, that the depth of compensation is greater than that used in the computations. If the density of the topography near the stations is greater than the 2.67, the average positive anomaly could be expected from that cause alone.

The average anomalies for the last columns of the table seem to be definitely related to the depth of compensation. They decrease from +36 milligals for a depth of 56.9 km to +8 milligals for the standard depth of 113.7 km. The rate of change with depth would indicate that a depth of about 140 km would give an average anomaly close to zero. There are not enough stations, however, to make this estimate of depth very reliable, and in addition it may be seriously affected by lack of complete isostatic adjustment in this area. The seismic activity here indicates a possible lack of complete equilibrium.

In figure 3 are shown the locations of the stations with their isostatic anomalies based on a depth of compensation of 113.7 km. Equal anomaly lines have been sketched in. Here again the scarcity of stations is a serious limitation on the accuracy of the general conclusions. If there were more stations, the lines would undoubtedly look quite different. A few gravity-at-sea stations on either side of the Isthmus of Panama have been included in the illustration and also 3 old stations in Ecuador determined by a French expedition about 1900.

Some of the most impressive features of the gravity picture are: The strong gravity gradient between Lima and Huarás, the apparent negative trough extending from Lima to Panama, and the positive area in Colombia. Any attempt to account for these features will be left to interested geologists who have detailed information regarding the structural conditions in this area.

From the viewpoint of the geodesist, the important results accomplished by the present observations may be listed somewhat as follows in order of importance:

(1) Accurate base stations are now available in both countries on the accepted international datum and these may be used to coordinate any future gravity surveys in either country.

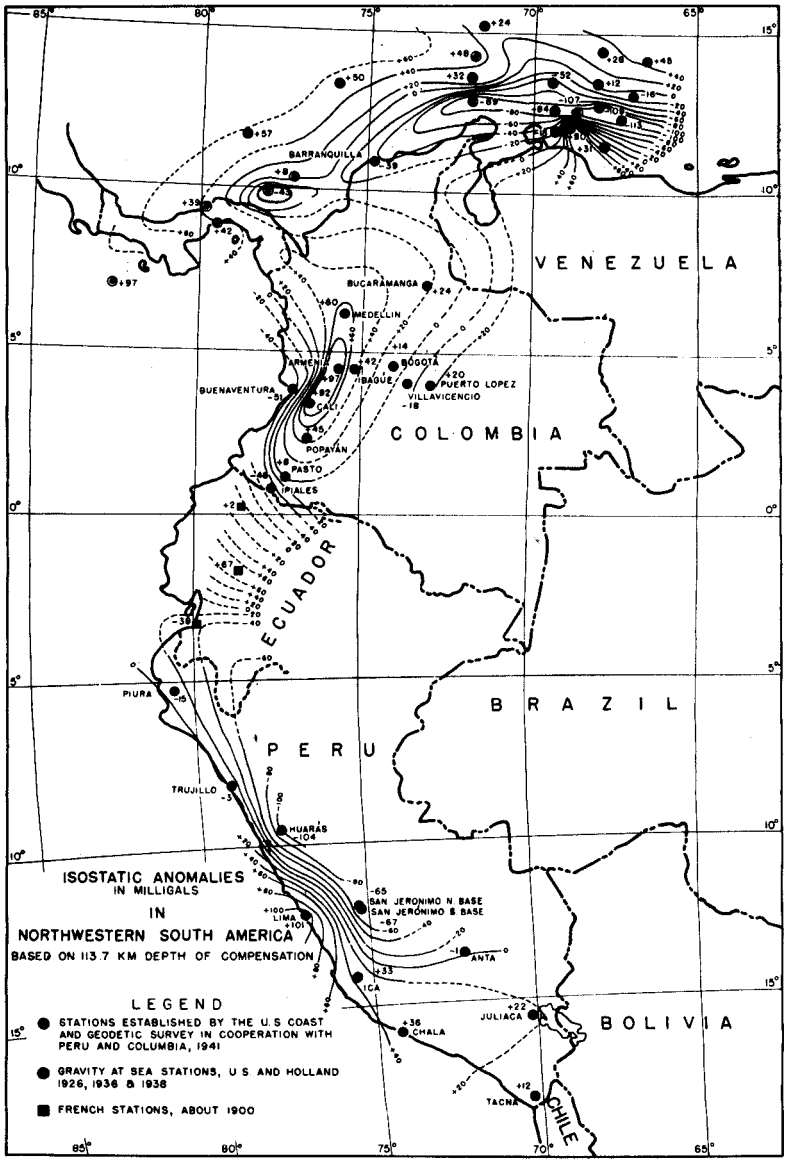


FIGURE 3.—Anomaly map.

(2) A generalized gravity picture of the area covered has been obtained. This picture tends to supplement the gravity-at-sea work already completed in the Caribbean Sea and west of Panama. Additional gravity stations in this area may now be placed where they

will be of the greatest effectiveness in bringing out the most important details of the gravity irregularities.

(3) It has been shown that the International Gravity Formula and the International Spheroid fit reasonably well in the equatorial belt of South America.

(4) Finally, the small beginning which has been made will, it is hoped, stimulate further work in this important area and will result in the near future in gravimetric and isostatic investigations of great scientific interest.

## DESCRIPTIONS OF STATIONS

The following descriptions are intended to make it possible to identify the locations of the stations after many years have elapsed. In reoccupying an old gravity station in order to connect other gravimetric surveys or for other reasons, it is not absolutely essential that the exact horizontal location be identified, but it is important that the redetermination be made at the same elevation. The relative importance of the horizontal and vertical coordinates of a gravity station is indicated by the rapidity of change of gravity with changes in the latitude and elevation. At latitude 2°, gravity varies about 0.1 milligal per minute of latitude, at latitude 4°, about 0.2 milligal per minute of latitude, and at latitude 10° about 0.5 milligal per minute. Gravity varies about 0.3 milligal per meter of elevation. In these low latitudes where the change of gravity with latitude is small, the gradient of the anomaly may be considerably larger than the latitude change, and therefore too much discrepancy in horizontal position should be avoided if possible.

### STATIONS IN PERU

**Lima,** Lima Department, Peru, Servicio de Transmisiones (C. I. Aslakson, March 1941).—Station is in the Communication School (of the Army), in the troop dining room, 9 meters from the east door and 3 meters from the south wall. The building is in poor condition due to earthquake cracks and the ceiling is shored up with timbers. The pendulum apparatus was set on the tile floor.

**Piura,** Piura Department, Peru (C. I. Aslakson, April 1941).—Station is in the rear of the Comandancia del Agrupamiento del Norte at 592 Calle Tacna, in a building owned by Lopez Albujar. To reach from Plaza de Armas, pass to rear of first patio, through passage on north side of Comandancia to second small patio in rear and then through door to third small patio. Station is in a small room about 2 by 4 meters in size on the north side of this patio, about 50 meters west and 10 meters north of the door which faces Plaza de Armas, and 1 meter from the north wall of the room. A small drafting room with arched portal adjoins this room on the east and a room, marked "mesa de Partes," is on the west. The pendulum apparatus was set on the tile floor.

**Trujillo,** Liberta Department, Peru (C. I. Aslakson, April 1941).—Station is in the southwest part of Trujillo, in the Trujillo Cuartel, 0.39 km southwest of the southwest corner of Plaza de Armas and 33 meters southeast of Calle Francisco Pizarro, in the southeast end of the officers' bar, 1 meter from the southeast wall. To reach from Trujillo Torre, go northwest 0.2 km and southwest 0.39 km. The pendulum apparatus was set on the tile floor.

**Huarás,** Ancachs Department, Peru (C. I. Aslakson, April 1941).—Station is in Huarás, in the Prefectura at 106 Calle 28 de Julio, in the room opening off the east side of the patio on the ground floor, in the southeast corner of the room, about 0.6 meter from the east wall and 1.6 meters from the south wall. It is 50 meters east and 120 meters south of triangulation station Catedrál Huarás. Pendulum apparatus was set on concrete floor which is not very solid. This station was undoubtedly destroyed by the landslide which occurred in November 1941.

**Ica,** Ica Department, Peru (C. I. Aslakson, April 1941).—Station is in Ica, in the Prefectura at 135 Calle Loreto, one-half square northwest of Iglesia San Francisco, and 230 meters west of the center of Plaza de Armas, in the north corner of the room which is immediately east of the rear or western one of the two patios in the building, 2 meters from the northeast and 2 meters from the northwest walls of the room. The pendulum apparatus was set on the tile floor.

**Chala,** Arequipa Department, Peru (C. I. Aslakson, April 1941).—Station is in Chala, a small port in Camana Province, in the new government tourist hotel, the largest building in town, a concrete structure not yet completed, just south of the Carretera Pan Americana and one-half block from Calle Comercio, in the northwest room, near the center of the north side of the room and about 0.6 meter from the north wall. The city water supply, a square concrete tank on a small rocky hill about 15 meters high, is about 40 meters northeast of the station. The pendulum apparatus was set on the tile floor.

**Tacna,** Tacna Department, Peru (C. I. Aslakson, May 1941).—Station is in Tacna, in the cuartel "de Husares de Junin No. 1" at 86 Calle 2 de Mayo, opposite its intersection with Calle Francisco Lazo, in the north corner of a small patio which is entered by the second door on the left from the main entrance to the cuartel, in the open about 2 meters from the northeast and 2 meters from the northwest walls. The Sala de Esgrima (fencing room) is on the northeast side of the patio. The station is 340 meters N. 46° W. (magnetic) from triangulation station Mastil Plaza. The pendulum apparatus was set on the concrete walk.

**Juliaca,** Puno Department, Peru (C. I. Aslakson, May 1941).—Station is in the southern part of Juliaca, Puna Province, in the Sala de Esgrima (fencing room) of the Casino de Oficiales, on the west side of the room, directly opposite the door and about 1 meter from the west wall. The pendulum apparatus was set on the tile floor.

**Anta,** Cuzco Department, Peru (C. I. Aslakson, May 1941).—Station is in Anta, on the summit of the hill, on the long porch or veranda of the Consejo Provincial de Anta, on the south side of Plaza de Armas, about 1½ meters from the west end of the porch. The church on the opposite side of the plaza is about 85 meters distant, N. 50° W. (magnetic). The pendulum apparatus was set on the concrete floor.

**San Jerónimo North Base,** Junin Department, Peru (C. I. Aslakson, May 1941).—Station is about 2.0 km west of the western edge of San Jerónimo, Province of Huancayo, 15 meters south of the center line of the Huancayo-Oroya Road, immediately south of the junction of the main road and the road leading straight into San Jerónimo and 30 meters east of a line of eucalyptus trees along a small irrigation ditch. Station is 7 meters south of a small rock cairn, 1 meter high, built beside the road and 441 meters from triangulation station San Jerónimo north base, 4½° to the left of the line to south base. The pendulum apparatus was set in the ground on plaster of Paris bases.

**San Jerónimo South Base,** Junin Department, Peru (C. I. Aslakson, May 1941).—Station is about 1.3 km southeast of the east side of the pueblo of Cajas, Province of Huancayo, 15 meters east of the center line of the road that leads north from the highway toward Cajas across a railroad parallel with the highway. The station is about 300 meters north of the intersection of the Cajas road and the railroad and 10 meters east of a rock cairn, 1 meter high, built beside the road. It is about 380 meters southwest of triangulation station San Jerónimo south base. The pendulum apparatus was set in the ground on plaster of Paris bases.

### STATIONS IN COLOMBIA

**Buenaventura,** Valle del Cauca Department, Colombia (C. I. Aslakson, June 1941).—Station is in the port of the same name, in a reinforced concrete structure along the extreme south side of the Mole which extends into the bay on an extensive system of concrete piling. The building contains a spacious central hall for use as the luggage room for the custom service. The station is in the central one of three rooms on the east side of the building, each about 5 meters square, for the reception of passengers, in the east corner of the hall about 1½ meters from each of the two nearer walls. The pendulum apparatus was set on the tile floor.

**Popaván,** Cauca Department, Colombia (C. I. Aslakson, July 1941).—Station is in Popayán in the Salón de Quimica (chemical laboratory) of the school of

industrial engineering of the University of Cauca. It is about 180 meters N. 90° E. (magnetic) from the cathedral, in the western corner of the room, about 1 meter from each of the two walls. The pendulum apparatus was set on the concrete floor.

**Cali,** Valle del Cauca Department, Colombia (C. I. Aslakson, July 1941).—Station is in the western part of Cali, in the residential section, in a building facing northwest which is used as the barracks of the infantry battalion "Pichincha." The north end of a prominent ridge is about 1.3 km N. 45° W. (magnetic) from the station and the other end of the same ridge is about 0.8 km N. 84° W. (magnetic). The station is in the large room opening onto the court at the north corner of the building, about 25 meters to the east of the main entrance and about 2 meters from the south or front wall of the room. The pendulum apparatus was set on the concrete floor.

**Bogotá,** Cundinamarca Department, Colombia (C. I. Aslakson, July 1941).—Station is in Bogotá at the Instituto Geográfico Militar y Catastral, in the easternmost building which extends north and south, faces west, and is used for clerical offices and warehouse. The station is in a small room at the extreme south end of the building, 7 meters from the principal entrance, in the southwest corner of the room. The pendulum apparatus was set on the tile floor.

**Bucaramanga,** Santander Department, Colombia (C. I. Aslakson, July 1941).—Station is in the northeastern part of the city, at the Cuartel Militar, in the officers' clubhouse beyond the westernmost building of the Cuartel. It is in the entrance hall below the principal staircase, 10 meters west of the entrance door and near the northwest corner of the hall. The pendulum apparatus was set on the tile floor.

**Barranquilla,** Bolivar Department, Colombia (C. I. Aslakson, July 1941).—Station is in the northern part of the seaport city of Barranquilla, in the officers' clubhouse of the Cuartel Militar, in the northeast corner of the spacious hall from which a staircase with two branches gives access to the second floor. The pendulum apparatus was set on the tile floor.

**Medellin,** Antioquia Department, Colombia (C. I. Aslakson, August 1941).—Station is in Medellin, in the three-story building which houses the University of Antioquia, near the main entrance and principal stairway with two branches leading to the patio. It is in the space left by the spread of the south branch, on the side toward the patio. The pendulum apparatus was set on the concrete floor.

**Ibagué,** Tolima Department, Colombia (C. I. Aslakson, August 1941).—Station is in Ibagué, at the Edificio Nacional which is at the west corner of the Plaza Bolivar. On the west side of this building and 35 meters from the corner there is a wide door which serves as the entrance to a garage and to a small patio. The station is beyond the garage, in the corridor of the patio, near the north wall and 150 meters N. 10° W. (magnetic) from the tower of the Cathedral. The pendulum apparatus was set on the tile floor.

**Armenia,** Caldas Department, Colombia (C. I. Aslakson, August 1941).—Station is in Armenia, which is on the western side of the great knob of Quindio opposite the city of Ibagué, in the extreme northeastern part of the town, in a new building which is used as a market and which occupies an entire square. It is in the northeast corner of the building, in the last hall along the southeast side, a rectangular room with a curved corner. The station is 480 meters in azimuth 10° from the geographic station Plaza, Armenia Survey. The pendulum apparatus was set on the concrete floor.

**Pasto,** Nariño Department, Colombia (C. I. Aslakson, August 1941).—Station is in Pasto near the center of the city and northwest of the principal plaza, the Plaza Nariño, in the building which houses the university. It is near the southeasternmost entrance, in the corridor below the staircase leading to the second floor, 9 meters from the axis of the hallway and 9 meters from the street. The pendulum apparatus was set on the tile floor.

**Ipiales,** Nariño Department, Colombia (C. I. Aslakson, August 1941).—Station is in Ipiales, which is near the boundary between Colombia and Ecuador, in a concrete building called "Edifiicio Nacional" and used for government offices, on the south side of the plaza "Veinte de Julio." It is 5 meters east of the east door of the principal entrance, below the stairway leading to the second floor and near the north wall. The station is 70 meters west of the church, Iglesia, which is a geographic station. The pendulum apparatus was set on the tile floor.

**Villavicencio,** Meta Department, Colombia (C. I. Aslakson, September 1941).—Station is in the village of Villavicencio, in room 12 of the hotel Meta on the east corner of Plaza Santander, 52 meters northeast of the northeast corner of the plaza, 3 meters northwest of the street curb along the southeast side of the hotel and 8 meters east of the east corner of the hotel patio. It is 115 meters east of the church, Iglesia Villavicencio, which is a geographic station. The pendulum apparatus was set on the concrete floor.

**Puerto Lopez,** Meta Department, Colombia (C. I. Aslakson, September 1941).—Station is in the village of Puerto Lopez, which is on the Metica River about 100 miles southeast of Bogotá, in a building owned by Mr. Solano and rented by the Texas Oil Co., 52 meters northwest of a square, white building which stands by itself on the bank of the river and which is adjacent to and south of the Government Salt Depository. The station is in the northwest corner of the building. The pendulum apparatus was set in plaster of Paris on the concrete floor.

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