U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

BOUGUER GRAVITY MAPS, ROCK PROPERTY DATA, AND PRINCIPAL FACTS FOR GRAVITY DATA COMPILED FOR THE ISLAND OF PUERTO RICO AND VICINITY

By

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CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The island of Puerto Rico is located in a tectonically complex region of the Caribbean arc (Fig. 1). The island has been the subject of several gravity studies (Bromery and Griscom, 1964; Griscom, 1972; Griscom and Rambo, 1970; Shurbet and Ewing, 1956) in order to determine crustal structure on a regional scale as well as to identify smaller structures that may be useful for mineral and energy resource assessment. In August 1990, the U.S. Geological Survey (USGS) conducted a gravity survey of the central part of the island in order to fill in large gaps in regional data coverage. The study was initiated because of a new interest in the mineral resource assessment of the island. This report incorporates the gravity stations collected in 1990 into a database of 3064 stations covering the entire island of Puerto Rico and part of the adjacent islands, between 17° 45' and 18° 35' north latitude and between 65° 10' and 67° 20' west longitude. All of the data have been reduced to the same datum. Terrain corrections were calculated using a digital elevation model; complete Bouguer anomalies were calulated using the 1967 ellipsoid formula (International Union of Geodesy and Geophysics, 1971).

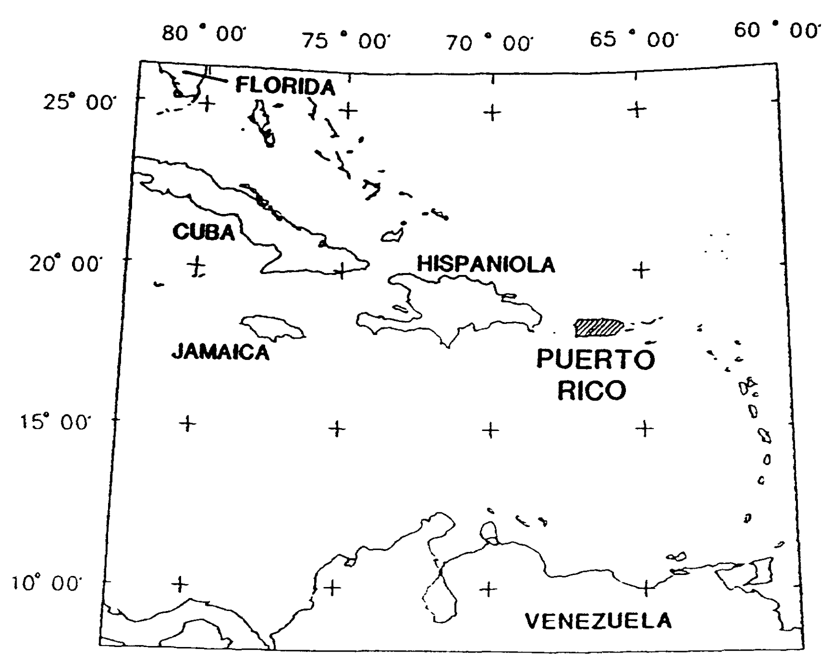


Figure 1. Index map for Puerto Rico and adjacent islands.

SOURCES OF DATA

Gravity stations included in this report have been grouped into 4 data sets according to the sources listed below. The Shurbet and Ewing gravity reconnaissance survey (1956) is not included here because most stations have been reoccupied. Stations having redundant gravity values or uncertain locations have also been excluded. Principal facts for each data source are listed on the diskette (see Appendix) and station location plots for each source are shown in Figures 2a-d.

1990 DATA: 282 stations, numbered PR001 to PR283, were collected in August 1990 by the USGS throughout central Puerto Rico. Lacoste-Romberg meter G-8n was used for all readings.

EAST COAST DATA: This data set includes 787 stations collected by the USGS from 1962 to 1972, and 12 stations, numbered USN01 to USN13, from a U.S. Naval Oceanographic Office unpublished manuscript (1963). Lacoste-Romberg meters were used. All of these data, except for 9 of the U.S. Naval stations, were previously published by Griscom (1972).

SOUTH COAST DATA: 665 previously published stations (Griscom and Rambo, 1970), collected by the USGS in 1963, are contained in this data set. A Lacoste-Romberg meter was used to collect approximately half of the stations and a Worden meter was used for closely-spaced road surveys.

OTHER USGS DATA: These data include 1318 stations collected by the USGS between 1962 and 1968 using both Lacoste-Romberg and Worden meters. 148 of these stations were discussed in a paper by Bromery and Griscom (1964). William L. Rambo collected much of these unpublished data as well as some of the East Coast data, and did most of the associated data processing, including the inner-zone terrain corrections.

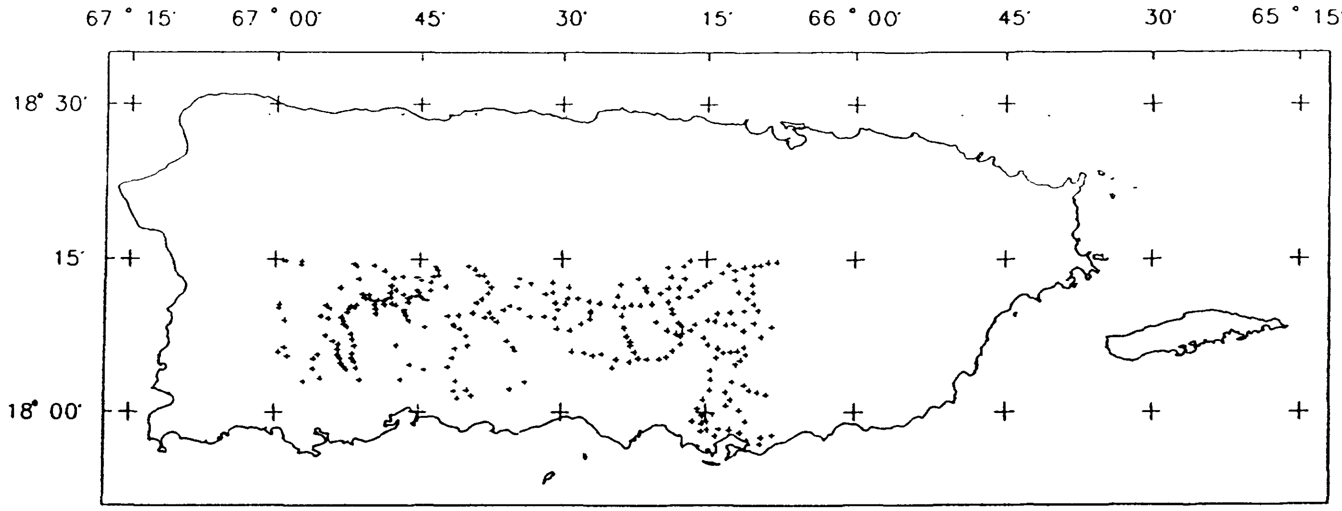


Figure 2a. Locations of gravity stations occupied by the USGS in 1990.

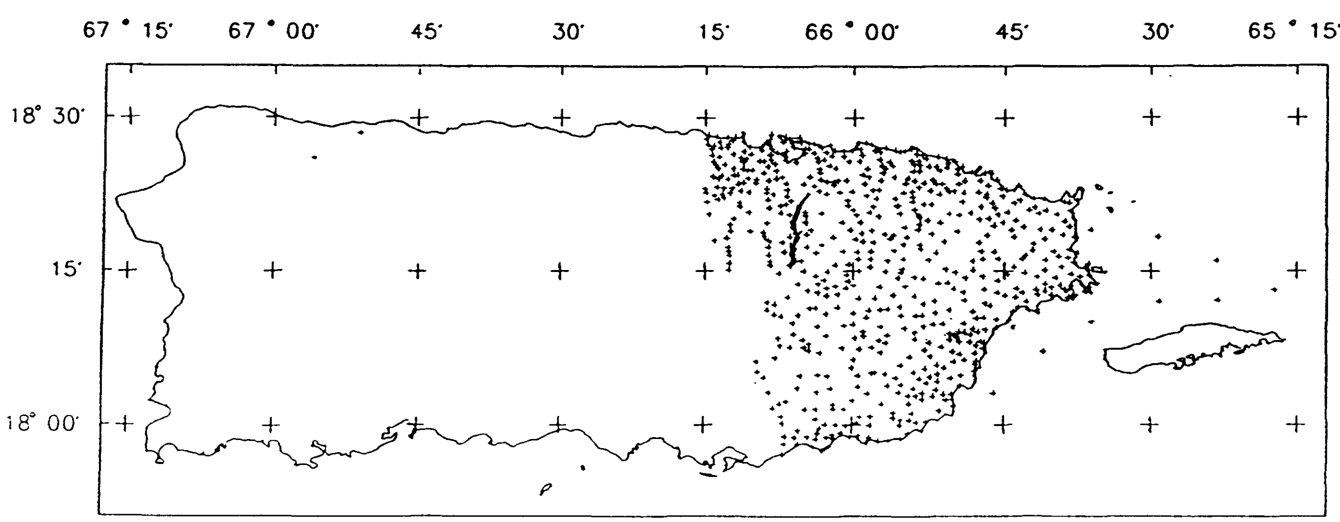


Figure 2b. Locations of East Coast gravity stations from Griscom (1972) and U.S. Naval Oceanographic Office (1963).

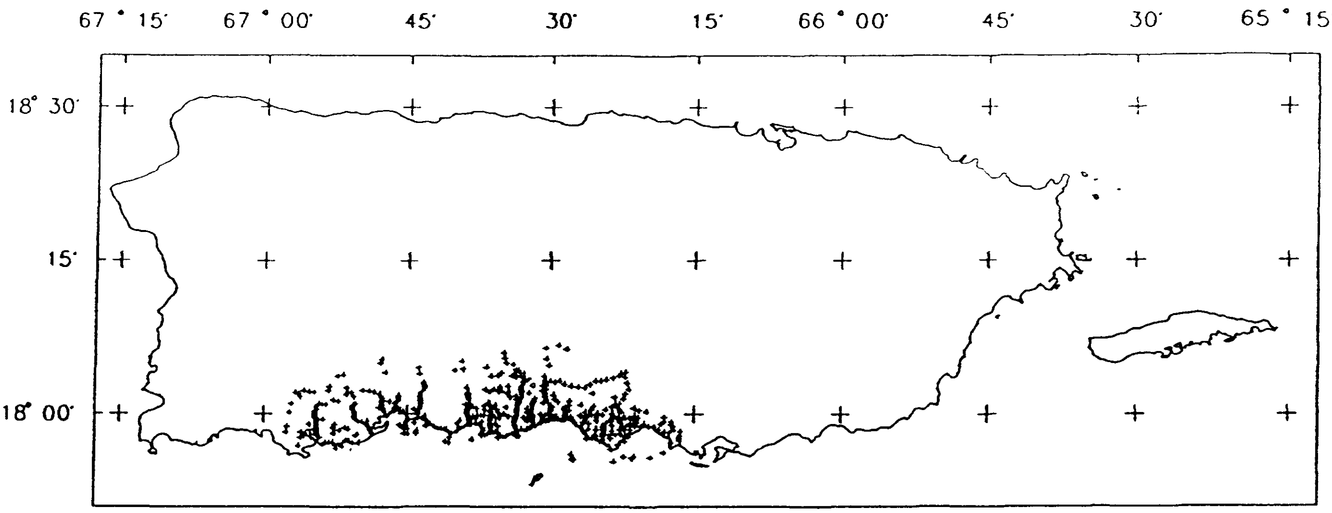


Figure 2c. Locations of South Coast gravity stations from Griscom and Rambo (1970).

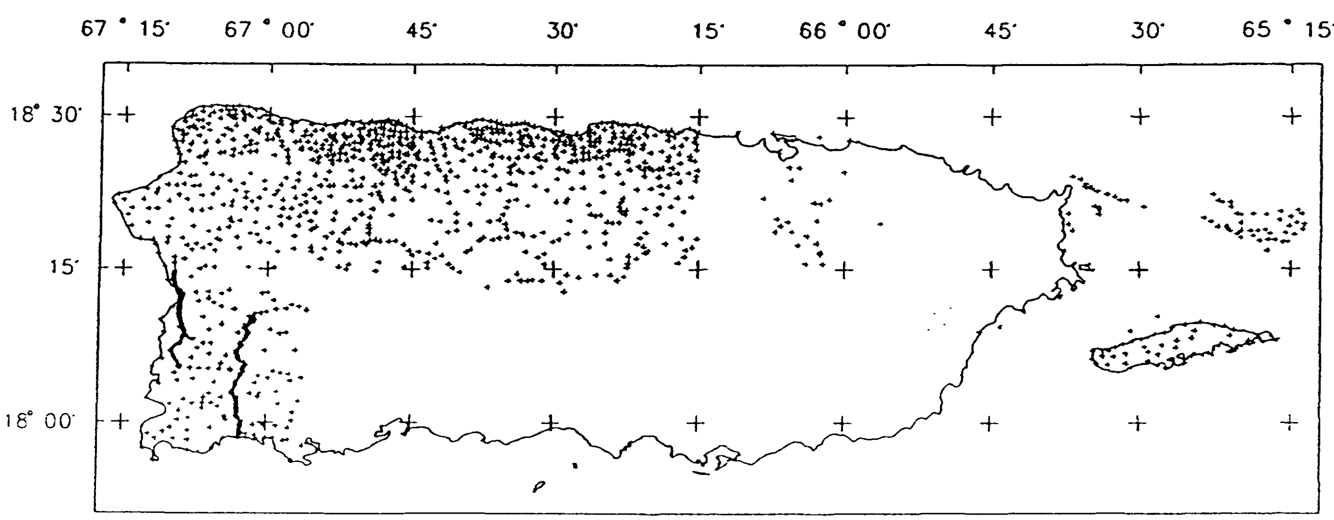


Figure 2d. Locations of gravity stations from Bromery and Griscom (1964) and unpublished USGS gravity stations. Stations that appear to be offshore were measured on small islands.

GRAVITY DATUM

Observed gravity values for all stations in this report are referenced to the International Gravity Standardization Net of 1971 (IGSN 71) as described by Morelli (1974). Theoretical Gravity is based on the Geodetic Reference System of 1967 (GRS67; International Union of Geodesy and Geophysics, 1971). All data collected prior to 1990 were originally referenced to the Woollard and Rose datum (1963) and have been adjusted to the IGSN 71 datum by subtracting 13.7 mGal from observed gravity values. This number represents the difference between observed gravity values on the old and new datums measured at the Commerce Building base station in Washington, D.C. (base ACIC 165-0; Jablonski, 1974), to which most of the Puerto Rico base stations used for this data set are tied, directly or indirectly. Two gravity stations were reoccupied in the 1990 survey; differences in complete Bouguer anomalies between the old values converted to the IGSN 71 datum and the new values are less than 0.02 mGal. This small difference indicates that no large datum shift exists between the various data sets that would significantly affect the use of the integrated data set for regional-scale studies.

BASE STATIONS

Base stations used for data discussed in this report are described on the following pages. Gravity stations observed in 1990 were all tied to a new base station at the Hotel Melia in Ponce (PONCE HM), which was established through several ties to the PONCE IH, SJ AIRPORT, and SJCAP OUT bases. All east coast stations, except for the 12 U.S. Naval stations, were tied to the inside base at the House of Representatives in San Juan (SJCAP IN). South coast stations were tied to one of two bases, PONCE IH or SJCAP IN. The remaining stations were tied to one or more of the described base stations. Base station locations are shown in Figure 3.

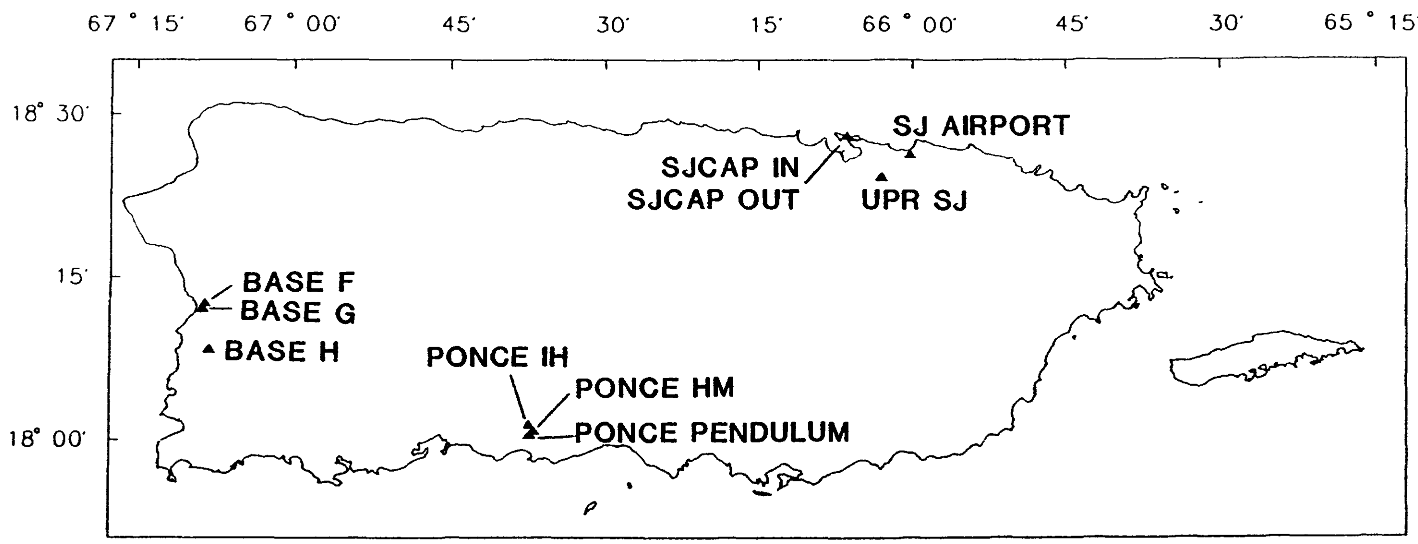


Figure 3. Locations of described gravity base stations.

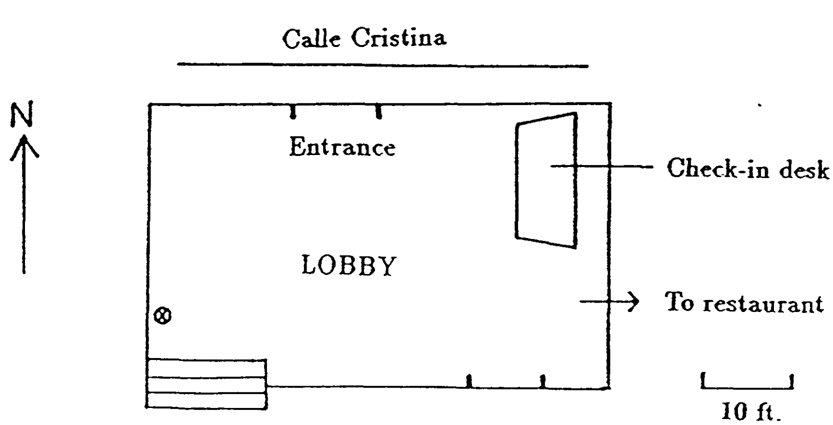
STATION NAME: **PONCE HM**

7 $\frac{1}{2}$' QUADRANGLE: Ponce ELEVATION: 16 meters

LATITUDE: 18° 0.83' N LONGITUDE: 66° 36.80' W

OBSERVED GRAVITY: 978613.66 mGal

Located in the city of Ponce at the Hotel Melia on Calle Cristina, one block east of Plaza Degetau. Measurements were taken 5 feet north of the stairs in the hotel lobby against the western wall. Meter was read facing the wall.



STATION NAME: **PONCE IH**

7 $\frac{1}{2}$' QUADRANGLE: Ponce

ELEVATION: 130 meters

LATITUDE: 18° 1.45' N

LONGITUDE: 66° 37.28' W

OBSERVED GRAVITY: 978595.44 mGal

Located at the Ponce Intercontinental Hotel, which closed in the summer of 1990. Observations were taken in the north corner of the parking lot.

STATION NAME: **PONCE PENDULUM**

7 $\frac{1}{2}$' QUADRANGLE: Ponce

ELEVATION: 9 meters

LATITUDE: 18° 0.49' N

LONGITUDE: 66° 37.23' W

OBSERVED GRAVITY: 978613.94 mGal

Located about 1 km east of the Plaza, in Barldoriti Park (commonly known as Luvena Park), at the intersection of Calle Munoz Rivera and Calle Martin Corchado. Station is at the approximate location of the U.S Coast and Geodetic Survey (U.S.C. & G.S.) Ponce pendulum base.

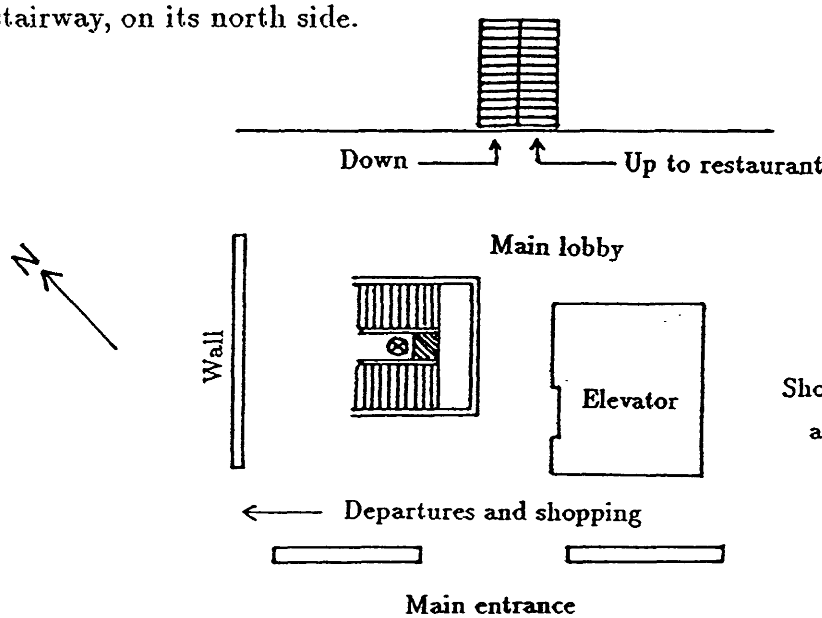
STATION NAME: **SJ AIRPORT**

7 ½' QUADRANGLE: San Juan | ELEVATION: 3 meters

LATITUDE: 18° 26.4' N | LONGITUDE: 66° 0.2' W

OBSERVED GRAVITY: 978669.79 mGal

Located at the Puerto Rico International Airport in San Juan, in Terminal C building. The station is located on the ground floor near the center of the building where a stairway leads upstairs to the airport hotel. Observations were taken in front of a pillar encircled by the stairway, on its north side.



STATION NAME: **SJCAP IN**

7 ½' QUADRANGLE: San Juan | ELEVATION: 8 meters

LATITUDE: 18° 28.11' N | LONGITUDE: 66° 06.37' W

OBSERVED GRAVITY: 978661.62 mGal

Located in the House of Representatives wing of the New Capitol in San Juan, on the ground floor of the northwest room. Observations were taken on the floor in the center of the room. Station is at the approximate location of the U.S.C & and G.S. Pendulum station.

STATION NAME: **SJCAP OUT**

7 ½' QUADRANGLE: San Juan ELEVATION: 7.6 meters

LATITUDE: 18° 28.10' N LONGITUDE: 66° 06.37' W

OBSERVED GRAVITY: 978662.74 mGal

Located at the south side of the New Capitol building in San Juan, on the center of the sidewalk in front of the steps at the front entrance. Observations were taken on a tablet stamped "29-Y-1934"; "U.S. 7.55 PBM" is painted on the steps.

STATION NAME: **UPR SANJUAN**

7 ½' QUADRANGLE: San Juan ELEVATION: 28.4 meters

LATITUDE: 18° 24.29' N LONGITUDE: 66° 3.03' W

OBSERVED GRAVITY: 978680.88 mGal

Located at the University of Puerto Rico in Rio Piedras, in the southern part of San Juan. Observations were taken in the center of a large medallion at the administration building, also known as University Tower.

STATION NAME: **BASE F**

7 ½' QUADRANGLE: Mayaguez ELEVATION: 22 meters

LATITUDE: 18° 12.7' N LONGITUDE: 67° 8.5' W

OBSERVED GRAVITY: 978651.68 mGal

Located at the University of Puerto Rico in Mayaguez, at the northeast corner of the Celis Building. Observations were taken on a concrete walk outside the building, underneath the first window on the east side nearest the northeast corner of the building.

STATION NAME: **BASE G**

7 $\frac{1}{2}$' QUADRANGLE: Mayaguez ELEVATION: 10 meters

LATITUDE: 18° 12.17' N LONGITUDE: 67° 8.66' W

OBSERVED GRAVITY: 978649.59 mGal

Located 60 feet southeast of the southeast corner of the the U. S. Post Office building at the corner of a wooden fence, 15 feet west of a dirt street that runs along the west side of a high-school building. Observations were taken on the ground beside a concrete pier at the corner of the fence. Station is at the approximate location of the U.S.C & G.S. Mayaguez pendulum base.

STATION NAME: **BASE H**

7 $\frac{1}{2}$' QUADRANGLE: Mayaguez ELEVATION: 10 meters

LATITUDE: 18° 8.4' N LONGITUDE: 67° 8.1' W

OBSERVED GRAVITY: 978651.53 mGal

Located southeast of Guanajibo on New Route 2, 100 feet east of the intersection with Route 103. Observations were taken at kilometer post Km 193 H5.

CALCULATION OF GRAVITY ANOMALIES

All gravity data were reduced using the following standard gravity corrections: a) Earth-tide, to correct for the tidal effects of the sun and moon; b) instrument drift; c) latitude, to correct for variation in the Earth's gravity with latitude; d) free-air, to correct for the difference in elevation between each station and sea-level; e) Bouguer, to correct for the gravitational effect of the mass between each station elevation and sea-level; f) curvature, to correct for the Earth's curvature to 166.7 km; and g) terrain, to correct for the gravitational effect of topography to 166.7 km.

After removal of instrument drift and tide corrections, free-air anomalies were calculated using the GRS 67 ellipsoid formula and Swick's formula (1942, p. 65) for the free-air correction. Bouguer, curvature, and terrain corrections were then added to the free-air corrections to arrive at complete Bouguer anomaly values at standard reduction densities of 2.50 and 2.67 g/cm^3.

TERRAIN CORRECTIONS

Inner-zone terrain corrections were determined by hand to various radial distances (0.59, 0.895, and 1.280 km) using topographic maps and conventional templates of Hayford and Bowie (1912) or Hammer (1939). Inner-zone corrections for most stations also include field estimates of nearby topography to 223 ft (Hayford-Bowie zones A-B). The extent of the inner-zone correction for each station is included in the principal facts listing on the diskette (see Appendix).

Terrain corrections from the outer limit of the hand terrain correction to a distance of 166.7 km were calculated using a computer procedure by Godson and Plouff (1988) based on digital elevation models (DEMs) with latitude-longitude spacings of 3 minutes, 1 minute, and 1/4 minute. Because of problems with the offshore 1 minute DEM, terrain data were digitized from a 1:250,000 scale map of Puerto Rico and merged with the onshore 1 minute data. The 1/4 minute DEM did not contain data below 18° 00' north latitude as well as a block between 67° 00' and 66° 30' west longitude, so these areas were filled in with data from the 1 minute DEM (Fig. 4).

Hand-calculated terrain corrections to 166.7 km were available for the South Coast data set, however, computer-calculated corrections for the same stations were consistently lower by about 1.3 to 1.7 mGal. The computer-calculated corrections were used because of doubtful accuracy of the hand-calculated corrections and because they are more consistent with terrain corrections calculated for the remaining data sets.

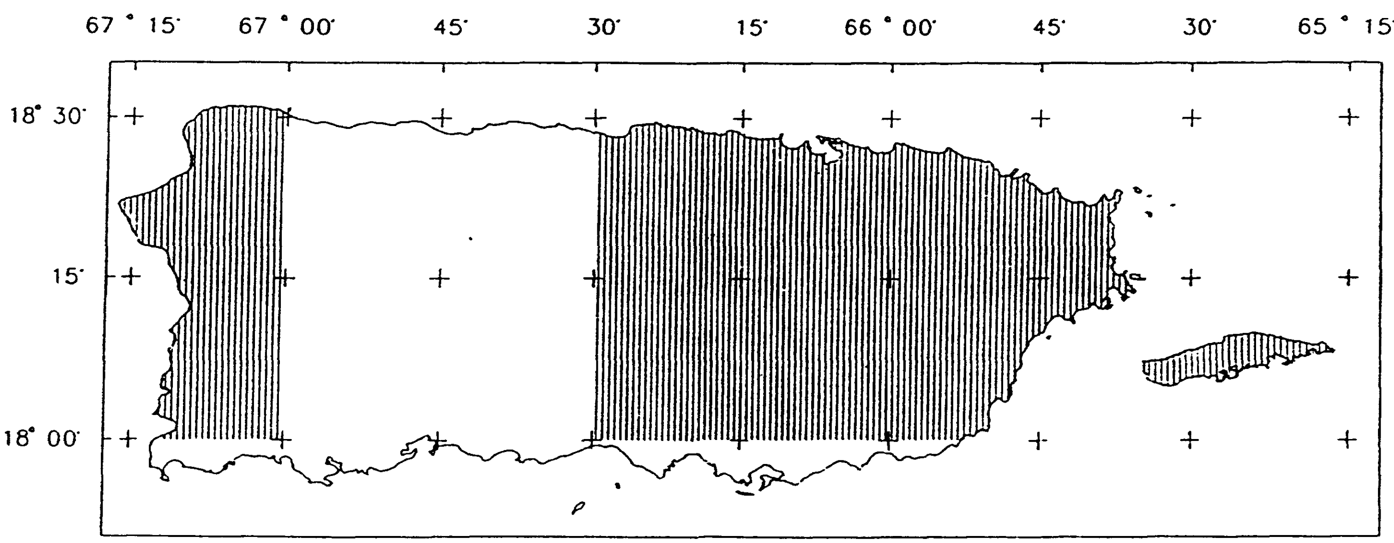


Figure 4. Sources of quarter-minute digital elevation model. Striped areas denote sections of data derived from three second terrain data; white areas are derived from one minute data.

SOURCES OF ERROR

The largest source of error for this data set is in the terrain correction; this error is generally considered to be 5 to 10% of the value of the total terrain correction. Because some of the terrain corrections are as high as 34 mGal, errors as high as 3.4 mGal are possible. The average terrain correction, however, is 8.6 mGal, so the expected error resulting from the terrain correction is around 0.4 to 0.9 mGal per gravity station. The majority of stations are located either at benchmarks, spot elevations, or surveyed elevations, which are accurate to about 0.1 to 3 m. This could result in a Bouguer gravity error of about 0.02 to 0.6 mGal. Elevations for all of the East Coast stations are accurate to 0.5 m, except for approximately 40 stations whose elevations were interpolated from topographic maps with a contour interval of 5 m; these stations are accurate to about 2.5 m, or 0.5 mGal. Elevations for most of the 1990 stations are accurate to 3 m, except for 91 stations whose elevations were determined by altimetry with an expected accuracy of 5 m. Small errors can also be expected from gravimeter readings; Lacoste-Romberg meters typically are accurate to 0.05 mGal and Worden meters to 0.1 mGal. Errors resulting from location inaccuracy are considered to be less than 0.05 mGal. In general, the total amount of uncertainty for the data presented in this report is less than 2 mGal.

A four-character accuracy code, described in Table 1, is included in the principal facts listing for the data set collected in 1990 and is available on the diskette (see Appendix); accuracy codes were not compiled for the older data sets. This code specifies the expected accuracies of location, elevation, latitude, and observed gravity for each station.

PHYSICAL PROPERY MEASUREMENTS

Grain densities were measured using the buoyancy method on 71 rock samples collected from locations shown in Figure 5 Densities ranged from 2.07 to 3.00 g/cm^3, with an average of 2.66 g/cm^3 (Table 2). Most of the samples collected were sedimentary and volcanic/volcaniclastic rocks with average densities of 2.62 and 2.68 g/cm^3, respectively. The average density of the serpentinites collected was lower, 2.42 g/cm^3, whereas the average density of plutonic rocks was higher, 2.85 g/cm^3. Of the eight plutonic samples, only four were of felsic composition, having a lower average density of 2.75 g/cm^3.

TABLE 1.–*Explanation of accuracy code (AC)*

[NGS, National Geodetic Survey; NMD, National Mapping Division; USGS, U. S. Geological Survey]

General elevation and location code–1st digit

Code	Explanation	Code	Explanation
A	Altimetry, good control	P	On or near surveyed mark
B	On USGS or NGS level-line bench mark	Q	River gradient interpolation
C	Contour line interpolation	R	Lake or reservoir elevation by leveling
D	Reference mark, destroyed or not found	S	Sea level elevation
E	Near level-line bench mark other than USGS or NGS	T	Photogrammetry by USGS, NMD
F	Map elevation, black or field checked	U	Unknown elevation source
G	Map elevation, brown or not field checked	V	On vertical angle bench mark
H	Near vertical angle bench mark	W	Map elevation, blue
I	Other special source	X	On or near boundary marker
K	Photogrammetry by other than USGS, NMD	Y	Altimetry, poor control
N	Near USGS or NGS level-line bench mark	Z	Special source (e.g. mobile elevation recorder)
M	On level-line bench mark other than USGS or NGS		

Code	Elevation code–2nd digit	Elevation accuracy (ft)	Approximate gravity effect (mGal)
1	On bench mark	0.2	0.01
2	Near bench mark	0.3	0.02
3	Transit or good alidade survey	1.0	0.06
4	Vertical angle bench mark or black map elevation	2.0	0.12
5	Black map elevation on old map or good photogrammetry	4.0	0.24
6	Brown map elevation or good photogrammetry on 20 ft contour interval map	10	0.6
7	Brown map elevation on 80 ft contour interval map or good altimetry	20	1.2
8	Contour interpolation on 80 ft contour interval map	40	2.4
9	Contour interpolation on 200 ft contour interval map or poor altimetry	80	4.8

Code	Latitude code–3rd digit	Latitude accuracy (min)	Distance accuracy (ft)	Approximate gravity effect (mGal)
1	Triangulation or special survey data	0.007	42	0.01
2	Location known to 0.04 in on 1:24,000 map (special care)	0.014	84	0.02
3	0.10 in on 1:24,000 map or 0.04 in on 1:62,500 map	0.035	210	0.05
4	0.21 in on 1:24,000 map or 0.08 in on 1:62,500 map	0.07	420	0.1
5	0.42 in on 1:24,000 map or 0.16 in on 1:62,500 map	0.14	840	0.2
6	0.40 in on 1:62,500 map or 0.1 in on 1:250,000 map	0.35	2,100	0.5
7	0.80 in on 1:62,500 map or 0.2 in on 1:250,000 map	0.7	4,200	1.0
8	1.60 in on 1:62,500 map or 0.4 in on 1:250,000 map	1.4	8,400	2.0
9	4.00 in on 1:62,500 map or 1.0 in on 1:250,000 map	3.5	21,000	5.0

Code	Observed gravity code–4th digit	Approximate gravity effect (mGal)
1	Local survey with special gravity meter	0.01
2	Multiple observations with LaCoste and Romberg gravity meter	0.02
3	Average LaCoste and Romberg or multiple observations with Worden gravity meter	0.05
4	LaCoste and Romberg observation with small vibrations or average Worden gravity meter	0.1
5	Data from loop with closure error this large	0.2
6	Data from loop with closure error this large	0.5
7	Data from loop with closure error this large	1
8	Data from loop with closure error this large	2
9	Data from loop with closure error this large	4

Magnetic susceptibilities were measured using a Scintrex SM-5 susceptibility bridge and were found to vary widely from 0.00 to $4.50x10^{-3}$ cgs units, with an average of $1.15x10^{-3}$ cgs units. In general, the sedimentary rocks had the least magnetic susceptibilities, except when the sample contained an appreciable amount of volcanic debris; the average susceptibility is $0.59x10^{-3}$ cgs units, ranging from 0.00 to $2.40x10^{-3}$ cgs units. Serpentinites and volcanic rocks tended to be more magnetic, with average susceptiblilities of 1.20 and $1.53x10^{-3}$ cgs units. The most magnetic rocks generally were plutonic, in particular the diorites and associated hornblendites.

Although these physical property measurements are from surficial samples and may not be representative of densities at depth, they do help constrain density and susceptibility contrasts needed for more detailed analysis of the gravity and magnetic fields.

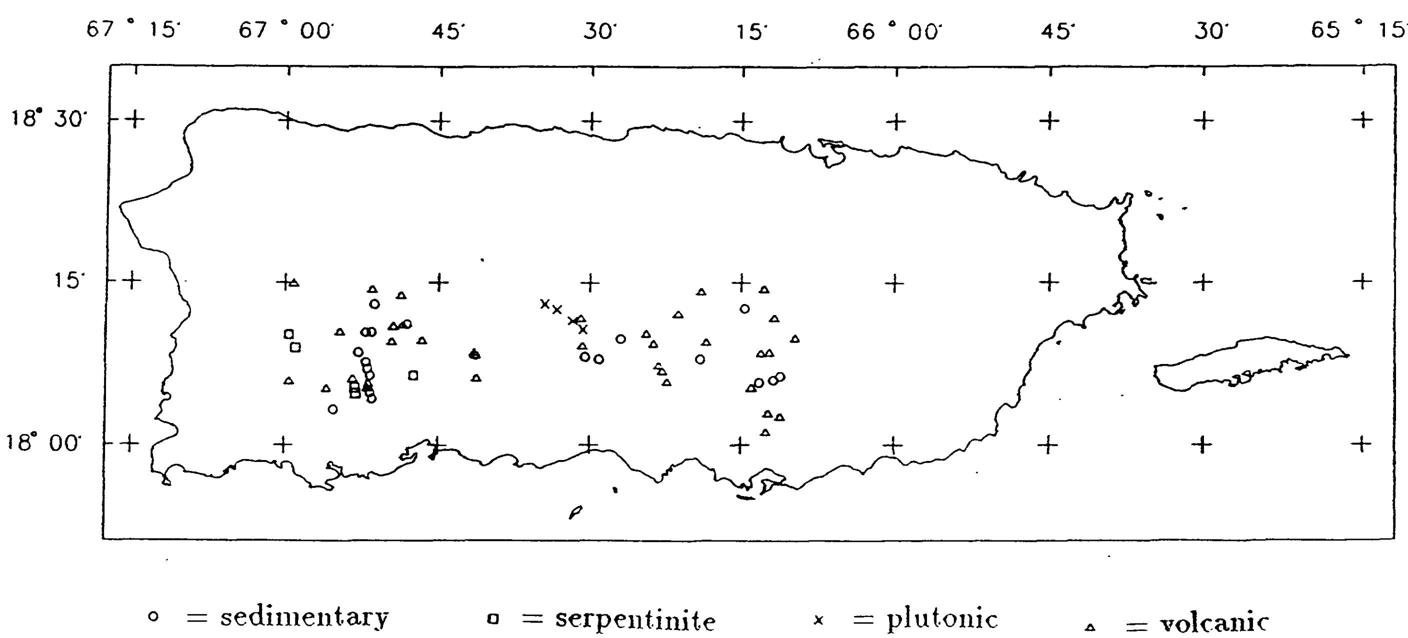


Figure 5. Locations of rock samples.

TABLE 2.–*Rock density and magnetic susceptibility data.*

lithology	number of samples	average density (g/cm^3)	std. error (g/cm^3)	range (g/cm^3)	average suscep. (cgs units x 10^{-3})
Sedimentary rocks	21	2.62	0.15	2.07-2.79	0.60
Serpentinites	6	2.42	0.17	2.23-2.71	1.53
Plutonic rocks	8	2.85	0.11	2.73-3.00	2.05
granitic	4	2.75	0.02	2.73-2.78	1.98
amphibolite	4	2.95	0.03	2.93-3.00	2.13
Volcanic rocks	36	2.68	0.12	2.29-2.86	1.21
basalt	3	2.68	0.20	2.29-2.86	1.23
andesite	11	2.65	0.07	2.51-2.76	0.80
other	22	2.69	0.13	2.29-2.85	1.41

CONCLUSIONS

This report contains Bouguer gravity values for 3064 stations on the island of Puerto Rico and vicinity, compiled from several sources of data. All data sets have been reduced to the IGSN 71 datum. Two complete Bouguer gravity maps were created from a merged data set (Figs. 6 and 7), at a reduction density of 2.67 g/cm^3. Figure 6 shows the unfiltered gravity field; complete Bouguer values range from 83 to 175 mGal, with the highest values occuring over the central part of the island. Because of the large gradient resulting from this central high, the data have been filtered using the computer program MFILT (unpublished program by Jeffrey Phillips, USGS) to remove wavelengths greater than about 11 km and thereby enhance smaller-wavelength anomalies. Subtle bends in the unfiltered gravity field become isolated anomalies; for example, in the northern and western parts of the island, northwest-trending anomalies that are associated with known faults become more pronounced.

Another method of removing long-wavelength effects that has been effectively used in the continental United States is the isostatic correction. This method attempts to remove the long-wavelength effect of deep crustal and/or upper mantle masses that isostatically compensate regional topography and is a more geophysically-based filter than the mathematicallybased method of MFILT. However, the isostatic correction method does not remove the regional gradient across the island and instead increases the gradient. Figure 8 shows a profile (A-A') of topography and both isostatic and Bouguer gravity across Puerto Rico, extending from the city of Ponce to San Juan. The highest topography occurs in the general area of the highest Bouguer values. This suggests that Bouguer gravity, possibly combined with filtered gravity, would be more effective than isostatic gravity for analysis of the gravity field of Puerto Rico.

ACKNOWLEDGMENTS

We wish to thank John Mariano for assisting in collection of data and planning of the 1990 field work, Peter Sauer for sorting through and organizing the data, William Dinklage for reading data off punch cards, and Sarah Baylis for processing terrain corrections.

APPENDIX 1

DESCRIPTION OF DISKETTE

The data described in this report are available on one 5 1/4-inch double-sided, high-density diskette, formatted for IBM-PC's using DOS 2.0 or higher versions. The diskette contains five files: four gravity data files and README.TXT, which contains the title-page information, a description of the principal facts format, and a brief description of the other files. The four gravity data files are divided by source, described on page 2: 1990.CBA contains 282 stations collected in 1990; ECOAST.CBA contains 799 East Coast stations from Griscom (1972); SCOAST.CBA contains 665 Griscom and Rambo (1970) South Coast stations; and OTHER.CBA contains 1318 other USGS stations, most of which are previously unpublished.

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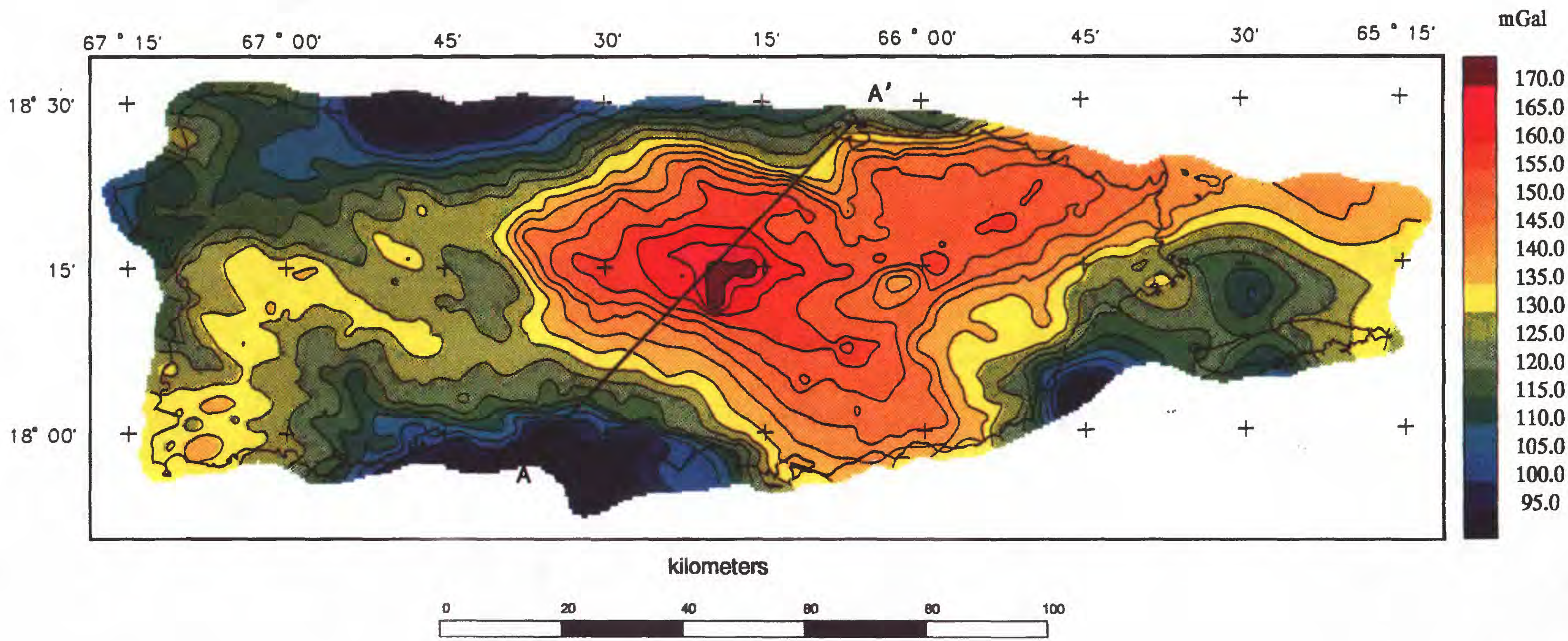

Figure 6. Bouguer gravity map of Puerto Rico.

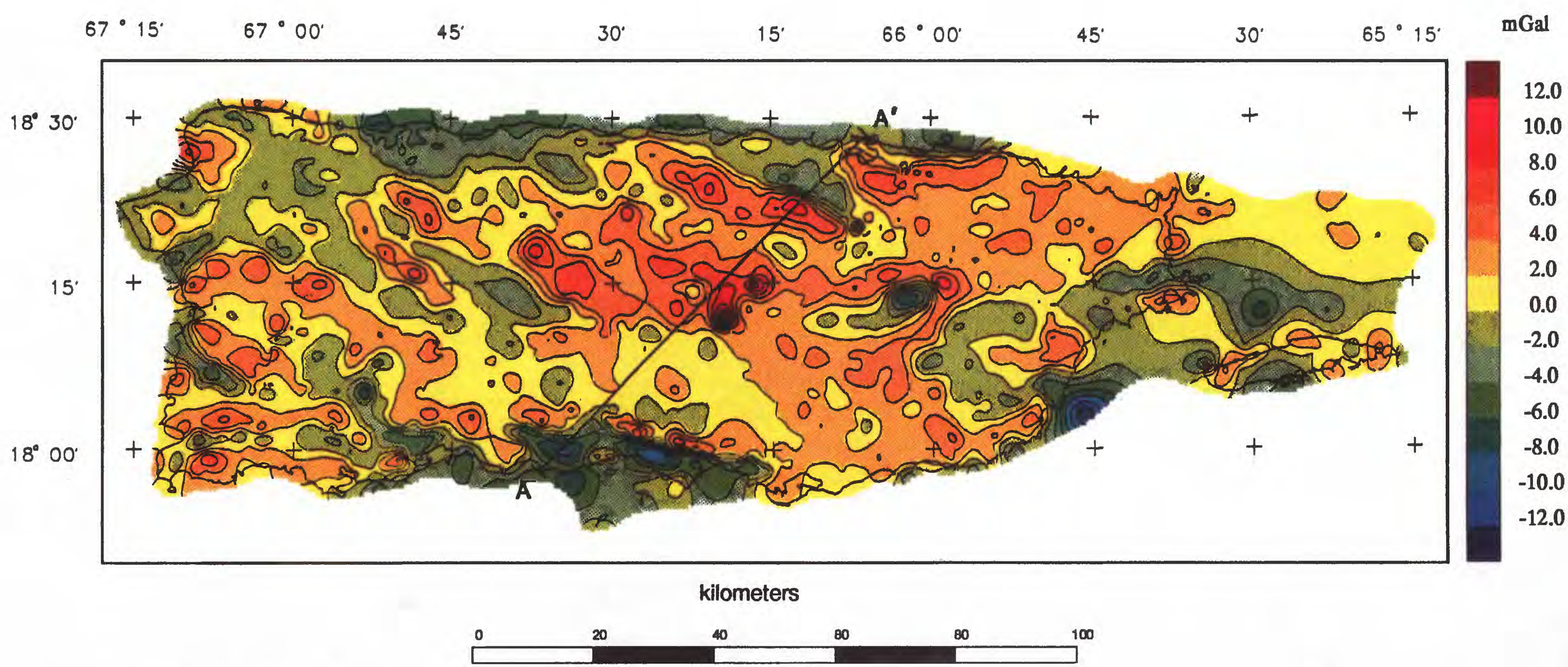

Figure 7. Filtered Bouguer gravity map of Puerto Rico (wavelengths < 11 km).

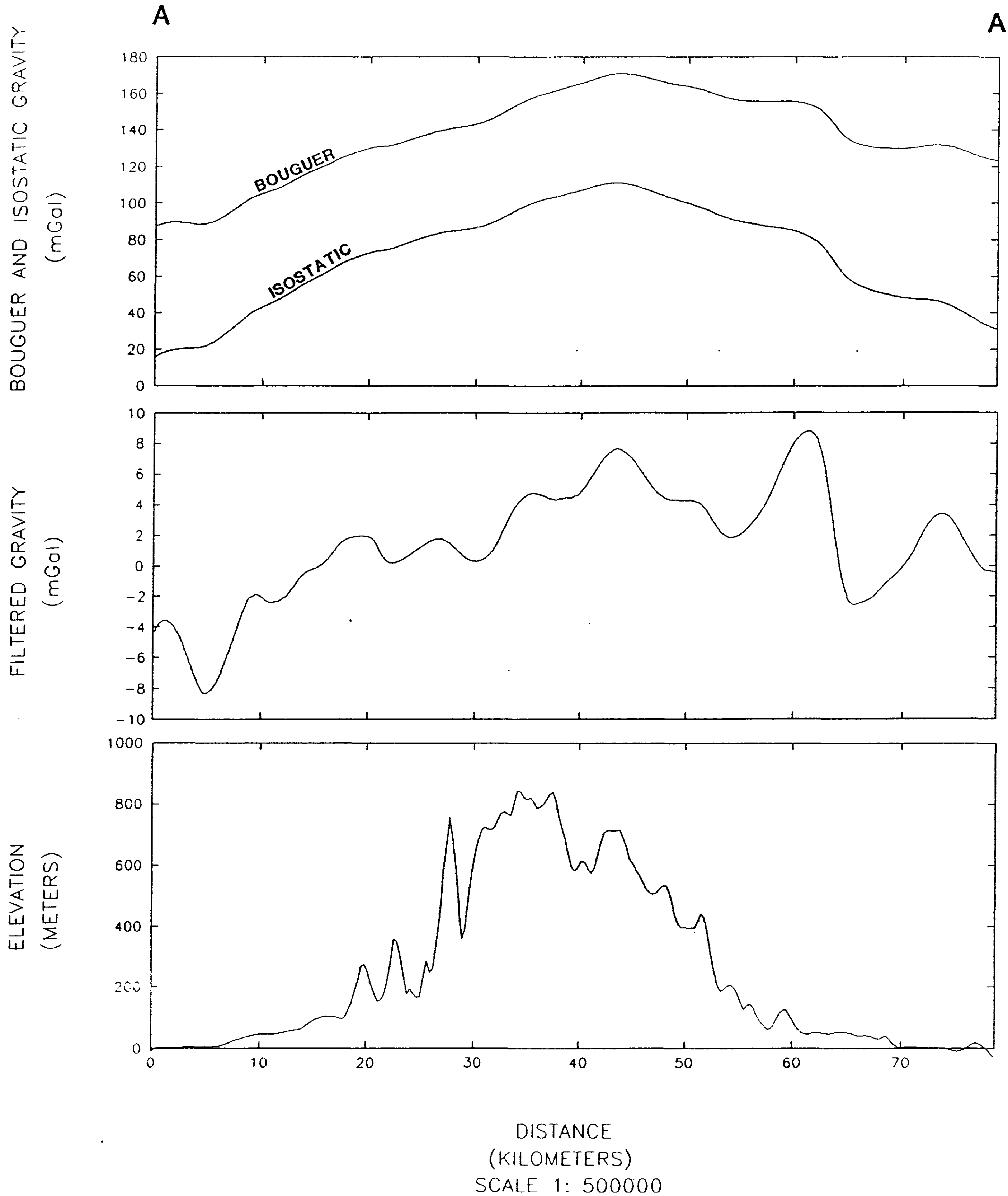

Figure 8. Bouguer and isostatic gravity, filtered Bouguer gravity, and topography across Puerto Rico along profile A-A'.