Complete Bouguer Gravity Map of Puerto Rico

by

Andrew Griscom, Nami E. Kitchen, and William L. Rambo

INTRODUCTION

This complete Bouguer gravity map of Puerto Rico(Arc/Info export file, raster file) is based upon about 2,950 gravity stations, all but 6 of which were collected by the U.S. Geological Survey from 1962 to 1990. Kitchen and others (1991) described the data set and sources in detail, so only a few of the more important aspects are repeated here. An earlier gravity map of Puerto Rico was published by Shurbet and Ewing (1956). It is based on a smaller number of stations, which in general have since been reoccupied. Observed gravity values for the present survey are referenced to the International Gravity Standardization Net of 1971 as described by Morelli (1974). Theoretical gravity is based on the Geodetic Reference System of 1967 (International Union of (Geodesy and Geophysics, 1971). The reduction density is 2.67 g/cm3. Inner-zone terrain corrections were manually calculated from templates, and outer zones to a distance of 166.7 km were calculated by computer according to a digital elevation model. Absolute error for each station is mainly in the terrain corrections and for the most part is probably no more than 0.4-0.9 mGal.

Relative error between nearby stations is generally much less than the absolute error and in reasonably level terrain is less than 0.2 mGal. The smoothness of the gravity contours in areas of high station density is testimony to the relative accuracy of the data set.

To prepare the map, the complete Bouguer gravity values were interpolated into a rectangular grid having a spacing of 0.5 km and then contoured by means of a computer program.

INTEPRETATION

Interpretation of the Bouguer gravity map is here confined to the major gravity features of the island, that is, those features whose narrowest dimensions exceed about 20 km. The smaller features are in general better defined by the filtered Bouguer gravity map (wavelengths <13 km) and are discussed in the text accompanying that map.

High-density rocks produce gravity highs and large volumes of low-density rocks produce gravity lows. In general, volcaniclastic or clastic rocks, of which the island is mostly composed, increase in density with age, mainly because of decreasing porosity: alluvial deposits are the lowest in density, say 1.8-2.2 g/cm3; the Oligocene and younger Tertiary rocks are higher in density, about 2.2-2.5 g/cm3; then the Paleocene and Eocene rocks, about 2.4-2.7 g/cm3; and lastly the Cretaceous rocks, most of which probably have densities of about 2.65-2.75 g/cm3 (Bromery and Griscom, 1964a), depending upon the relative proportions of andesitic or basaltic volcanic debris. Local massive basaltic flows may have densities as high as 2.95 g/cm3. Plutonic rocks vary in density depending upon composition. Granitic rocks have densities in the range of 2.65-2.70, granodiodtes and quartz diorites in the range of 2.67-2.77, and more mafic rocks 2.77-2.90 g/cm3. The above statements about rock densities are only general estimates because relatively limited amounts of density data are available. Densities for 29 miscellaneous Cretaceous rock samples from southwestern Puerto Rico are available in Bromery and Griscom (l964a) who also obtained an average density of 2.55 g/cm3 for samples of serpentinite taken every 3-5 m along a 305-m core from a drill hole near Mayaguez. Mitchell (1957) reported wet and dry densities for 38 samples of "typical rocks"; results include average saturated bulk densities of 2.42 g/cm3 for 10 samples of younger Tertiary rocks, 2.79 g/cm3 for 11 samples of volcanic rocks, and 2.90 g/cm3 for 5 samples of metamorphic rocks (presumably metamorphosed mafic volcanic rocks). Kitchen and others (1991) reported densities of 71 rock samples that are older than middle Tertiary and that were collected from the south half of the island; their results show great scatter and emphasize the difficulty in determining average densities for such heterogeneous rock units.

Average density contrasts between the sedimentary rocks of middle Tertiary sedimentary basins on the north and south coasts and the older rocks beneath the basins can be calculated by using basement well data, that is, known thickness of the sedimentary rocks, together with reasonable extrapolations of regional gravity gradients over the older rocks out into the basins. Griscom and Rambo (1970) calculated the density contrast of the south coast basin rocks to be -0.4 and -0.425 g/cm3 on the basis of two gravity profiles that intersected deep wells to basement. Similarly, A. Griscom (unpubl. data, 1975) calculated a density contrast of 0.4 g/cm3 for the north coast basin on the basis of a north-south gravity profile intersecting Test Well No. 4CPR (Briggs, 1961). These results imply that the average saturated bulk density for these basin rocks is approximately 2.25-2.35 g/cm3, a range that is based upon the likely densities for the average Cretaceous volcaniclastic rocks. Briggs (1961) reported average dry bulk of 2.40 g/cm3 on three samples from each of two cores of Lares Limestone from depths of 3,704 and 3,726 ft (1,130 and 1,137 m) in well 4CPR on the north coast. Using the measured total porosity of 13.0 percent and the grain density of 2.75 g/cm3, this density recalculates to a saturated bulk density of about 2.52 g/cm3, a result that is not too useful considering the very restricted sample locality.

The resistivity log of the Lares Limestone indicates a relatively constant resistivity in excess of 80 ohms m2/m for most of the formation, indicating that its density may be relatively constant throughout. The density of the other middle Tertiary units is probably somewhat less than that of the Lares Limestone because of the somewhat greater amounts of dense limestone in the latter unit.

We discuss below the three major features on the Bouguer gravity map of Puerto Rico. Shurbet and Ewing (1956) and Mitchell (1957) also made general mention of these features and their causes.

1. The gravity field of Puerto Rico is characterized by a major gravity high along the eastern two-thirds of the island. This feature is best displayed in the central third of the island, where it trends approximately N75W. The high seems to correlate generally with the location and strike of the oldest rocks in this part of Puerto Rico and thus follows the crest of a broad antiform. The cause of this high is two-fold, mainly high-density rocks at shallow depths near the center of the island and secondarily, low-density rocks on the north and south sides of the island (see point 3, this discussion). The high-density rocks are probably, for the most part, not exposed and may be uplifted former oceanic or deep island-arc crust in the core of the antiform. Mitchell (1957) reached a somewhat similar conclusion, ascribing the gravity high to an "underlying basement complex." The maximum gravity values at the crest of the high are about +175 mGal, which may be compared with average high values of about +135 mGal in the flatter gravity field of

western Puerto Rico. Using an average density contrast of 0.25 g/cm3 between Cretaceous rocks and hypothesized former oceanic crust (presumed to be 2.95 g/cm3), the 40 mGal of relief implies about 4 km more of Cretaceous material in the western third of the island than at the crest of the antiform. The relatively lower and flatter gravity field in western Puerto Rico indicates that no major antiformal structure is present here and that a major tectonic boundary is probably located at the fault system striking N60W, across the island and following approximately the southwest side of the Utuado batholith.

The appearance of the central gravity high in the eastern third of the island is substantially distorted by the low gravity field of the San Lorenzo batholith (see point 2, this discussion) so that here the hypothetical "pre-batholith" form of the high is uncertain

The amplitude of the gravity high over Puerto Rico is influenced also by the isostatic effects of the thickened crust that lies beneath the island and that supports this topographic high relative to the oceanic water depths on either side. This thickened crust is lower in density than the mantle material that lies at shallower depths beneath the adjacent oceanic crust and therefore produces a gravity low over the island. Correcting for this low will increase the relative amplitude of the gravity high over the island and produce steeper gravity gradients on each flank.

2. The San Lorenzo batholith, in the southeast corner of the island, displays a subcircular gravity reentrant or valley on the flanks of the high discussed in point 1. This low has an amplitude of at least 15 mGal in the center of the batholith and at least 35 mGal at the shore. Batholiths customarily display gravity lows, in general being lower in density than the rocks they intrude. The +144-mGal contour approximately follows

the west and north contacts of this quartz diorite pluton but does not contain the plutonic rocks in the extreme southwestern parts of the batholith. These southwestern-most plutonic rocks are thus interpreted to be either relatively thin or of somewhat higher density than the rocks in the main body of the pluton. The gravity low becomes even lower in the extreme eastern put of the batholith near the shore. Here the composition of the pluton changes from quartz diorite to a granodiorite that must be even lower in density. The gravity field falls still lower offshore to a single gravity station, the accuracy of which is unknown.

The northeast contact of the batholith is only weakly defined by a low-amplitude (5-mGal) gravity ridge extending along the country rocks just outside the pluton. The main gravity gradient leaves the north end of the pluton and extends northeast towards the east end of the island along the 140- and then, farther east, the 130-mGal contours. This pattern is interpreted to signify that the batholith extends east in the subsurface beneath country rocks and lies generally south of the 130-mGal contour where it crosses the east shoreline. These batholithic rocks probably connect in the subsurface to the southeast with those exposed on the Isla de Vieques.

3. Gravity lows on the north and south coasts of Puerto Rico are associated with a sequence of sedimentary rocks of Oligocene and younger age that form basins unconformably overlying older rocks. These layered rocks dip gently and thicken seaward, becoming even thicker offshore. The effect of these low-density masses upon the gravity map is to produce steep gravity gradients in the vicinity of the north and south coasts, the gradients sloping down to the north and south, respectively, out into offshore areas of low

gravity. Local steepening of these gradients is interpreted to signify basin-margin faults, downdropped toward the basin; interpreted examples of such east-west-trending faults (see the Gravity Boundary Map of Puerto Rico) occur in the vicinity of San Juan and, on the south coast, along the basin margins east of Ponce for a distance of about 30 km. The south coast sedimentary basin becomes more shallow about 10 km offshore at Isla Caja de Muertos where gravity values rise slightly to 90 mGal and pre-Oligocene sedimentary rocks are exposed. Various earlier geophysical studies of this basin are described and reproduced in Griscom and Rambo (1970).

Filtered Bouguer Gravity and Gravity Boundary Maps

of Puerto Rico

Andrew Griscom and Nami E. Kitchen

INTRODUCTON

The filtered complete Bouguer gravity map of Puerto Rico is derived from the complete Bouguer gravity map by removing the long-wavelength components from the gridded gravity data by means of the computer program MFILT (unpublished program by Jeffery Phillips, U.S. Geological Survey). In this map we have preserved data displaying wavelengths less than 13 km; this particular wavelength was chosen because it is comparable to, or larger than, the width of major rock units such as the Utuado batholith. The map thus portrays well the gravity expression of the smaller geologic features of Puerto Rico.

Users of the filtered map should be aware that such a short wavelength will locally create ‘artifact’ anomalies adjacent to broad, steep gravity gradients. For example, the broad, steep gravity gradient east of San Juan on the Bouguer gravity anomaly map is displayed on the filtered gravity map as having a local residual gravity high and low on the south and north sides, respectively, of the gradient. The east half of the high and all of the low are probably not "real" and are merely artifacts of the filtering process. We believe that such features are relatively unimportant throughout most of the map area and are present mainly near certain gradients within the north and south coast sedimentary basins and in the vicinity of the San Lorenzo batholith, all three gravity features having been discussed separately on the Bouguer anomaly map. In any event, these three gravity features are relatively long in wavelength, so they are substantially removed, as intended, from the filtered map, in order to emphasize the smaller gravity features.

INTERPRETATION

High-density rocks produce gravity highs and large volumes of low-density rocks produce gravity lows. In general, volcaniclastic or clastic rocks, of which the island is mostly composed, increase in density with age mainly because of decreasing porosity: alluvial deposits are the lowest in density, say 1.8-2.2 g/cm3; the Oligocene and younger

Tertiary rocks are higher in density; then the Paleocene and Eocene rocks; and lastly the Cretaceous rocks, which probably have densities of about 2.65-2.75 g/cm3 (Bromery and Griscom, 1964a), depending upon the relative proportions of andesitic or basaltic volcanic debris. Local massive basaltic flows may have densities as high as 2.95 g/cm3. Plutonic rocks vary in density depending upon composition. Granitic rocks have densities in the range of 2.65-2.70, granodiorites and quartz diorites in the range of 2.67-2.77, and more mafic rocks 2.77-2.90 g/cm3. The above statements about rock densities are only general estimates because relatively limited amounts of density data are available. Densities for 29 miscellaneous Cretaceous rock samples from southwestern Puerto Rico are available in Bromery and Griscom (1964a) who also obtained an average density of 2.55 g/cm3 for samples of serpentinite taken every 3-5 m along a 305 rn core from a drill hole near Mayaguez. Kitchen and others (1991) reported densities of 71 rock samples that are older than middle Tertiary and that were collected from the south half of the island; their results show great scatter and emphasize the difficulty in determining average densities for such heterogeneous rock units.

Because of the detail on the filtered gravity map and because of the small contour interval (1 mGal), the map reliability is locally highly dependent upon the number of gravity stations defining the contours. The usershould keep in mind the local distribution of gravity stations when evaluatingthe map. In addition, local gravity features defined by only one gravity station should be viewed with doubt because of the possibility of error.

The filtered gravity map displays a variety of highs and lows, generally linear, and trending in various directions. These gravity features are caused by belts of rocks having higher or lower densities than the adjacent rocks. In order to locate the boundaries of these anomaly sources we used an automatic technique (Cordell and Grauch, 1985; Blakely and Simpson, 1986) that calculates the maximum horizontal gradient on the anomaly margins and plots a sinuous series of dots that represent the density boundaries. This method depends upon the theoretical observation that anomaly gradients tend to be steepest over the edges of gravity sources. The filtered gravity map represents a computer plot of these dots for the filtered gravity field of Puerto Rico. In areas where this program failed to identify boundaries along the margins of anomalies, we connected them along the steepest gradient by visual inspection of the filtered gravity map. In a few areas where gravity stations are locally absent or too sparse, the automatic program results may be disregarded, and instead a line is drawn following the inferred location of the anomaly gradient.

A series of 26 gravity anomalies are numbered on the gravity boundary map and are discussed below by number, and generally from east to west, though locally from north to south.

1. This discontinuous gravity low appears to be associated with Cretaceous plutonic rocks that are exposed near the lowest parts of the low. The plutonic rocks may be more continuous in the subsurface.

2. A gravity low having an amplitude of 2-3 mGal is associated with a Cretaceous or Tertiary pluton that appears to be located at or near the headwaters of streams containing gold placers.

3. A gravity high over country rocks on the east side of the San Lorenzo batholith appears to be associated with basalt and chert of El Rayo Formation and is better displayed on the Bouguer anomaly map. Contact metamorphism by the batholith may have locally increased the density of these rocks.

4. The main contact of the San Lorenzo batholith with country rock is displayed as a curvilinear gradient that surrounds the main gravity low caused by granodiorite and quartz diorite. The amplitude of this broad gravity low is, of course, substantially reduced by the wavelength filter, even though the marginal gradients are correspondingly emphasized. The various plutonic rocks on the south and southwest flanks of the batholith cause local gravity highs and are therefore higher in density, being probably somewhat more mafic.

Of considerable interest is the observation that the local gravity highs and lows within the San Lorenzo batholith correlate inversely with anomalies shown on the aeroradioactivity map (MacKallor, 1965). The lower density rocks are probably more nearly granodiorite in composition, whereas the higher density rocks are more likely closer in composition to diorite and quartz diorite. The density variations thus imply lesser amounts of hornblende and pyroxene in the granodiorite, whereas the aeroradioactivity data imply that larger amounts of potassic minerals (feldspar in particular) are present in the interpreted granodiorite as compared with the dioritic rocks. MacKallor (1965) stated that the southwestern put of the batholith is low in radioactivity, so he correctly predicted that more diorite and gabbro may be present here; again, higher gravity values are found in this area.

5. Where the San Lorenzo batholith intersects the southeast shoreline, there is a strong local gravity low over the granodiorite of the plutonic complex of Punta Guayanes (Kpsg), the rocks of this complex evidently being significantly lower in density than those of the main part of the batholith. This feature also correlates with an aeroradioactivity high (MacKallor, 1965), indicating a rock containing a larger percentage of potassic minerals.

6. A linear gravity low trends approximately N90E in the center of the island. The deepest part of the low lies at its east end over the Caguas pluton, a granodiorite. Other plutons crop out along the west half of the low but appear to be somewhat younger. Nevertheless, it seems that the best explanation for this feature is that it is caused by a pluton about 30 km long and 6 km wide and for the most part concealed below the surface.

7. This small gravity low is associated with an irregularly shaped Cretaceous or Tertiary pluton that is located in the area of the headwaters of the Rio Bayamon, a stream containing placer gold deposits.

8. This gravity low strikes northwest from an exposed graben containing lower Tertiary sedimentary rocks. Also associated with this low are Cretaceous or Tertiary plutonic rocks that appear more likely to be the primary source of the gravity low because they correspond better to the location and width of the low. Low 8 thus may connect with low 7 and have a similar source.

9. This gravity high strikes approximately N80W from exposed Cretaceous volcanic rocks out into the area covered by younger Tertiary sedimentary rocks of the north coast basin and is interpreted to indicate the general tectonic trends of the pre-middle Tertiary rocks. The crest of the anomaly correlates with outcrops of the Cerro Garde Lava, a massive basalt unit, relatively high in density, that is interpreted to be the source of the anomaly.

10. Anomaly 10 is a gravity low striking N80W from the older rocks of the island out into the north coast sedimentary basin. The causes of the anomaly appear to be multiple: 10A is associated with Eocene sedimentary rocks; 10B is associated with a very narrow graben of Eocene sedimentary rocks and some associated Cretaceous or Tertiary plutonic rocks that are the probable source because the anomaly is at least 3km wide; 10C lies somewhat west of the main anomaly trend and is correlated with a major Cretaceous pluton, granodiorite of the Morovis stock.

11. Gravity high 11A trends approximately N90W and is located on the crest of a large Bouguer gravity high of Puerto Rico. Maximum gravity values occur over the Magueyes Formation (tuffaceous sandstone and basaltic flows) and the Perchas Formation (mostly submarine basaltic lavas). The adjacent circular gravity high, 11B, is associated with volcaniclastic rocks and is not explained, but is defined by only two gravity stations that should be remeasured in case of error. Comparison with the magnetic map indicates that the Perchas Formation produces the strongest magnetic anomalies in Puerto Rico, but that the area of anomaly 11B is not especially magnetic.

12. A linear gravity low strikes N80W and is predominantly associated with the area of the Cretaceous Pozas Formation (a subaerially deposited volcaniclastic rock unit containing local ash flow tuffs), the unit presumably having sufficient porosity to explain the low density. The northwest end of this low is associated with the lower Tertiary Yunes Formation, a vitric tuff containing volcanic sandstone and siltstone. The lower Tertiary rock units in general are lower in density than the Cretaceous layered rocks and are also associated with gravity lows in anomalies 8 and 10.

13. Linear gravity high 13A is associated with rock units that are composed predominantly of volcaniclastic rocks interbedded with some lava flows: the Tetuan Formation, the Manicaboa Formation, and the Vista Allegre Formation. A few kilometers to the east is the anomaly 13B, which may have a different source because it is associated with Torrecilla Breccia, a unit of volcanic breccia and interlayered lava flows.

14. A small local gravity low correlates with exposures of Malo Breccia, a mafic tuff containing interbedded breccia, flows, sandstone, and siltstone. Perhaps the tuft has considerable porosity that would explain the lower density.

15. A major gravity low is associated with the granodiorite and quartz diorite of the Utuado batholith. The low extends N65W into the area of the north coast sedimentary basin and indicates that the batholith extends for at least 15km unconformably beneath the middle Tertiary cover rocks.

16. A linear gravity high extends approximately N60W along the southwest margin of the Utuado batholith. The high is associated with volcanic breccias and flows of the Anon and Maricao Formations, the rocks near the batholith having been contact-metamorphosed to the hornblende-hornfels facies (Cox, 1985). A belt of gold-bearing porphyry-copper deposits follows this feature (metallic mineral deposits). The deposits display characteristic magnetic highs that may be associated with more local magnetic lows due to alteration.

17. Anomaly 17 is a low associated with a belt of volcanic breccia interbedded with flows and volcaniclastic rocks. The rock units include the Anon Formation and the interbedded Lago Garzas and Anon Formations. Although these rocks are described as similar to the rocks producing the adjacent gravity high (16), there must be some major differences to account for the lower density; lack of contact metamorphism is probably not a sufficient explanation. This gravity low trends diagonally across southwestern Puerto Rico and appears to be associated with the major fault system or suture that separates the two major gravity and tectonic domains of Puerto Rico, as described on the complete Bouguer gravity anomaly map. The gravity low branches at its northwest end and the west branch is associated with the middle Eocene Rio Culebrina Formation, which is composed of mudstone, breccia, and volcanic sandstone. A belt of mineral occurrences and deposits correlates with this major gravity boundary.

The northwest ends of anomalies 15, 16, and 17 plus two flanking gravity highs (unnumbered) all appear to be terminated by a linear boundary striking about N80E. Inspection suggests that this line may be extended until it intersects the north shoreline at about long 65^{o}37' W. This boundary appears to form the northwest limit for the N60^{o}-65^{o} W grain of the central Puerto Rico gravity field and would appear to be the gravity signature of a major fault predating the middle Tertiary cover rocks and is possibly late Eocene in age. This boundary is also apparent in the magnetic data.

18. A pronounced gravity high having unknown source rocks concealed below the middle Tertiary north coast sedimentary basin has an equidimensional shape and strongly magnetic signature. The cause of the anomaly is interpreted to be a mafic pluton because of the shape, but mafic volcanic rocks are also a possibility.

19. An arcuate gravity high is associated with an area of Cretaceous pillow basalt flows and volcanic breccia of the Conception Formation and with a large area of the Lago Garzas Formation composed mainly of volcanic breccia and lava flows. The Lago Garzas is an unusual example of a Cretaceous or Tertiary unit seeming to produce a gravity high whereas generally the rocks of this age produce lows. Perhaps this unit includes an unusually high percentage of flows; or much of it is underlain at shallow depth by Concepcion Formation.

The western part of the north boundary of this gravity high has an unusual northeast strike that is not easily explained because the geologic map indicates the north contact to be a fault striking approximately N85W beneath the alluvial cover in this area. Perhaps the alluvium is thick enough near the shore to explain some of the local minimum (-5mGal) west of this boundary.

20. An irregular gravity low strikes southeast from Mayaguez across the southwest corner of the island. The low is mainly associated with serpentinite but is also associated in part with large areas of two-pyroxene olivine basalt distributed irregularly along the northeast sides of the serpentinite body. Because intrusive basalt has a high density, it is suprising to find the basalt in a gravity low. We interpret that the basalt must be thin, in general less than 0.5 km thick, and also underlain by more of the low-density serpentinite that causes the gravity low. The serpentinite is interpreted to be generally antiformal in shape with outward-dipping contacts, the north contact dipping far less steeply than the south contact.

21. This linear gravity low is also associated with serpentinite and appears toconnect at its east end with gravity feature 20, also caused by serpentinite. The two detailed gravity profiles (closely spaced stations) that cross feature 21 indicate that the source has an antiformal shape with the north flank dipping less steeply than the south flank. A computed model cross section along the westernmost gravity profile (Bromery and

Griscom, 1964a, fig. 3) uses a density contrast of 0.15 g/cm3 and shows the serpentinite extending to depths of at least 2.8 km, the south contact dipping about 70^{o} S. and the north contact dipping about 50^{o}N.

22. A gravity low, trending generally east-west, follows a valley floored by alluvial fill and lower Tertiary sedimentary rocks. The source of the gravity low continues east beneath the Tertiary sedimentary rocks of the south coast sedimentary basin. On the basis of the abrupt change in gravity level, the south side of the valley appears to be a fault whereas the north side may merely be the feather edge of the sedimentary deposits.

23. Two local gravity highs are connected by an east-west-trending gravity ridge having a somewhat lower amplitude. The highs are underlain by massive outcrops of high-density amphibolite, which may also underlie the connecting gravity ridge in the subsurface.

24. A linear gravity high is located on the north flank of the south coast sedimentary basin. In two places where closely spaced gravity stations are available this high is associated with Cretaceous volcaniclastic rocks south of a belt of lower density lower Tertiary rocks. The south side of this high is a fault, down to the south, marking the border of the south coast sedimentary basin.

25. A gravity high west of anomaly 24 appears to be associated with Cretaceous or Tertiary diorite intrusions.

26. Anomaly 26 is a gravity high bounded on both sides by east-striking faults that appear to define a horst in the south coast Tertiary sedimentary basin.

Magnetic Map of Puerto Rico

By

Andrew Griscom and Nami E. Kitchen

INTRODUCTION

Detailed contoured aeromagnetic surveys are available for approximately half of the island of Puerto Rico; other less detailed magnetic data are listed in Hill (1986). The accompanying index map and table describe four individual detailed magnetic surveys and their flight specifications. The north coast survey (Briggs, 1961) is the only one that has been published, but copies of the other maps have been generously made available to us from the files of the Commonwealth of Puerto Rico and of the Kennecott Copper Company. The contoured magnetic data were digitized by the U.S. Geological Survey from maps at scales of 1:20,000 and 1:50,000. The data were in general digitized along flight lines and include both contour line values and local maxima and minima. Following digitizing the data were gridded, contoured by computer, and compared with the original maps, after which we corrected any observed errors and, where necessary in areas of relatively flat magnetic field, added enough additional digital data to reproduce the original contours. The final magnetic map of Puerto Rico was compiled by merging the various data sets, a process that involved interpolating the data to form a 0.2-km grid of data points and then arbitrarily adjusting datum levels and merging the contour lines between adjacent maps with a series of computer programs. Because of the intricate detail on these maps flown at altitudes of 153 m (500 ft) above ground, it was necessary to smooth them mathematically before attempting to present the data at our publication scale of 1:200,000. The smoothing was done by continuing the data upwards (except for the north coast survey) a distance of 500 m. The result is a data display that approximately duplicates a magnetic survey flown at a height of 653 m above the ground surface.

INTERPRETATION

Magnetic minerals, where locally concentrated or depleted, may cause a high or low magnetic anomaly that can be a guide to mineral occurrences or deposits. The most important magnetic mineral is magnetite, although a few magnetic anomalies are caused by ilmenite and pyrrhotite concentrations. The magnetic anomalies on the magnetic map of Puerto Rico are produced by magnetite-bearing volcanic rocks, plutonic igneous rocks, serpentinites, magnetite-bearing skarns, and, to a lesser extent by some sedimentary and volcaniclastic rocks that contain substantial amounts of volcanic debris. In general, the rock units including large amounts of massive mafic lava flows, predominantly basalt and andesite, produce the largest magnetic anomalies. Many of the volcanic units, because they chill rapidly from a melt, also possess a large remnant magnetization in addition to their induced magnetizations. The vector of this remnant magnetization may be in the normal or reversed direction and, where the rocks have been folded or tilted, may also be rotated into other directions. In those areas where the remnant vectors point upwards, strong magnetic lows may show on the magnetic map.

Kitchen and others (1991) reported magnetic susceptibilities of 71 rock samples that are older than mid-Tertiary and that were collected from the south half of the island. The volcanic, plutonic, and metamorphic rocks all have, as expected, moderately high average susceptibilities ranging from l to 2 x 10-3 emu/cm3, but, as is usually the case, the considerable scatter in the results precludes useful average values. The serpentinites of southwestern Puerto Rico have been studied by several investigators. Kitchen and others (1991) reported an average susceptibility of 1.5 x 10-3 emu/cm3 for six serpentinite samples. Griscom (1964) reported on 49 samples of serpentinite having an average susceptibility of about 2.64 x 10-3 emu/cm3 and average remnant magnetization of about 1.22 x 10-3 emu/cm3. Cox and others (1964) reported an average susceptibility of 1.1 x 10-3 emu/crn3 and average remnant magnetization of 0.5 x 10-3 emu/cm3 for 43 specimens from 15 samples of serpentinite core taken from the Mayaguez drill hole.

NORTH COAST MAGNETIC SURVEY

An interpretation of the north coast magnetic survey (Agocs, 1958) is available in a private report to A.D. Fraser; a copy of the report is on file at the Department of Natural Resources, Puerto Rico. The purpose of the survey was to investigate the structure of the north coast sedimentary basin and to obtain more information relating to its petroleum potential. The wording of the report suggests that an interpretive map may have accompanied the text but we have not located a copy of this map. The interpretation identifies certain east- and northeast-trending faults, all down to the north; it finds basement depths at the shoreline of more than 1.52 km (5,000 ft) in the Manati area, more than 1.22 km (4,000 ft) near Cuecibo, and more than 0.92 km (3,000 ft) northwest of Quebradillas; and it describes certain broad structural features in general agreement with the earlier reflection seismograph survey. This latter survey was made in 1947 by United Geophysical Company for the Puerto Rico Industrial Development Company and is described by W.H. Myers in a report that is reportedly (Briggs, 1961, p. 11) on file at the Department of Natural Resources, Puerto Rico. This report has not been located by the writers and the full title is unknown to them.

CENTRAL PUERTO RICO SURVEY

The central Puerto Rico aeromagnetic map was interpreted in a series of private reports to A.D. Fraser by W.D. Bergey (Bergey, l957a, b, 1960, 1963). The "Central Concessions," or central map area lying approximately between long 66^{o}12' W. and long 66^{o}30' W. was interpreted by Bergey (1960), who pointed out that much ground work remained to be done before this extremely detailed and complicated map can be understood or even properly prospected. Bergey (1960, p. 8) emphasized "two conspicuous regional features:

l) strong magnetic highs in the central and north-central put of the area caused by basic volcanic rocks ; and

2) east-west to northwest linear trends of highs and lows related to zones of faulting and associated alteration.

The geological complexity is apparent in the magnetic pattern. Anomaly trends tend to be discontinuous except where they reflect the regional faulting. In a region underlain by volcanic rocks that have been subjected to intense deformation, infusion and hydrothermal alteration, complex anomaly patterns are to be expected. The interpretation of these patterns requires a considerable amount of geological control.

Bergey (1960) demonstrated that the plutons in this area (he described eight stocks) are for the most part weakly magnetic or nonmagnetic. Only the Cuyon stock (lat 18^{o}07' N., long 66^{o}.15' W.) produces a magnetic anomaly. At least two plutons, the Cuyon and the Morovis stock (lat 18^{o}20' N., long 66^{o}19' W.) appear to display magnetic anomalies that are caused by older rocks outside the contacts and yet the anomalies extend across puts of the pluton. Bergey (1960) suggested that such features may be caused by trains of inclusions locally extending through the stocks. The larger magnetic anomalies thus appear all to be caused by volcanic rocks, the basalts of the Perchas Formation producing anomalies as large as 4500 nT at 153 m (500 ft) above the terrain. Bergey (1960) described several different types of mineralization that he observed to be visible as anomalies on the magnetic map. Contact metamorphism adjacent to some plutons can cause magnetic highs due to increased amounts of magnetite in the metamorphosed rocks. Where limestone may be in contact with plutons, magnetite-bearing skarns can form; Bergey suggested skarn as a possible cause of magnetic highs on the south side of the Pinas stock (lat 18^{o}12' N., long 66^{o}14' W.) and the north side of the Coamo Arriba stock (lat 18^{o}08' N., long 66^{o}22' W.). Hydrothermal alteration can destroy magnetite, the iron ending up as non-magnetic pyrite and chalcopyrite; such alteration was described by Bergey (1960) as being associated with local magnetic lows at the north sides of the Cuyon stock (lat 18^{o}07' N., long 66^{o}15' W.) and of the Cedro Abajo stock (lat 18^{o}17' N., long 66^{o}17' W.). The Cuyon stock in this assessment is considered favorable for porphyry copper- molybdenum mineralization. Another major source of magnetic lows are the west- and northwest-trending altered zones associated with fault zones in the eastern half of the island. Bergey (1960) identified such an area north and northeast of the Cedro Abajo pluton for distances of at least 8 km, and in fact a pronounced magnetic low here is displayed.

East of long 66°12' W. the detailed aeromagnetic map of the central area was described by Bergey (1957a, b). He demonstrated that the plutonic rocks are considerably more magnetic than those of the "Central Concessions" area discussed previously. The San Lorenzo batholith and associated plutons produce substantial anomalies. Large-amplitude, short-wavelength anomalies observed on the detailed aeromagnetic map near the contacts of these plutons are favorable for possible sources that may be copper-bearing iron skarn deposits. At least six such anomalies are near lat l8°11' N., long 65°50' W., and several others are observed on the north and southwest sides of the batholith. Bergey (1960) mentioned that promising areas of copper mineralization also can contain pyrrhotite (rather than magnetite) as a gangue mineral sufficiently abundant to produce magnetic anomalies. The extreme northeast corner of the magnetic survey covers the southwest quadrant of a Cretaceous or Tertiary pluton associated with the headwaters of streams containing placer gold. This pluton is very magnetic, producing an anomaly of more than 1,000 nT, and may have copper-bearing magnetite-rich skarns near its contacts. Local sharp magnetic anomalies observed adjacent to the pluton on the detailed aeromagnetic map may be caused by such skarns. Hydrothermal alteration is also present in this eastern area and may cause pronounced magnetic lows. A major linear low trends about N 80° W at latitude 18°15' N between long 65°45' W and long 66°00' W; this low is associated with a major alteration zone. The altered zone extends N. 75° W. across northeastern Puerto Rico and is associated with a corresponding zone of high aeroradioactivity (see map of MacKallor, 1965). The magnetic low and the high aeroradioactivity indicate the possibility that potassium has been introduced by the hydrothermal fluids.

UTUADO BATHOLITH SURVEY

The detailed aeromagnetic survey of the Utuado batholith area in west- central Puerto Rico was generously provided by the Kennecott Copper Company to the U.S. Geological Survey and the Commonwealth of Puerto Rico. This survey was flown primarily to search for gold-bearing porphyry-copper deposits (Cox, 1985) made up of inner alteration zones that contain abundant magnetite and outer alteration zones that are depleted in magnetite; the deposits are localized in tonalite porphyry stocks of late Eocene age. These deposits form a belt along the south margin of the Cretaceous Utuado batholith. Many of the geophysical studies performed by private companies in this area are not presently available to the public, but one geophysical report by Wilson (1966) for the Kennecott Copper Company is on file at the Department of Natural Resources, San Juan, Puerto Rico. The areas favorable for porphyry copper-gold, porphyry copper-molybdenum, and epithermal quartz-alunite gold deposits are associated with regional magnetic highs along the south side of the Utuado batholith. The general sources of the highs are magnetic volcanic rocks, whose magnetizations may locally be increased due to contact metamorphism by the batholith. The regional highs thus probably reflect an environment suitable for the mineral deposition but are not specifically caused by the mineralization, which, where studied, is considerably younger than the batholith. Superposition of the detailed aeromagnetic map (not reproduced in this report) shows that local aeromagnetic highs are observed over the known porphyry copper deposits (Tanama and Helecho) and their associated Eocene plutons as well as over known areas of copper mineralization nearby and that lows are associated with outer alteration zones. In addition, some of the small tonalite porphyry plutons appear to cause aeromagnetic anomalies even though they may not be mineralized, and other local magnetic highs observed on the map have at present no explanation. It is apparent that more geologic investigations combined with geophysical studies in this area may locate additional porphyry copper deposits.

Magnetic Boundary Map of Puerto Rico

By

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INTRODUCTION

The magnetic boundary map displays the boundaries of the magnetic sources producing the major anomalies on the magnetic map. The boundaries were created predominantly from the magnetic data with a computer program that locates the edges of source bodies from magnetic anomalies (Cordell and Grauch, 1985; and Simpson, 1986). Comparison of this map with the magnetic map shows that, in general, depending upon whether the boundary is on the south or north side of a magnetic mass, the boundaries are located respectively near magnetic highs or near magnetic lows; however, in either case the boundary is a short distance to the south of the magnetic high or low. These particular locations relative to magnetic anomalies are a consequence of the inclination of the Earth's main field (about 49^{o} down to the north in Puerto Rico); in other words the calculated magnetic signature of a rectangular magnetic prism at the latitude of Puerto Rico displays a magnetic high near, but north of the south contact and a magnetic low near, but north of, the north contact. The user of this boundary map should bear in mind that it is somewhat generalized by the computer process (upward continuation) used to smooth the magnetic data. In addition, the boundary map is not necessarily the same as a geologic map because it may combine similar magnetic rock units together or it may identify a magnetic feature that is only a part of a geologic map unit. Only a few magnetic boundaries appear to be artifacts of the data collection process and are caused by adjacent flight lines having slightly different datum levels; examples of such artifacts are seen in the survey of the Utuado batholith area (a few linear features trending N30^{o}E near long 66^{o} 45' W) and in the survey of central Puerto Rico (three north-trending boundaries at the north edge of the survey near long 66^{o} 15' W). We extended and connected the automatically located boundaries by visual inspection of the magnetic map and added hachure marks to indicate the direction of less magnetic material at the boundaries.

INTERPRETATION

Comparisons of the boundary map with the magnetic and geologic maps indicate that many of these boundaries can be explained in terms of the general geology and also that many magnetic features are either combinations of several magnetic geologic units or are simply a magnetic portion, possibly massive flows, of a larger, less magnetic geologic unit. Some of the magnetic features defined by the boundaries are described below, but much more detailed geologic and geophysical work will be necessary to decide upon the economic significance, if any, of numerous other anomalies on the map.

1. This boundary marks the southwest contact of a highly magnetic Cretaceous or Tertiary pluton that is located at the headwaters of streams containing gold placers and that may have magnetite-bearing skarn deposits at contacts with carbonate rocks.

2. This boundary, as far west as approximately long 66^{o} 00' W, is the south limit of a linear zone of nonmagnetic altered rocks that provide an environment permissible for quartz-alunite gold deposits.

3. These eight locations contain one or more intense local magnetic highs on the detailed aeromagnetic maps and are thus favorable locations for magnetite-bearing skarn deposits at the contacts of the San Lorenzo batholith and satellite plutons.

4. These two areas, one subcircular, the other defined by an elongated elliptical boundary, are the strongest magnetic features on the magnetic map. These anomalies are predominantly caused by the Perchas Formation (mostly submarine basaltic flows). This same area correlates with the highest gravity anomalies on Puerto Rico at the crest of the central antiform.

5. The southwest border of the Utuado batholith is displayed as a linear boundary between the weakly magnetic batholith and the strongly magnetic metamorphosed basaltic country rocks.

6. Approximately parallel and adjacent to boundary 5 is a boundary that forms the southwest contact of a belt of magnetic country rocks. This magnetic boundary correlates with the gravity boundary map that separates gravity anomaly 16 (a high) to the northeast from gravity anomaly 17 (a low) to the southwest. The magnetic boundary also correlates with a contact on the geologic map, but the rock unit descriptions seem similar on both

sides of the contact. The rocks northeast of the boundary may be more magnetic for two reasons: (l) a higher percentage of magnetic mafic flow rocks and (2) contact metamorphism by the Utuado batholith, which may have fanned extra magnetite in the metamorphosed volcanic rocks. Most of the promising porphyry-copper deposits in this area are associated with local magnetic highs and lows distributed along the belt of magnetic volcanic rocks lying between boundaries 5 and 6. Locations of known porphyry copper mineralization are plotted on the boundary map, and the detailed magnetic data indicate other deposits are possible.

7. Boundary 7 is another relatively straight and long boundary farther southwest but also subparallel to boundaries 5 and 6. The boundary lies for the most part within generalized geologic units and implies that an important geologic contact remains still to be identified in this area.

8. Boundary 8 lies southwest of and subparallel to boundary 7. The boundary appears to be associated with contacts of the Anon Formation, which here is relatively magnetic compared to the adjacent rock units.

9. Boundary 9 is the south contact of a narrow antiformal belt of magnetic serpentinite that is substantially covered but appears to connect the two major serpentinite belts of southwestern Puerto Rico with each other. This serpentinite belt is similarly interpreted from the narrow gravity low (gravity anomaly 21) that is also in this location. The wide magnetic gradient sloping down for distances of 5-8 km to the north of this boundary implies that the serpentinite may be present at shallow depths of less than 1 km beneath the Cretaceous and Tertiary rocks associated with the magnetic gradient.

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