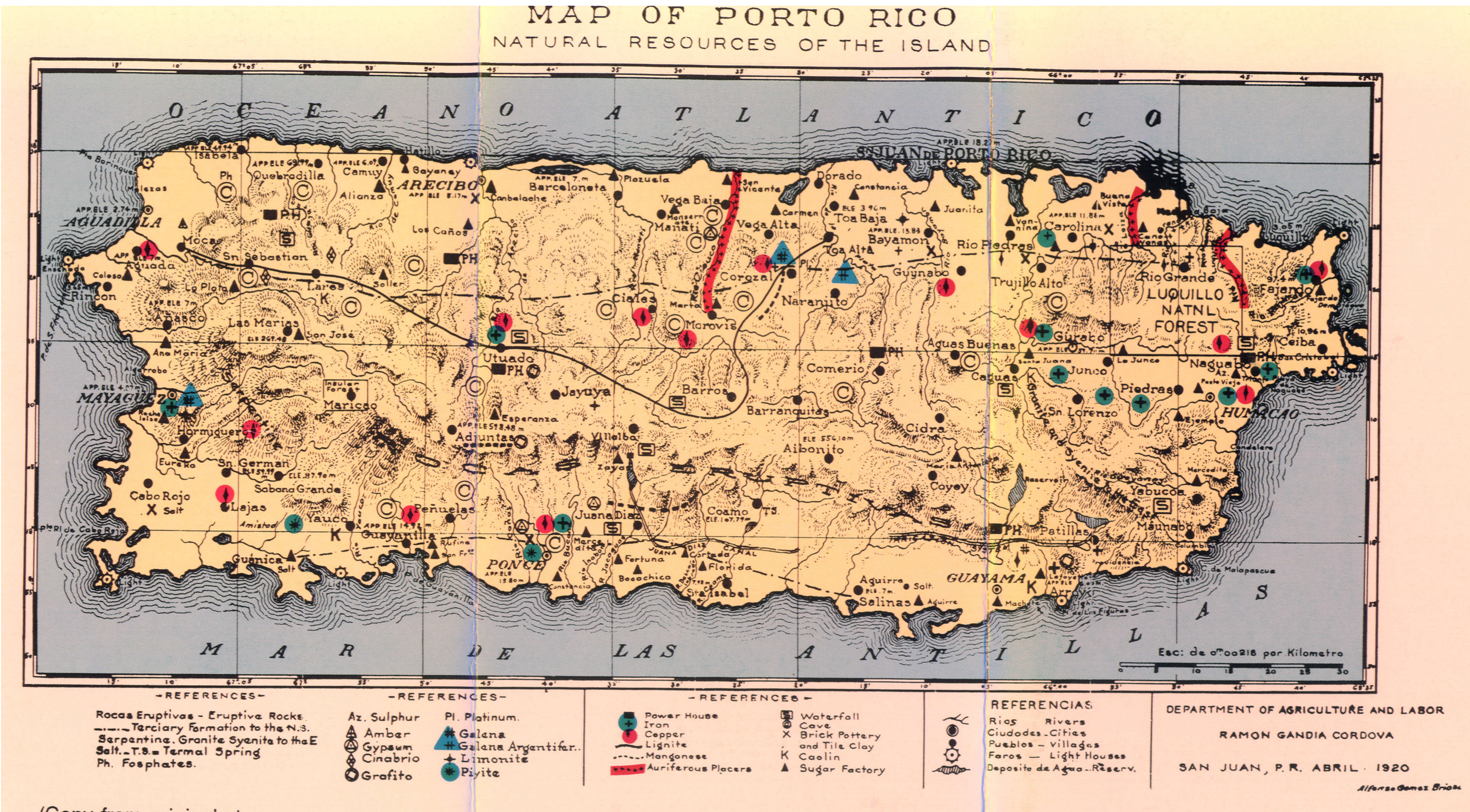
U.S Geological Survey
Open-File Report 98-38

Geology, Geochemistry, Geophysics, Mineral Occurrences and Mineral Resource Assessment for the Commonwealth of Puerto Rico



(Copy from original at Syracuse University Library, New York)

Department of Agriculture and Labor, San Juan, Puerto Rico April, 1920

by U.S. Geological Survey Minerals Team
Editor: Walter J. Bawiec

In Cooperation with:

Puerto Rico Department of Natural Resources
University of Puerto Rico at Mayagüez

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Cover Image

The map on the title page shows a 1920 Map of Natural Resources of Puerto Rico published by the Puerto Rico Department of Agriculture and Labor. The historical perspectives of this map and legend can be observe by zooming into an area of interest.

PREFACE

1) OVERVIEW

The Commonwealth of Puerto Rico has been investigated over a very long period of time by earth scientists from many disciplines and with diverse objectives in the studies. This publication attempts to apply much of the geologic, geochemical, geophysical, and mineral occurrence information to a single objective focused on producing a mineral resource assessment for the Commonwealth of Puerto Rico. However, the value of this publication lies not within the results of the mineral resource assessment nor within the interactive PDF files which can be viewed on the screen, but within the geologic, geochemical, geophysical, and mineral occurrence digital map coverages and databases which can be used for their own unique applications.

The mineral resource assessment of Puerto Rico represents compilation of several decades of mineral investigations and studies. These investigations have been the joint efforts of the U.S. Geological Survey, the Puerto Rico Department of Natural Resources, and the University of Puerto Rico. This report contains not only the mineral-resource assessment, but also much of the scientific evidence upon which the assessment was based. The user may view, navigate, and print on demand any page of the Adobe Portable Document File (PDF) which is included on the CD-ROM. A search tool provided with this file also allows the user to find information anywhere in the database easily.

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Quantitative Mineral Resource Assessment of Puerto Rico by W.J. Bawiec

TOPICAL STUDIES

3) SYSTEM REQUIREMENTS

A color display monitor is strongly recommended with all platforms.

Macintosh:

Mac OS 7.0 or later

Macintosh 68020-040: 2Mb of application RAM

Power Macintosh: 4.5Mb of application RAM

5 MB hard disk space

Windows:

386, 486, or Pentium (R) processor-based personal computer

Microsoft(R) Windows 3.1, Windows 95, Windows NT(TM) 3.5 or later

4 MB of RAM

5 MB hard disk space

DOS:

386- or 486-based personal computer (486 recommended)

DOS version 3.3 or later

2 MB of application RAM (4 MB recommended)

5 MB hard disk space

Unix:

Sun(TM) SPARCstation(R) workstation

SunOS(TM) version 4.1.3 or later, Solaris(R) 2.3 or 2.4

OpenWindows(TM) (3.0 or later) or the Motif(TM) window manager
(version1.2.3 or later)

32 MB of RAM

8 MB of disk space

HP Series 9000 workstation, model 700 or higher

HP-UX 9.0.3 or later

HPVUE desktop environment

32 MB of RAM

6 MB of disk space

4) DISC ORGANIZATION AND CONTENTS

The computer files are stored in a variety of formats, such as Microsoft Excel 97.0, Adobe Illustrator 7.0, Microsoft Word 97.0a, Adobe Acrobat 3.0 and 4.0, and Arc/Info 7.1.1 Export. An Acrobat Reader is included on the disc that allows the user to view the Acrobat PDF files.

The following section contains brief descriptions of the files and formats on the CD-ROM and the way they can be used.

Text.PDF Portable Document File

There are six separate PDF files present to allow multiple files/windows to be open simultaneously. This ability allows the user to read descriptive text from the manuscript.PDF, and have maps, tables, appendices, and figures 'open and viewable' at the same time. PDF files included are:

1. Manuscript.PDF - includes all text and serves as the main body of the manuscript;
2. Graphics.PDF - includes all maps and figures referred to in Text.PDF;
3. Legends.PDF - includes all legends necessary for understanding colors and patterns used on maps. Most maps are linked to legends. (Links are obvious when a 'blue border' surrounds the map and a pointed finger icon appears.);
4. Geochem.PDF - contains all the tables and figures referred to in geochemistry text;
5. Models.PDF - includes digital copies of mineral deposit descriptive models and grade and tonnage models for deposits of Puerto Rico;
6. Appendix.PDF - includes all appendices referred to in the text. These include:
    - Appendix A. - Geologic Map Unit Descriptions
    - Appendix B. - Metallic Mineral Occurrences
    - Appendix C. - Nonmetallic Mineral Occurrences
    - Appendix D. - Geochemical Databases (dBase format)
    - Appendix E. - Complete Puerto Rico MRDS records and GSSEARCH retrieval software.

Descriptions of other computer folders found on the CD-ROM follow in alphabetical order:

Acrobat (folders) - contains Acrobat executable and 'Help' files for Windows 98 and Mac The format used is Adobe Portable Document File (PDF), which is readable by means of the freeware program, Acrobat Reader 4.0, included on the CD-ROM. Instructions below describe how to install Acrobat Reader, as well as launch, view, navigate, and search the Word file. (Word 97)

AML (folder) - contains copies of all aml's used to produce map coverages. Many of the map coverages are compilations and overlays of individual thematic layers, also provided on this CD-ROM. This information can be quite useful in understanding the thematic layers used and in recreating the plot file on the users own system. (Word 97)

EPS (folder) - contains compressed Encapsulated PostScript plot files for those users who can use them. They are in an ASCII file format. These EPS files are provided to allow the user to produce their own plots or PDF files. File root names ending in 'hp' use color sets preferred by HP plotters. To extract files, double click on the WinZip icon.

EXPORT (folder) Contains all map coverages provided in ARC/INFO export format. (ARC/INFO 7.1.1)

GRA (folder) - contains GRA graphic plot files for map coverages and legends. These files are used to produce plots on Versatec electrostatic plotters.

TIFF (folder) - Tagged Image File Format. These files, which are mostly geophysical maps, were scanned in order to provide a raster image to users.

APPENDIX D (folder) - USGS Open-File Report 92-353 text is contained in this folder as a PDF file and geochemical sample analysis as dbase format. These include sample analysis for the main island of Puerto Rico, and Culebra and Vieques.

APPENDIX E (folder) - Contains complete Puerto Rico MRDS mineral occurrence data and GSSTK retrieval software. In order to execute GSSTK, Appendix E instructions must be followed.

5) ACROBAT READER INSTALLATION

Installation procedures vary slightly among the platforms, but, generically, the procedure is as follows:

1. Double click on appropriate Installation folder for your platform; follow instructions
2. Install appropriate Acrobat Reader 4.0 on your hard drive.
3. Launch Acrobat Reader and then open the MANUSCRIPT.PDF file.

6) HINTS FOR USING ACROBAT

The Acrobat toolbar is located along the top of the Acrobat screen. Most of the tools are self-explanatory when the cursor is placed over them. The arrow-head keys move forward and back one page at a time. The bar-arrow tools go to the first or last page in the file. The thick-arrow tool allows the user to go forward and backward to retrace previous views. This is important because most documents lack a "back" button.

The power of using the Acrobat Reader is contained in the ability to view more than one window at a time. This allows the simultaneous viewing of text, maps, tables, and legends. To insure that Acrobat Reader is configured for viewing multiple windows, go to; File, Preferences, General, and insure that ‘Open Cross-Doc Links in Same Window’ is not checked.

The maps, spreadsheets, legends, appendices and text files, which provide additional information, are available through ‘RED’ hypertext links for the MANUSCRIPT.PDF and ‘BLUE’ hypertext links for maps and legends. The cursor changes to a pointing hand over links. After clicking on a link, in most cases, a new figure, table, legend, or map will appear as another window. The user can accommodate this new window by using the command sequence ‘Window; Tile Horizontally’ However, it must be remembered that a map coverage which is hypertext linked to a text, legend, etc. (has a blue border) CANNOT use the ‘zoom’ button. ‘Up’ and ‘Down’ scroll arrows and the ‘magnification’ button at the bottom of the window must be used to zoom into a specific area.

The bookmarks in the left-hand column allow direct access to all pages. Clicking on the ‘+’ symbols at the extreme left expand individual bookmark chapter headings into sub-headings.

In the Acrobat file, the words that include those in the maps are searchable with the binocular tool. The second and third tools from the left allow switching between bookmark and thumbnail views in the left-side scrollable area.

Owners of older computers may wish to interrupt a slow drawing map. In this situation, simply select another destination in the bookmarks. This stops the current map drawing and displays the next document. On the Macintosh, hold down the Command and period keys to interrupt the current map draw.

7) ACROBAT TUTORIAL

The following Acrobat Tutorial demonstrates viewing of several types of data. The user can open the MANUSCRIPT.PDF document twice to keep these instructions available in another window, or print out this Tutorial.

Select the "MANUSCRIPT.PDF" and adjust window to fit screen.
If Bookmarks are not already visible, click on ‘Show/Hide Navigation Pane’, the sixth icon from the left.
Select the ‘Bookmarks’ tab
The chapter ‘Geology of Puerto Rico’ should be visible, with four subheadings below it.
Click on the subheading ‘Geology of Puerto Rico’. This is page 25 of 337 pages.
Click on the ‘Next Page’ icon four times until ‘Geology of Southwestern Puerto Rico’ is found.
Click on ‘Geology of Southwestern Puerto Rico’. A geologic map appears in a separate window.
Select ‘Window, Tile, Horizontally’ to see both windows simultaneously. If you cannot see both windows, refer to previous section of this CD-ROM : **6. Hints for using Acrobat**
The cursor on the geologic map appears as a ‘pointed finger’, indicating that the map is hypertext linked.
Click on the geologic map. A new window appears displaying Puerto Rico map units.
Select ‘Window, Tile, Horizontally’ to see all three windows simultaneously. These windows are Manuscript.PDF, Graphics.PDF, and Legends.PDF.

In the Legends.PDF window, select a scale of 400% to view map unit patterns and mnemonics. You can now read the manuscript text, examine the geologic map, and use the legend to identify units.

Click on Legends.PDF to view descriptions of map units.

Select ‘Window, Tile, Horizontally’ to view four separate windows and themes.

This example shows capabilities of this Previewing Software which can also be used with the geochemistry, geophysics, mineral occurrences, and resource assessment.

8) DISCLAIMER

Graphical map depictions on this disc are intended to be used within the map scale limits applicable to the source data. Although software enables the user to show images on the disc at various scales, the user is cautioned that enlarging the maps beyond a scale of 1:100,000 is not warranted.

INTRODUCTION

by

Sherman P. Marsh

The mineral resource assessment of the Commonwealth of Puerto Rico was initiated under the auspices of the North American Mineral Resource Assessment Program (NAMRAP) of the U.S. Geological Survey (USGS) and was done with the cooperation and assistance of the Puerto Rico Department of Natural Resources (DNR) and the University of Puerto Rico at Mayaguez.

The mineral resource assessment of Puerto Rico represents a compilation of several decades of mineral investigations and studies. These investigations have been the joint efforts of the U.S. Geological Survey, the Puerto Rico Department of Natural Resources, and the University of Puerto Rico. This report contains not only the mineral-resource assessment, but much of the scientific evidence upon which the assessment was based. This includes the geologic map and maps derived from the geologic map, geophysical maps, geochemical maps and data, mine and mineral occurrence maps and data, and maps showing terrane permissive for various mineral deposit types. Although much of this information existed prior to our assessment and some of it was published in various formats, none of it has previously appeared comprehensively in a single publication. All of the data used in this report are in digital format and may be used as input into a variety of computer-generated geographic information system (GIS) products.

Several topical studies have been included in this assessment that provide additional information on specific areas or commodities. This more detailed information has also been integrated into the mineral resource assessment.

The purpose of this mineral resource assessment is to provide an inventory of the known mineral occurrences, to give an estimate of the potential for undiscovered mineral resources in the Commonwealth, and to provide a multipurpose earth science database. The earth science data presented in this report will assist in long-range planning for environmental, health, and mineral resource concerns in the Commonwealth of Puerto Rico and will provide a clearer understanding of the mineral potential of the island.

ACKNOWLEDGEMENTS

The mineral-resource assessment of Puerto Rico, Isla de Vieques, and Isla de Culebra reflects the contributions of many individuals over many decades without whose help and cooperation the completion of the project would not have been possible.

The initial planning by Gregory E. McKelvey (Phelps Dodge Mining Inc.), Norman J Page (USGS), and Ramon Alonzo (DNR) resulted in the mineral-resource assessment of Puerto Rico becoming a project in the U.S. Geological Survey North American Mineral Resource Assessment Program (NAMRAP).

The following are some of the many individuals who have made this mineral-resource assessment of Puerto Rico possible. M. Babas, K. Bond, R. P. Briggs, M. W. Doughten, V.A. Langenheim, D. LaRue, J. Mariano, M. Ceulo, J. C. Moya, I. Perez, M. H. Podwysocki, M. Queen, M. Quiñones, P.E. Sauer,

We also wish to thank our colleagues in the Branch of Atlantic Marine Geology and USGS Water Resource Division in Puerto Rico for their help and assistance during the 1991 field season and throughout the course of the project. A special thanks to P. D. Collar, R. W. Rodriguez, A. A. Sepulveda, J. W. Troester, R. M. Webb, and A. L. Zack.

C.M. Nelson of the U.S.G.S. Office of Scientific Publications contributed significantly to the historical account of the U.S. Geological Survey involvement in Puerto Rico.

A special thank you goes to the Technical Reviewers of the many sections of this report including: Paul Schruben, Steve Snyder, George Mason, D. McGuire, Robert Learned, Norman J Page, E. Mosier, Herb Pierce, J.D. Bliss, John M’Gonigle, D.A. Ponce, H. Alminas, Klaus Schulz, Mike Foose, D. Foster, P. Popenoe, J. Hathaway and others who may have been forgotten.

The GSSEARCH program developed for Windows is a result of the work of Kim P. Buttleman, of the USGS, which is used to retrieve MRDS mineral occurrence records.

History of Previous Activities of the U.S. Geological Survey in Puerto Rico

by

Robert E. Learned

The U.S. Geological Survey's activities in Puerto Rico began nearly a century ago. In fact it was on January 9, 1899, the month following Spain's cession of the island to the United States on December 10, 1898, that R.T. Hill and H.B.C. Nitze conducted a reconnaissance of the island's geology and mineral resources. They subsequently published the results of their mineral resource investigations in the USGS twentieth Annual Report for 1898-1899. H.M. Wilson's concurrent investigation of the topography and water resources of Puerto Rico was published as Water-Supply paper No. 32.

In January of 1900, Director Charles Walcott requested $16,000 from Congress to carry out topographic and geologic surveys of Puerto Rico, but it was not until March of 1908 that E.M. Douglas led a team to survey the boundaries of the Luquillo National Forest. Later that year, USGS topographers mapped 150 square miles of the southern coastal plain near Ponce and Guayama in support of a proposed irrigation project. In the meantime, in 1901, Henry Gannett, Chief Geographer, published a 50 page gazetteer of the island as USGS Bulletin 183 (Gannett, 1901).

During World War I, on March 2, 1917, Congress passed the Jones Act, which granted U.S. citizenship to Puerto Rico's inhabitants. In the spring of 1918, the USGS extended its search for war-critical minerals to the Caribbean, where Max Roesler led the effort in Puerto Rico.

The Survey's topographic work in Puerto Rico recommenced in the first half of 1922 (January-June), again in support of an irrigation project. D.H. Watson, accompanied by geologist G.H. Mansfield, led a team of topographers to map some 40 square miles along the northwestern coast between Rio Guajataca and the town of Aguadilla.

USGS efforts in Puerto Rico continued during the Great Depression as the Public Works Administration, in 1933, allocated $25,000 for topographic surveys in Puerto Rico as part of a $2.4-million program of topographic mapping in the United States. During the months of February to July 1934, a USGS party led by topographer B.H. Yoakum completed triangulation of the island and extended spirit leveling in the western half. Then, in 1935, a USGS party led by topographer W.R. Chenworth mapped an area of 150 square miles in the southwestern corner of the island in support of a proposed irrigation project in the Lajas Valley. In 1937, Congress amended the Temple Act (1925) to include Puerto Rico in the cooperative State/USGS topographic mapping program. Accordingly, a USGS topographic team led by K.W. Trimble commenced systematic topographic mapping of the island at 1:20,000 scale. The mapping was completed after World War II, and the USGS National Mapping Division continues to revise maps as changes dictate.

Puerto Rico's post-war Operation Bootstrap, a program designed to promote industrial development, was launched in 1945. That same year, the USGS, in cooperation with the Puerto Rico Development Company (PREDA), an agency of the insular government, conducted a geologic investigation of the islands' coastal plains to assess oil and gas potential. Teodoro Moscoso, Director of PREDA, and Rafael Fernandez Garcia, Chief Engineer, provided logistical support to the USGS team of geologists, A.D. Zapp, B.R. Berquist, and C.R. Thomas. The results of their investigation were published in 1948 as USGS Oil and Gas Investigations Map No. 85 (Zapp and others, 1948).

USGS investigations of the water resources of Puerto Rico were also initiated in 1945, when A.G. Unklesbay conducted a brief investigation of the ground-water supplies of the San Juan area, at the request of PREDA. A cooperative investigation between the USGS and the Puerto Rico Aqueduct and Sewer Authority began later that year and continued into 1947. Its purpose was to obtain island-wide information on ground-water supplies with respect to its quality, quantity, and availability for public supply systems and domestic, industrial, and agricultural uses. Sergio Cuevas Bustamante, Administrator and Chief Engineer of the Puerto Rico Aqueduct and Sewer Service, took the initiative in arranging for the cooperative investigation and facilitated its conduct. Alberto Hernandez, Chief of the Production and Distribution Division, provided valuable information on ground-water supplies. C.L. McGuiness, a USGS hydrologist, presented the results of the investigation at the 1947 annual meeting of the Society of Economic Geologists, and published the results in volume 42 of Economic Geology.

From March of 1949 to September of 1951, USGS geologist C.A. Kaye served as advisor to four Puerto Rican Government agencies, providing those agencies with geologic advice of an engineering nature. The lead personnel of the cooperating agencies with whom he worked included Antonio Lucchetti, Executive Director of the Puerto Rico Water Resources Authority; Rafael Fernandez Garcia, Director of Industrial Research of the Puerto Rico Economic Development Administration; Sergio Cuevas Bustamante, Administrator of the Puerto Rico Aqueduct and Sewer Authority; and Enrique Rubio, Official of the Insular Department of the Interior. During the same period, Kaye carried out field studies that resulted in a geologic map of the San Juan area, a report on shore line forms and processes, and a geologic report on Isla de Mona, all of which appeared in USGS professional paper 317, (Kaye, 1959 a-f).

In the same year that Puerto Rico became self governing (1952), the USGS, in cooperation with PREDA, carried out an investigation to determine the adequacy of available geologic and mineral resource data, and to examine the field occurrences of the known mineral resources. Rafael Fernandez Garcia, Director of Research at PREDA, actively supported the USGS project geologists, H.M. Bannerman and R.J. Smith. One of the principal conclusions of their investigation was that basic geologic data needed for the appraisal and development of the Island's mineral resources be collected through detailed geologic mapping. Consequently, in 1955, the USGS Office of Regional Geology, in cooperation with PREDA, inaugurated a program of geologic quadrangle mapping that ultimately produced sixty 7 1/2-minute geologic maps, as well as a great many related scientific reports. More than 20 USGS geologists participated in the program, which was led consecutively by resident geologist-in-charge R.J. Smith, J.P. Owens, W.H. Monroe, R.P. Briggs, and J.M. Aaron. Puerto Rican participants included Eduardo Aguilar, Jose Francisco Cadilla, Carlos Cram, Angel Curet, Pedro Gelabert, and Leovigilda Vasquez. Two geologic maps of the entire island were published at 1:240,000 scale by R.P. Briggs in 1964 (HA-197, I-392).

In 1957, the Water Resources Division of the USGS, in cooperation with the Puerto Rico Water Resources Authority and other Puerto Rican Government agencies, established a program to investigate the water resources of Puerto Rico. This program, which is still in operation today, has produced many water-supply reports and other significant publications during the 35 years since its inception. Resident hydrologists-in-charge have been in chronological order D.B. Bogart, D.G. Jordan, C.B. Bentley, E.D. Cobb, F. Quinones, and A.L. Zack.

In 1968, the USGS Office of Marine Geology, in cooperation with the PREDA initiated a study of the insular shelf of Puerto Rico. When the marine project was integrated into the Puerto Rico Department of Natural Resources in 1973, its emphasis was redirected toward systematic geologic mapping of the entire insular shelf. The resident USGS scientific and support staff has consisted almost entirely of Puerto Ricans. Rafael Rodriguez, the current project chief and USGS geologist-in-charge succeeded J.V.S. Trumbull, who had served since the project's inception.

In 1969, the USGS Office of Mineral Resources, in cooperation with the Puerto Rico Department of Public Works, began an investigation of the mineral resources of the island and established a geochemical laboratory in San Juan. Antonio Santiago Vasques, Secretary of the Department, and Cruz Matos, Sub-Secretary of the Department's Area of Natural Resources, were instrumental in initiating the project and supported it vigorously until its completion in 1974. Much of the project's attention was focused on the geology and geochemistry of the porphyry copper deposits in west-central Puerto Rico, an area that also served as a training ground for several Puerto Rican geologists. The geochemical laboratory, which analyzed all the samples collected by project geologists, was staffed entirely by Puerto Rican personnel. Ileana Perez, the current Chief Chemist, succeeded Rafael Boissen, who had served in that capacity from 1969 to 1973. The project produced many scientific publications, including a metallogenic map of Puerto Rico by D.P. Cox, who served as resident geologist of the project.

In 1974, at the request of the Puerto Rico Electrical Power Authority, the USGS designed and established a seismic network to assess regional and local seismicity that could affect the proposed construction of a nuclear power plant. The Power Authority's objectives were accomplished by 1979, but USGS scientists continue to provide limited support in the interpretation and processing of accumulated data.

In 1980, the USGS Office of Mineral Resources and the Puerto Rico Department of Natural Resources (PRDNR) initiated a systematic geochemical survey of the drainage basins of Puerto Rico. Geologists Robert E. Learned, USGS, and Ramon Alonso, PRDNR, led the project. Lack of financial support terminated the undertaking before its completion, but the results for one major drainage basin were published in 1981 and the remainder is incorporated in the present work.

Immediately following the Puerto Rico landslide disaster of October 7, 1985, a hazard research team from the USGS Office of Earthquakes, Volcanoes, and Engineering responded to requests for an assessment of the hazards related to the landslide. Reports of their evaluation and recommendations were provided to federal and insular government agencies, and were subsequently published in 1985 and 1986.

In 1985, the USGS, in cooperation with the United Kingdom Institute of Oceanographic Sciences, conducted a side-scan sonar survey (GLORIA) of Puerto Rico's Exclusive Economic Zone (EEZ) and in 1987 published the resulting maps in its "Atlas of the Exclusive Economic Zone, Gulf of Mexico and Eastern Caribbean Areas".

Side-looking airborne radar imagery (SLAR) of Puerto Rico was produced for the USGS in 1987, and in 1989, K.M. Scanlon and C.S. Southworth combined GLORIA and SLAR mosaics to more effectively interpret the tectonics of the northern Caribbean plate boundary zone.

In 1990, USGS geoscientists began compilation of the information required to make a mineral resource assessment of the island. This assessment constitutes the subject matter of the present work.

For almost a century, geoscientists of the USGS, often in cooperation with agencies of the insular government, have studied many aspects of Puerto Rican geology. Their efforts have resulted in major contributions to an understanding of the island's geology, and to the welfare of its people.

Geology of Puerto Rico

Geology of Puerto Rico

by

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INTRODUCTION

U.S. Geological Survey scientists and others have studied the geology of Puerto Rico for decades, and, as a result, the USGS has published geologic maps and reports that illustrate the geology of most of the island. But, even with decades of work, Puerto Rico is not yet completely mapped at a scale of 1:20,000. Because different workers initiated their work in different areas and at different times, stratigraphic names proliferated to the point that they now may be thought to obscure the understanding of the geology of the island. This compilation and interpretation is intended as an introduction to the geology of Puerto Rico. For detailed information, the reader is referred to the original works cited. The purpose of this discussion and the digitized geologic map of the island is to draw some of this work together and to make it more comprehensible to those who are not expert in the geology of the island.

TECTONIC SETTING OF PUERTO RICO

Puerto Rico, the easternmost island of the Greater Antilles, is a volcanic island-arc terrane in which the geologic record spans about 150 million years. The island consists of volcaniclastic and epiclastic rocks of volcanic origin as well as other sedimentary rocks of Late Jurassic to Paleocene and Eocene age and intrusive mafic and felsic plutonic rocks of Late Cretaceous and early Tertiary age. These rocks are overlain unconformably by Oligocene and younger sedimentary rocks and sediments (Monroe, 1972). Puerto Rico is bounded on the north by the Puerto Rico Trench, on the south by the Muertos Trough, on the east by the Anegada Passage and on the west by the Mona Canyon.

The microplate of which Puerto Rico and the Virgin Islands are the subaerial expression lies within the seismically active Caribbean-North American plate boundary zone. A well-defined southward-dipping Benioff zone lies beneath the east half of the island but is absent in the west half (Schell and Tarr, 1978; Sykes and others, 1982; McCann and Sykes, 1984). Extension, as a result of left-lateral relative motion between the Caribbean and North American plates, created the Puerto Rico Trench. Left-lateral motion between the two plates may have been in part taken up by counter-clockwise rotation of the Puerto Rican microplate in the boundary zone (Speed and Larue, 1991). The left-lateral transpressive movement between the plates and counter-clockwise rotation of the island resulted in left-lateral wrench faults throughout the island. Left-lateral wrench faults also appear to be illustrated in off-sets in the Puerto Rico Trench (EEZ-SCAN Scientific Staff, 1987). Rotation of the microplate has caused thrusting in the Muertos Trough (Byrne and others, 1985) and extension in the Anegada Passage (Larue and others, 1990). Extension in the Mona Canyon (Gardner and others, 1980) may have been caused by differences in the rates of rotation between the eastern and western ends of the microplate (Speed and Larue, 1991).

Paleomagnetic study of Puerto Rico indicates that it, probably together with Cuba and Hispaniola, was originally deposited as part of an island-arc off the west coast of South America, initially located at about the present latitude of the Peru-Ecuador border. Beginning at some time in the Eocene, continuing throughout the Oligocene, and ending at some time in the Miocene, the island-arc was rafted northward and then eastward between the North and South American plates (Elston and Krushensky, 1983; Krushensky and Elston, 1983). Eastward rafting was accompanied by a clockwise rotation that exceeded 90 degrees.

Elston (written communication, 1998), in response to questions raised by Gose (1985), reports that the above scenario was deduced from a general correlation with the polarity time scale of sets of antiparallel polarity reversals from Early Cretaceous to Eocene rocks. Ages for the rocks were derived from fossils and isotopic dating. These ages were refined by geologic mapping that gave rise to correlations described later. Because of the mapping, geologically well controlled rocks of Puerto Rico allowed development of the only large, temporally extensive, relatively well-controlled paleomagnetic data set in the Caribbean. Importantly, the Puerto Rican data-set led to identification of the first defensible Normal polarity paleomagnetic direction from Caribbean rocks.

Elston further notes that normal polarity for the Puerto Rican set was originally derived from a general correlation of polarities from the dated rocks with the polarity time scale of Lowrie and Alvarez (1981). Gose (1985, p. 295) subsequently noted that this time scale differed in some detail from a more recent time scale reported for the Decade of North American Geology. For this reason, he considered the correlation proposed by Elston and Krushensky to be suspect, and he proposed inverting the polarity scheme to bring the normal polarity direction for Puerto Rico into agreement with the assessments of other paleomagnetic data from the Caribbean. Not acknowledged in Gose's critique, is the observation that inversion of the polarity zonation would lead to a major conflict and disconnect between the polarity zonation from dated rocks of Puerto Rico and ages assigned the zonation on the polarity time scale.

The problem of discrepancies in detailed correlation among the polarity time scales has increased as the number of proposed time scales has increased. It was only with the continuous coring of several 1.5 to 2 km deep holes in late Miocene and Pliocene strata of the Pannonian basin of Hungary that an answer to this discrepancy became apparent. Oriented samples from the Pannonian basin collected on 1 m intervals provided extremely high resolution magnetostratigraphic records. These records displayed myriads of reversals not shown on any of the published polarity time scales.

Correlation of the Hungarian records with the polarity time scale was accomplished only by correlation of the larger intervals of normal and reversed polarity. Therefore, all of the several published time scales should be considered to be highly generalized. Their intervals of normal and reverse polarity, no matter how brief, in themselves almost certainly contain unrecognized and unrecorded reversals. Additionally, brief reversals within the larger intervals of normal and reverse polarity, in themselves characteristically contain multiple reversals. As shown by the Hungarian magnetostratigraphic data, reversals are not simple switches of polarity. Rather they are the product of an oscillating ambient field that has ranged from relatively stable to highly unstable (Elston, Lantos, and Hamor, 1994).

For the above reasons, the correlation of polarity switches between stratigraphic units and the polarity time scale has little chance of being precisely correct. Nonetheless, correlations sufficiently accurate for general geological purposes are still possible, but they need to be derived from correlations with the larger intervals of normal and reversed polarity in the time scale. Such correlations were possible in the Puerto Rican magnetostratigraphic record, and the record from Cretaceous rocks has allowed a reliable normal polarity direction to identified. The process involved identifying strata deposited during the long interval of normal polarity, later Aptian to Campanian, and identifying strata and intrusive igneous rocks deposited and emplaced during Campanian time, older part, reverse polarity; younger part, normal polarity. Strata identified with the long normal interval included parts of the Robles and Cariblanco formations. Strata identified with lower Campanian interval of reverse polarity include the Yauco, Achiote, Maravillas, and Pozas Formations, and Perchas Lava. Ar-Ar dated intrusive rocks of the San Lorenzo Batholith, have ages and a uniform polarity that coincides with and spans the age range of the normal polarity interval assigned to the upper Campanian. Thus, for an interval spanning more than 30 m.y. of time, the Puerto Rican magnetostratigraphic record indicates that the east-directed declinations represent the normal polarity direction during Cretaceous and Eocene time.

The foregoing correlations thereby allowed low paleomagnetic inclinations associated with the directions to identify the northerly and southerly latitudes of deposition, eruption, and intrusion. Rotations during changes of paleolatitude also were identified. Negative normal polarity inclinations indicated formation south of the equator during the Cretaceous, and a pronounced clockwise rotation following movement to north of the equator. The paleolatitudes and movements are best interpreted as indicating Puerto Rico formed on the west side of South America.

In this and other paleomagnetic studies, the westerly directed declinations derived from Cretaceous rocks plot closer to North America and the North American normal polarity pole than antiparallel easterly directed declinations. In most (all?) other studies, westerly directions from the Caribbean have been inferred to represent the normal polarity Cretaceous direction. This assumption has led to a routine evaluation of poles from the westerly directions with respect to the Cretaceous normal polarity pole for North America. Discordances between the North American and Caribbean poles then have been interpreted to reflect the senses of rotation and amounts of translation of rocks in the Caribbean. Such evaluations have led to a widely reported and accepted counter-clockwise rotation of the island terranes of the Greater Antilles (e.g., MacDonald, 1990; Renne and others, 1991). From this, a counter-clockwise-rotating roller-bearing model has served to explain the apparent westerly rotation of Caribbean paleomagnetic directions past the Cretaceous direction and pole for North America.

In contrast, a 90 degree + clockwise rotation of Cretaceous-Eocene directions is indicated from the large Puerto Rican magnetostratigraphic data set. Additionally, the latitude of formation, dominantly south of the equator during Cretaceous to middle Eocene time, shifts north of the equator in late Eocene time. In order to arrive at its present location, Puerto Rico then must have been transported strongly eastward during Oligocene into early? Miocene time. Similar rotations, shifts in paleolatitude, and translations presumably occurred elsewhere in the Greater Antilles.

The foregoing scenario is fully compatible with a Cretaceous-Eocene island arc source for Puerto Rico, a terrane that originally resided near and north of the Nasca plate. Cretaceous movements were followed by the development of left-lateral shear and displacement on faults along the northern margin of the Carribean plate during later Paleogene and Neogene time. In this framework, the observed left-lateral shear and displacements reported from
geological studies would arise as a consequence of drag along and near the northern margin of an easterly moving Caribbean plate. These displacements would have occurred as more central parts of the Caribbean plate lying south of Puerto Rico moved differentially to the east.

Finally, Elston (written communication, 1989) notes that, without the results of the extensive geologic field studies described in the following pages, development of the many reliable paleomagnetic directions for Puerto Rico would not have been possible. Nor could the directions have been correlated with the polarity time scale to allow a critically needed normal polarity direction to be identified.

Ubiquitous closely spaced strike-slip and normal faults, the generally massive nature of the volcanic and volcaniclastic rocks, the very local nature of many lithofacies, the irregular interbedding of most volcanic and volcaniclastic rock types, and the lack of reported fossils from all but a few stratigraphic units have severely inhibited a detailed demonstration of the true structural nature of the island and the recognition of a coherent island-wide structural history. However, the history of movements and rotations of Puerto Rico interpreted from the paleomagnetic data can help explain some of the structural character of Puerto Rico.

Prior to the completion of mapping of the western and southwestern parts of the island, earlier workers had subdivided Puerto Rico into northeast, central, and southwest structural-stratigraphic blocks on the basis of the perceived presence of major strike slip faults or fault zones and the lack of continuation of stratigraphic units across these faults. Detailed mapping in the eastern part of Puerto Rico indicates that the Cerro Mula-Quebrada San Francisco Fault, a left-lateral wrench fault, does indeed separate distinctive formations in the northeast block from those in the remainder of the island. A southwest Puerto Rico fault zone that was conjectured to separate central and southwest blocks was placed at various locations (Glover, 1971, Briggs, 1973; Cox and Briggs, 1973), but its presence and function in the separation of lithologically unlike blocks was not demonstrated. The presence of oceanic plate rocks in the southwestern part of the island might be thought to characterize a southwestern block, but the detailed delineation of the block is not possible because of the widespread cover by younger Cretaceous and Tertiary rocks and the presence of pervasive normal and strike-slip faults. Nevertheless, division of the island into blocks for purposes of description and discussion helps in simplifying a complex stratigraphic picture, and that scheme will be followed here.

GEOLOGIC DESCRIPTIONS BY REGION

GEOLOGY OF SOUTHWESTERN PUERTO RICO

The oldest rocks in Puerto Rico, the Bermeja Complex (Mattson, 1960a) constitute an ophiolitic suite that was, at least in part, emplaced as a nappe (Mattson, 1973a). The Bermeja consists of serpentinite, serpentinite-enclosed amphibolite or metabasalt, and spilitized basalt, the Las Mesas Greenstone (Schellekens and others, 1990), which, at least locally, intrudes serpentinite (Mattson, 1960; Krushensky and Monroe, 1978a, Volckmann, 1984a, b, c; and Curet, 1986), unconformably overlain by the Mariquita Chert, which is locally interbedded with basalt, possibly the Cajul Basalt (Mattson, 1973a; Volckmann, 1984a, b). Foraminifers in the Mariquita range in age from Jurassic to Late Cretaceous, that is, early Tithonian (Mattson and Pessagno, 1979)to Turonian (Volckmann, 1984). Because epiclastic-appearing serpentinite breccia and conglomerate crop out stratigraphically beneath rocks of the younger volcaniclastic sequence in the Mayagüez quadrangle (Curet, 1986), serpentinite may have been exposed at the surface prior to deposition of the overlying volcaniclastic formations. Determination of the relative age of serpentinite as pre- or post-volcaniclastic sequence is difficult because serpentinite also has been emplaced as a "cold" intrusion into overlying volcaniclastic rocks (Curet, 1986). Gneissic and massive amphibolite probably have an ocean-floor origin, and spilitized basalts and dikes probably share an island arc origin (Schellekens and others, 1990).

Calc-alkaline and dacitic epiclastic volcanic rocks and volcaniclastic rocks, generally deposited in a marine environment, cover much of the Bermeja, and crop out from the southwestern corner of the island to the Ponce, Jayuya, and Adjuntas quadrangles in the east and in the Rincon, Central La Plata, and San Sebastian quadrangles to the north, beyond the boundaries of the ophiolite sequence. Where they overlie the ophiolite, these rocks may have been rafted into position along with the underlying oceanic rocks.

Marine siltstone, sandstone, and conglomerate of the Yauco Formation unconformably overlie the Mariquita and crop out from the Mayaguez and Rosario quadrangles in the southwest corner of Puerto Rico (Curet, 1986) east to the Ponce quadrangle in the central southern part of the island (Krushensky and Monroe, 1975). Graded siltstone of the Yauco hundreds of meters thick crops out over wide areas, but examination of the stratigraphic section in many areas in the western part of the island also reveals extensive interbedding of the Yauco with marine volcaniclastic breccia of the Sabana Grande Formation of Turonian to Maastrichtian age (Volckmann, 1984d; Krushensky, unpub. data, 1982), with trachybasalt breccia, the Maricao Formation, and andesitic breccia and lava of the Lago Garzas Formation. Trachybasalt breccia, first mapped as the Maricao Formation in the Maricao quadrangle (McIntyre, 1975), crops out to the east in the Monte Guilarte (Krushensky and Curet, 1984) and the Mayaguez and Rosario quadrangles (Curet, 1986). Outcrops of the Maricao in the Adjuntas and Jayuya quadrangles were originally mapped as the Robles Formation (Mattson, 1968a, b). Andesitic lava and breccia mapped as the Lago Garzas Formation, and locally as the Rio Blanco Formation (Hubbard, 1923; Slodowski, 1956; Mattson, 1960; and Pessagno, 1960), crop out in the Adjuntas, Central La Plata, Jayuya, Maricao, Monte Guilarte, Peñuelas, Ponce, Rosario, San Sebastian, and Yauco quadrangles (Mattson, 1968a, b; McIntyre, 1971; 1975; Tobisch and Turner, 1971; Krushensky and Monroe, 1975; 1978a; Krushensky and Curet, 1984; Curet, 1986) in the central-western and western parts of the island. Although individual lithofacies may be hundreds to more than 1,000 m thick in a single fault block, they are also present as interbedded sequences in which single lithic types may be only a few to tens of centimeters thick. Foraminifers in this interbedded sequence of disparate lithofacies indicate a generally Late Cretaceous through Paleocene age, with a range of Cenomanian through Paleocene (Krushensky and Monroe, 1978; Krushensky and Curet, 1984; Volckmann, 1984d; and Curet, 1986).

Locally, calc-alkaline lithofacies equivalent to the Boqueron Basalt and lava and tuff of the Lajas Formation are interbedded within the Yauco lithofacies in southwestern Puerto Rico (Volckmann, 1984a, b, c, d). The Boqueron and Lajas do not show pillow structures and were assumed to have been deposited under subaerial conditions. However, limestone lenses within the Boqueron and the presence of the Cotui Limestone immediately overlying the Lajas suggest near-shore marine to subaerial conditions of deposition for these basaltic rocks. The El Rayo Formation, a marine unit of pillowed basaltic lava, breccia, and limestone lies within and conformably overlies the Yauco Formation in the San German (Volckmann, 1984b) Sabana Grande (Krushensky, unpub. data, 1982) and Punta Verraco (Krushensky and Monroe, 1978b) quadrangles.

Carbonate banks, composed chiefly of rudist debris, occur sporadically throughout the Yauco and in the Lago Garzas and Sabana Grande Formations in southwestern Puerto Rico, locally in masses sufficiently large so as to allow their mapping as separate stratigraphic units. Examples are the Parguera Limestone of late Santonian to early Maastrichtian age, which unconformably overlies the Bermeja Complex (Almy, 1965b); the Cotui Limestone of early Campanian to early Maastrichtian age, which is overlain by the Sabana Grande and overlies the Lajas Formation; the Melones Limestone of late Campanian to middle Maastrichtian age (Volckmann, 1984a,d), and the Peñones Limestone of Maastrichtian age (Curet, 1986).

Thick sequences of rhyodacitic and dacitic tuff, breccia, and lava mapped as the Anon Formation crop out in the Ponce, Jayuya, and Adjuntas quadrangles (Mattson, 1968a, b; Krushensky and Monroe, 1975). The Rio Culebrinas Formation, in the San Sebastian, Central La Plata, and Rincon quadrangles (McIntrye and others, 1970; McIntrye, 1971; Tobisch and Turner, 1971), is lithologically identical to marine facies of the Anon in the Monte Guilarte Quadrangle (Krushensky and Curet, 1984). These rhyodacitic and dacitic rocks interbed widely with characteristic lithofacies of the Lago Garzas (McIntrye, 1975), and were mapped as the Palma Escrita and Mal Paso Formations in the Central La Plata, Maricao, Aguadilla, and Rincon quadrangles (Monroe, 1969; McIntyre, 1971; 1974, 1975) and as the Milagros and Matilde Formations in the Bayaney quadrangle (Nelson and Tobisch 1967, 1968). The Anon, Yauco, and Maricao also interbed variably in the Monte Guilarte, Yauco, and Bayaney quadrangles (Nelson and Tobisch, 1968; Krushensky and Monroe, 1978; and Krushensky and Curet, 1984). Foraminifers in the interbedded lithofacies of the Anon and Lago Garzas range from late Paleocene to early middle Eocene (Nelson and Tobisch, 1967; McIntyre and others, 1970; Krushensky and Monroe, 1975; McIntyre, 1975, Krushensky and Curet, 1984). Farther east in the Ponce, Jayuya, and Adjuntas quadrangles (Mattson, 1968a,b; Krushensky and Monroe, 1975) the Anon interbeds with, and is underlain by, a generally graded sequence of dacitic siltstone and sandstone, that contains minor tuff and conglomerate, chert, and bioclastic limestone, of the Monserrate Formation, of middle Eocene age. The Monserrate is the equivalent of the Rio Descalabrado Formation in the Rio Descalabrado quadrangle (Glover and Mattson, 1973) to the east. The Monserrate conformably overlies the Cuevas Limestone, a bioclastic limestone of early to middle

Eocene age in the Ponce and Jayuya quadrangles (Mattson, 1968b; Krushensky and Monroe, 1975).

The Cuevas Limestone, and locally the stratigraphically overlying Monserrate and Anon Formations, constitute an allochthonous plate that overlies the Maravillas Formation or the Achiote Conglomerate everywhere the Cuevas is exposed in the Jayuya and Ponce quadrangles (Mattson, 1968b, Krushensky and Monroe, 1975), or the Coamo Formation in the Rio Descalabrado quadrangle (Glover and Mattson, 1973). The Cuevas in these quadrangles is widely underlain by a fault gouge, the so-called Miramar Formation (Pessagno, 1960), which consists of clasts of whatever formation immediately underlies the Cuevas and clasts of the Cuevas Limestone in a hematite red, slickenside-riddled clayey gouge matrix (Krushensky and Monroe, 1975; Krushensky, 1978).

Although fossils of Tertiary age have not been reported to be present in the Yauco lithofacies, the presence of Foraminifers of Tertiary age in interbedded lithofacies of the Anon and Lago Garzas and of the Anon, Lago Garzas, and Maricao and the fact that the Yauco, Anon, and Lago Garzas, and the Maricao interbed conformably over wide areas, strongly suggests that the Yauco may also be Cretaceous and Tertiary in age. The conformable interbedding of these lithofacies over wide areas also indicates that there was no demonstrable break in sedimentation between the Cretaceous and the Tertiary in what is now western Puerto Rico (Krushensky, 1978).

The youngest volcaniclastic rocks in the southwestern part of the island, the Jicara Formation, consist of siliceous mudstone and siltstone of early Eocene age, which crop out over limestone of the El Rayo Formation in the San German quadrangle (Volckmann, 1984c), and in adjacent areas of the Sabana Grande quadrangle the Jicara overlies the Sabana Grande Formation (Krushensky, unpub. data, 1982). Contact of the Jicara and underlying rocks is disconformable.

The western part of the island is intruded by porphyritic trachybasalt mineralogically and texturally identical to the lava flows and breccia clasts of the Maricao Formation, andesite-diorite lithologically identical to the Lago Garzas lithofacies, two-pyroxene olivine basalt like the Rio Loco Formation (Krushensky and Curet, 1984), hornblende diorite, and andesitic diorite (Krushensky and Monroe, 1975, 1978; Volckmann, 1984a, b, c; Krushensky and Curet, 1984; Curet, 1986). Subvolcanic and possibly even partly extrusive, abundantly vesicular and amygdaloidal, aphyric to sparsely porphyritic dacite intrudes the interbedded lithofacies of the Yauco, Lago Garzas, and Anon in the Peñuelas quadrangle (Krushensky and Monroe, 1978).

Delineation of the margins of the obducted oceanic plate in southwestern Puerto Rico, as noted above, is not possible because of masking by overlying younger rocks and because of pervasive normal and strike-slip faulting. We suggest that the last stage of the emplacement of the oceanic plate was responsible for the formation of a well developed and closely spaced series of west-northwest-striking folds in the middle Eocene Rio Culebrinas Formation and for the formation of a reverse fault that dips northward beneath the Rio Culebrinas sequence in the Central La Plata quadrangle (McIntyre, 1971). The vertical attitude of the Jicara Formation (Krushensky, unpub. data, 1982) of early Eocene age, on the eastern edge of the Guanica quadrangle was also produced by the emplacement of the oceanic plate. Faulting and folding of middle Eocene rocks by the obducting plate suggests that the age of emplacement is middle Eocene but probably even younger.

CENTRAL PUERTO RICO

The oldest rocks in central Puerto Rico were mapped prior to working out the complex stratigraphy of the region. As a result, they were designated by letter rather than formation names; but with the mapping of broader areas, some of these letter designations were abandoned and formation names were adopted.

Formations A, B, C, and J crop out in the Cayey, Patillas, Comerio, Caguas, Central Aguirre, and Yabucoa quadrangles in eastern and east-central Puerto Rico (Berryhill, 1960; Berryhill and Glover, 1960; Pease and Briggs, 1960; Rogers, 1979; Rogers and others, 1979; and Glover, 1982). They are equivalent and consist of andesitic and basaltic volcaniclastic breccia, lava, and generally lesser quantities of tuff, sandstone, and minor limestone. Bedding in the sequence is either not discernable or generally poorly developed over broad areas, pillow structure is absent in lava flows, and breccias were described as autoclastic (Berryhill and Glover, 1960; Pease and Briggs, 1960; Rogers, 1979; Rogers and others, 1979). The presence of limestone that contains fossil rudists (Sohl, 1976), the apparent lack of pillow structure in the basaltic and andesitic lavas, and the local lens-like interbedding of breccia, lava, tuff, sandstone, and limestone suggest that the sequence may have been deposited under near-shore and shallow-water conditions, possibly in part under subaerial conditions and probably near volcanic centers. Although limestone has been described in a number of areas, fossils other than the rudists have not been reported. The sequence is thought to be Lower Cretaceous because it underlies the Torrecilla Breccia of early Albian age (Douglass, 1961; Sohl, 1976). Although, M'Gonigle (1978) considers Formation A and its equivalents to be lithologically like the Rio Abajo Formation, which crops out east of the San Lorenzo batholith in the Humacao quadrangle, the Rio Abajo there contains variable amounts of bipyramidal quartz crystals and quartz crystal fragments (Krushensky, unpublished data, 1983), which are unknown in Formation A and its equivalents.

A sequence of autoclastic breccia, lava, sandstone, siltstone, and conglomerate, much like Formation A and its equivalents, is mapped as the Torrecilla Breccia in the Barranquitas, Orocovis, Comerio, Aguas Buenas, and Cayey quadrangles (Berryhill and Glover, 1960; Pease and Briggs, 1960; Briggs and Gelabert, 1962; Pease, 1968b; and Briggs, 1969a; 1971a). It consists at the base, of the Aguas Buenas Limestone Member of early Albian age (Sohl, 1976). The Torrecilla is equivalent to Formation D in the Cayey quadrangle (Berryhill and Glover, 1960) and to Formation K in the Comerio quadrangle (Pease and Briggs, 1960; Briggs, 1969a). M'Gonigle (1977; 1978) has correlated the Torrecilla with the lithologically similar Pitahaya Formation in the Humacao quadrangle.

The Robles Formation, a sequence of volcanic sandstone and siltstone that contains minor pillowed lava and limestone overlies and is in part equivalent to the Torrecilla, and crops out in the Coamo, Juncos, Cayey, Caguas, Orocovis, and Comerio quadrangles (Berryhill and Glover, 1960; Pease and Briggs, 1960; Glover, 1961a; 1971; Briggs and Gelabert, 1962). The type section of the base of the Robles was described as the Rio Maton Limestone Member in the Cayey quadrangle (Berryhill and Glover, 1960). Fossils in the Rio Maton type section are of early Albian age. However, limestone thought to be the base of the Robles and mapped as Rio Maton in the Comerio quadrangle (Pease and Briggs, 1960) contains fossils of middle Albian age (Sohl, personal communication, 1982). Because confusion in the identification and mapping of the Rio Maton and Aguas Buenas was never resolved, the Robles as mapped in broad areas encompasses the Torrecilla. Areas mapped as Torrecilla may also include Robles.

Berryhill (1965) mapped a sequence of lava, clastic rocks, and limestone in the Ciales quadrangle, named it the Rio Orocovis Formation, and suggested that it was equivalent to the Robles as mapped in eastern Puerto Rico. Nelson (1967a), mapped similar lithofacies in the Corozal quadrangle, described them as the Rio Orocovis Group, and subdivided them into the Los Negros, Avispa, Perchas, and Magueyes Formations. Similar interbedded lava, sandstone and tuff lithofacies were mapped in the Barranquitas, Aguas Buenas, Naranjito, Comerio, Jayuya, Florida, Caguas, Gurabo, and Juncos quadrangles (Pease and Briggs, 1960; Briggs and Gelabert, 1962; Nelson and Monroe, 1966; Mattson, 1968b; Pease, 1968a, b; Seiders, 1971a; and Rogers, 1979). Nelson (1967a) mapped the Rio Orocovis Group as continuous with Formation L in the Barranquitas quadrangle (Briggs and Gelabert, 1962). Briggs (1969a) abandoned the term Formation L and substituted stratigraphic names from the Rio Orocovis Group. The Barrancas Limestone Member, the base of the Magueyes Formation which is the base of the Rio Orocovis Group correlates with the middle Albian Rio Maton Limestone (Sohl, oral communication, 1982) mapped as the base of the Robles in the Comerio quadrangle. The Manicaboa Formation, a sequence of volcanic breccia, conglomerate, and tuff may be equivalent to the Avispa (Berryhill, 1965) in the Ciales quadrangle.

Recurrent change in facies both vertically and laterally suggests that the Torrecilla Breccia, Robles Formation, and Rio Orocovis Group were probably deposited near volcanic centers, chiefly under submarine conditions, over wide areas, probably from multiple volcanic centers, and in shallow to deep water.

Volcaniclastic sandstone and siltstone, tuff, and minor pillowed basaltic and andesitic lava flows of the Vista Alegre Formation, conformably underlie and interbed with lithologically similar pillowed basaltic and andesitic lava flows and intercalated sandstone and siltstone of the Mameyes Formation. These lithofacies crop out in the Florida, Jayuya, Utuado, Adjuntas, and Orocovis quadrangles (Nelson and Monroe, 1966; Nelson, 1967b; Mattson, 1968a, b; Briggs, 1971a). The Vista Alegre and Mameyes are distinguished from one another only because the Mameyes contains more lava flows (Nelson and Monroe, 1966). The Vista Alegre is separated from the conformably underlying Robles Formation because the latter is finer grained and thinner bedded (Mattson, in Nelson and Monroe, 1966). Pumiceous and crystal-lithic tuff and pillowed basaltic and andesitic lava flows of the Tetuan Formation interbed with the Mameyes and are overlain by welded and non-welded ash flow tuff of the Alonso Formation in the Florida, Utuado, and Bayaney quadrangles (Nelson and Monroe, 1966a, b; Nelson, 1967b, Nelson and Tobisch, 1968). The tuffaceous facies of the Mameyes are lithologically identical with those of the Vista Alegre (Nelson and Monroe 1966a, b) and with the Cotorra (Mattson, 1967). The Tetuan also crops out in the Jayuya quadrangle. Vista Alegre and Tetuan lithofacies probably are differently mapped aspects of the same sequence; and the Mameyes represents only a local increase in number and thickness of basaltic and andesitic lava flows also present in the Vista Alegre and the Tetuan. The Malo Breccia, a hyaloclastite breccia that contains subordinate volcanic sandstone, is probably a lithofacies of the Mameyes. It interbeds with the top of the Robles and interbeds laterally with the Vista Alegre and the Tetuan. The Malo crops out in the Orocovis, Jayuya, and Barranquitas quadrangles (Briggs and Gelabert, 1962; Mattson, 1968b; Briggs, 1971a).

The lithologically similar Cotorra Tuff, a hyaloclastite breccia and pillowed lava, interbeds with the top of the Malo and pinches out to the east between the Robles and overlying Cariblanco Formation. The Alonso Formation, welded and partially welded ash-flow tuff and related breccia conformably overlies the Tetuan Formation. It was probably erupted and deposited, at least in part, under subaerial conditions and in close proximity to eruptive centers; however, the proximity of related units to eruptive centers is not established. The abundance of volcanic sandstone and siltstone in the Vista Alegre indicate only a time of erosion of the volcanic pile. Tuff in the Tetuan does indicate the presence of eruptive centers but their proximity is unknown. Lava flows of the Mameyes, Cotorra, and Malo, and to a lesser degree, the Vista Alegre and Tetuan were probably submarine or submarine extensions of subaerial eruptions. One ammonite specimen indicates a possible Late Cretaceous age for the Tetuan (Nelson and Monroe, 1966).

A thick sequence of graded, massive conglomerate, the Achiote Conglomerate, and the Cariblanco Formation, a contemporaneous and interbedded sequence of conglomerate, sandstone, lava, and limestone, overlie the Robles Formation and the Rio Orocovis Group. The Achiote and Cariblanco sequence indicates erosion of the volcanic pile accompanied by sporadic but minor contributions from volcanic eruptions. The Achiote, because of grading in the finer grained clastic sequences and the lack of sorting in major parts of the conglomerate facies, suggests deposition from high-concentration turbidity currents, and may indicate a farther off-shore environment of deposition; carbonate banks in the Cariblanco suggest deposition nearer to the shore. Marine pelecypods and gastropods from the upper part of the Achiote are of Santonian to Maastrichtian age (Sohl, in Mattson, 1967); and foraminifera from the limestone units of the Cariblanco are Santonian to early Campanian in age (Pessagno, 1962). The Achiote and Cariblanco are overlain and possibly interbedded with the Maravillas, Pozas, and Coamo Formations. The Maravillas consists of graded volcaniclastic sandstone and siltstone that contains minor pillowed lava and conglomerate like that in the Cariblanco. Carbonate banks locally present at the base and sporadically throughout the Maravillas contain rudists of late Campanian to Maastrichtian age (N.F. Sohl, oral communication, 1982). The Pozas Formation, a sequence of volcanic breccia, conglomerate, tuff, volcanic sandstone, limestone, and welded ash-flow tuff, ranges from marine at the base to probably subaerial in the largely welded ash-flow tuff of the Blacho Member (Berryhill, 1965). Calcarenite in the basal member of the Pozas and at higher stratigraphic levels that crop out in the Florida (Nelson and Monroe, 1966) and Barranquitas (Briggs and Gelabert, 1962) quadrangles indicates a largely submarine, but near-shore, environment of deposition. Rudists from the Pozas range in age from early Campanian to late Maastrichtian (Sohl and Kollmann, 1985).

The Coamo Formation of south-central Puerto Rico, a time and lithologic equivalent of the Maravillas and Pozas Formations, consists of generally unsorted, massive tuff, volcanic breccia, local lava flows, and carbonate banks. Included foraminifera are of late Santonian to early Maastrichtian age (Pessagno, 1962). Carbonate banks indicate that the Coamo was deposited under marine and probably near-shore conditions. Massive tuff beds were deposited as high-concentration debris flows, also in a marine environment.

The Los Puertos and Raspaldo Formations are very local in outcrop, intergrade laterally, and are isolated by faults from all other units. They are distinguished from the Coamo only by the presence of quartz-bearing dacitic tuff and lithic clasts. Foraminifers in the Los Puertos are of early Paleocene age (Glover, 1971), and Foraminifers reported from the Raspaldo are latest Paleocene to early Eocene age (Reiskind, in Glover, 1971). According to Glover (1971), they are disconformably overlain by the Cuevas Limestone. However, bedding in the Raspaldo dips at high angles into a vertical contact with the Cuevas. The contact is a fault, as are all other contacts between the Raspaldo and the Cuevas in the Coamo quadrangle.

The Cibuco Formation, structurally isolated at its base, consists in the Corozal quadrangle, of massive conglomerate, sandstone, siltstone, and tuff. It is interbedded with and conformably overlain by siltstone and tuff of the Carreras Siltstone (Nelson, 1966a; 1967a). The Yunes Formation, a sequence of marine volcanic sandstone, siltstone, limestone, and conglomerate is structurally isolated by faults from older rocks (Nelson and Monroe, 1966; Nelson, 1967b). The Yunes in the Utuado quadrangle is overlain by volcanic breccia, conglomerate, sandstone, and lava of the Jobos Formation (Nelson, 1967b). Lithologically, the Yunes and Jobos resemble the Anon lithofacies to the south and west. The Yunes may be late Paleocene to middle Eocene (Nelson and Monroe, 1966).

Intrusive rocks in the central part of the island range from gabbro to diorite, diorite-hornblendite, quartz diorite, granodiorite, quartz-hornblende dacite, and porphyritic augite-andesite. Potassium-argon ages for the San Lorenzo-Punta Guayanes intrusive complexes (Cox and others, 1977) range within the Campanian-Maastrichtian to the very early Paleocene (78 to about 65 Ma), some younger ages obtained were discounted by the original workers because of possible resetting or alteration. Similarly, potassium-argon dates from quartz diorite and quartz monzonite of the Utuado batholith range from Maastrichtian to early Paleocene (73 to 65 Ma) (Cox and others, 1977).

NORTHEASTERN PUERTO RICO

The left-lateral Cerro Mula-Qebrada San Francisco fault separates stratigraphic units in northeastern Puerto Rico from those in the central part of the island. Because no direct correlation of stratigraphic units is possible across this fault, the total exposed length of the fault, about 35 km, was considered by Briggs and Pease (1968) as the minimum displacement along the fault. Volcanic rocks in northeastern Puerto Rico of Early Cretaceous and Neogene age range from basalt to rhyolite; intrusive rocks reflect this compositional range.

Massive, andesitic breccia, lava, hyaloclastite breccia, and fine-grained volcaniclastic rocks make up the Daguao Formation, the oldest mapped sequence, in the Humacao, Naguabo, and Punta Puerca quadrangles in the northeast block (M'Gonigle, 1978, 1979). Although the age of the Daguao is not documented, it is assumed to be Early Cretaceous (M'Gonigle, 1977b, 1979) because of its position in the general stratigraphic succession in the region. The Daguao is overlain by and interbedded with the Figuera Lava (M'Gonigle, 1978, 1979), a sequence of pillowed andesitic lava flows. Fossils have not been reported to be present in the Figuera, but it is also assumed to be of Early Cretaceous age because of its stratigraphic relationship to the conformably overlying tuffaceous sandstone-siltstone and tuff breccia of the Fajardo Formation (Briggs and Aguillar, 1980). Ammonites identified as of late middle Albian age have been reported as collected from the Fajardo (Cobban, in Briggs, 1973). Pillowed lava present throughout the Fajardo is lithologically like the underlying Figuera Lava (M'Gonigle, 1979).

Calcareous and tuffaceous sandstone-siltstone and volcanic breccia of the Tabonuco Formation overlie and interbed with the Fajardo Formation and include foraminifera of Aptian to late Cenomanian age, and ammonites of Albian age (Seiders, 1971a). The Tabonuco crops out in the El Yunque, Cayo Icacos, and Fajardo quadrangles.

To the west, in the Gurabo quadrangle, calcareous volcanic sandstone and breccia, lithologically like the Tabonuco but mapped as the Barrazas Formation, also contain late Cenomanian foraminifera (Seiders, 1971c). The Barrazas is mapped as continuous with the Guaynabo Formation in the Aguas Buenas quadrangle adjacent on the west with the Gurabo quadrangle (Pease, 1968b). The Barrazas probably interbeds with and is a lithofacies of the overlying Hato Puerco Formation (Seiders, 1971a), a sequence of andesitic to basaltic volcanic sandstone, breccia, conglomerate, and basaltic lava flows (Seiders, 1971a, c) in the Gurabo and El Yunque, Rio Grande, Fajardo, and Cayo Icacos quadrangles. Foraminifera reported to be present in the Hato Puerco are of middle Cenomanian to Turonian age (Seiders, 1971b). Conformably overlying the Hato Puerco in the northern part of the Gurabo quadrangle, and in the El Yunque and Rio Grande quadrangles, is a sequence of pumiceous breccia, volcanic sandstone and mudstone, and welded ash-flow tuff of the Cambalache Formation. The Infierno Formation, lithologically like the Cambalache (Seiders, 1971b, c), is locally mapped as overlying the Hato Puerco in the western Gurabo quadrangle; both the Infierno and the Cambalache contain fossils of Turonian age (Pessagno, in Seiders, 1971c). The Hato Puerco and the Infierno in the Gurabo quadrangle are mapped as continuous with the sequence mapped as Carraizo Breccia in the Aguas Buenas quadrangle (Pease, 1968b; Seiders, 1971c).

The sequence of Hato Puerco through Cambalache rocks in the Gurabo and El Yunque quadrangles is conformably overlain by the Canóvanas Formation, a sequence of basaltic volcanic sandstone, and calcareous mudstone (Seiders, 1971b, c). The Canóvanas is conformably overlain by a locally pillowed basaltic andesite, the Martin Gonzales Lava, which was mapped as a member of the Guaynabo Formation in the Aguas Buenas quadrangle (Pease, 1968b). A structurally isolated sequence of pillowed lava, volcanic breccia, and volcanic sandstone mapped as the Celada Formation conformably overlies the Infierno Formation in the Gurabo quadrangle (Seiders, 1971c) and may be partly or completely equivalent to the Canóvanas (Seiders, 1971b, c). The Lomas, also structurally isolated (Seiders, 1971b, c), consists of basaltic to andesitic lava, volcanic breccia and sandstone. It is lithologically like the Celada and the Infierno, but its age and correlatives have not been established.

The Frailes Formation, volcanic mudstone, sandstone-conglomerate, and pillowed lava conformably overlies the Martin Gonzales and is of early Campanian to possibly early Maaestrichtian age (Seiders, 1971a, c). It is also partly equivalent to the Guaynabo mapped in the Aguas Buenas quadrangle, adjacent to the west(Pease, 1968b). The Frailes is conformably overlain by the Monacillo Formation, a sequence of volcanic mudstone-sandstone, basaltic lava, and, at the top, a miliolid limestone, the Trujillo Alto Limestone Member, (Seiders, 1971b, c). The overlying Guaracanal Andesite in the Aguas Buenas quadrangle consists of purple-gray lava breccia and includes Foraminifers of late Paleocene to early Eocene age (Pessagno, in Pease, 1968a ; Pessagno, in Seiders, 1971a). Rocks mapped as Guaracanal in the Gurabo quadrangle consist chiefly of a basal mudstone, limestone, and, at the top, a basalt. It is lithologically unlike the Guaracanal as previously defined.

In the Aguas Buenas and Naranjito quadrangles, a thick sequence of volcaniclastic and volcanic rocks is separated from the previously described formations by high-angle normal faults or covered by younger formations (Pease, 1968a, b, c). This structurally and stratigraphically isolated sequence of rocks has no demonstrable lithologic or depositional relationship to rocks in central or northeastern Puerto Rico. The Pájaros Tuff, at the base of this sequence (Pease, 1968b, c), consists of tuffaceous siltstone, tuff, and tuffaceous volcanic sandstone. The base of the Pájaros is everywhere concealed by younger deposits. It is conformably overlain by the Cerro Gordo Lava, basaltic lava flows, autoclastic flow breccia, and tuffaceous breccia. The El Ocho Formation conformably overlies the Cerro Gordo and consists of volcanic breccia, tuff, andesitic lava flows and siltstone. The Cancel Breccia, a sequence of massive volcanic breccia, autoclastic flow breccia, and lava conformably overlies the El Ocho. The ages of the Pájaros Tuff, Cerro Gordo Lava, El Ocho Formation, and Cancel Breccia are problematic in that fossils have not been reported to be present in them (Pease, 1968a).

A massive sequence of pillowed basaltic and andesitic lava, hyaloclastite breccia, tuff, and volcanic sandstone of the Santa Olaya Lava, crops out in the Corozal, Naranjito, and Aguas Buenas quadrangles (Nelson, 1966a; Pease 1968b, c). The Santa Olaya is laterally interbedded with the Rio de la Plata Sandstone, calcareous sandstone and conglomerate in the western and southern parts of the Naranjito and northeastern Corozal quadrangles, and with the Camarones Sandstone, a sequence lithologically similar to the Rio de la Plata that crops out in the central Aguas Buenas quadrangle (Pease, 1968a, b, c). The Santa Olaya Lava, in the Aguas Buenas quadrangle, is mapped as continuous with the Celada Formation in the Gurabo quadrangle (Seiders, 1971c). Although the contact of the Santa Olaya with the underlying Cancel Breccia is nowhere well exposed, Pease, (1968a) speculates that the Santa Olaya unconformably overlies the Cancel Breccia. Fossils have not been reportedfrom the Santa Olaya the Santa Olaya Lava, Camarones Sandstone, or Rio de la Plata Sandstone, and the age of the formations is problematic. According to Seiders (1971a), volcaniclastic rocks of the Infierno Formation, of Turonian age are lithologically similar to those of the Cambalache Formation.

Volcanic breccia, lava, mudstone-sandstone, and subordinate conglomerate and limestone lenses of the Tortugas Andesite conformably overlie the Camarones Sandstone and are interbedded with the Guaynabo Formation (Pease, 1968a, b). Although the Tortugas was described as subaerial by Pease (1968a), the presence of limestone lenses in the breccia and the sandstone-mudstone facies suggests that the rocks were deposited in a marine environment. Volcanic sandstone, limestone and conglomerate of the La Muda Formation overlie the Tortugas Andesite. The contact is described as unconformable because basal conglomerate of the La Muda contains clasts lithologically like the underlying Tortugas (Pease, 1968a). Rudists in the La Muda have been described as Maastrichtian and possibly Campanian (Sohl oral commun., 1990). Tuff, tuffaceous sandstone, conglomerate, and tuffaceous breccia mapped as the Naranjito Formation crop out in the Naranjito (Pease, 1968c) and Corozal (Nelson, 1967a) quadrangles. Interbedded volcanic siltstone and sandstone, mapped as the Palmarejo Formation, crop out in the Naranjito and Corozal quadrangles where the formation conformably overlies the Naranjito Formation (Nelson, 1967a; Pease, 1968c). Foraminifera from the Palmarejo range in age from Paleocene to Eocene (Pessagno, in Nelson, 1966a). The Guaracanal Andesite, a sequence of coarse volcaniclastic breccia, conformably overlies the Monacillo Formation and appears to be lithologically equivalent to part of the Naranjito (Pease, 1968a). Volcanic sandstone, siltstone, and conglomerate of the Rio Piedras Siltstone conformably overlie the Guaracanal in the Aguas Buenas and Naranjito quadrangles (Pease, 1968b, c), but in the San Juan quadrangle, the Guaracanal is absent and the Rio Piedras overlies the Monacillo (Pease and Monroe, 1977). Foraminifers from the Rio Piedras are late Paleocene (Reiskind, in Pease, 1968a).

The Corozal Limestone, a sequence of massive limestone and limestone breccia, calcareous sandstone, siltstone, and bentonitic clay (Nelson, 1966a, 1967a) conformably overlies the Palmarejo Formation and is conformably overlain by the Ortiz Formation. Foraminifera from the Corozal range in age from Paleocene to early or middle Eocene (Applin, in Kaye, 1956; Todd, in Kaye, 1956). The Ortiz consists of interbedded volcanic sandstone, limestone conglomerate, and tuff. It is unconformably overlain by middle Tertiary rocks (Nelson, 1966a, 1967a).

INTRUSIVE ROCKS

The northeastern block is intruded by Late Cretaceous and Tertiary rocks that include granodiorite, hornblende quartz diorite, quartz diorite, granodiorite, augite andesite porphyry, diorite, gabbro, and quartz keratophyre. Biotite and hornblende from quartz diorite of the Rio Blanco stock (Seiders, 1971b) have ages of 46.2 Ma and 45.7 Ma respectively (Cox and others, 1977).

MIDDLE TERTIARY SEDIMENTARY ROCKS

Rocks of Oligocene and Miocene age overlie the Jurassic to Eocene core of the island with a profound unconformity along the south-central and southwestern and north coasts of the island. Although the north- and south-coast sequences are both Oligocene and Miocene in age, they cannot be directly correlated (Monroe, 1980c).

On the south coast, middle Tertiary formations crop out from the village of Descalabrado in the east to Guanica Bay in the west. The Juana Diaz Formation, the oldest middle Tertiary formation in this area, consists of basal gravel overlain by a thin-bedded to very thick-bedded coralline limestone, and locally a channel fill of sand and gravel (Monroe, 1980c). Because the Juana Diaz is separated from the overlying Ponce Limestone by an erosional unconformity, Moussa and Seiglie (1970, 1975), include these channel-fill deposits with the overlying Ponce Limestone.

Middle Tertiary rocks on the north coast crop out from the Rio Grande quadrangle in the east to the west coast of the island. The middle Tertiary sequence there consists, from the base up, of sand, gravel, and locally clayey limestone of the San Sebastian Formation, which is conformably overlain by, and interbedded with, limestone of the Lares Limestone. Overlying limestone and sand-gravel beds of the Cibao Formation grade laterally to the east into sand and gravel of the Mucarabones Sand. The Mucarabones overlies the San Sebastian from Ciales to the San Juan quadrangle (Monroe, 1980c). The conformably overlying Aguada Limestone grades into limy and clastic phases indistinguishable from the Cibao (Monroe, 1980c). Limestone unmixed with other clastic rocks is distinguished as the Aymamón Limestone. The Aymamón is unconformably overlain by sandy lime and chalk of the Camuy Formation, the youngest middle Tertiary rock on the north coast of Puerto Rico (Monroe, 1980c).

SEDIMENTATION MODEL FOR PUERTO RICO

Puerto Rico consists of complexly interfingering shallow- to deep-water, marine alluvial-fan and well-bedded turbidity-flow deposits, as well as hyaloclastite breccia, autoclastic flow-breccia, and pillowed lava flows, and carbonate bank deposits. The alluvial fan deposits accumulated from submarine debris flows characterized by high particle concentrations; sandstone-tuff that show partial or complete Bouma cycles were produced by turbidity flows having low particle concentrations. Lava flows are preserved as hyaloclastite breccia, autoclastic flow breccia, and pillow lava. Carbonate banks are preserved as formed in the original near-shore environment or as talus and debris flow materials admixed with volcaniclastic debris originally deposited in deeper water. Volcaniclastic rocks, breccias, and tuff, were derived directly from pyroclastic eruptions and indirectly from alluvium composed of pyroclastic debris as well as epiclastic debris. Materials of pyroclastic and epiclastic origin are mixed to varying degrees, they are seldom, if ever, present as pure unmixed end-members. Subaerial deposition is probably evidenced by welded ash-flow tuff, however Kokelaar and Busby (1992) suggest that even submarine eruptions may give rise to rocks that resemble subaerial welded ash-flow tuff deposits. Subaerial deposition is not otherwise unequivocally demonstrated. Although formations that consist of red and green rocks were described by the original mappers as of subaerial origin, the presence throughout their vertical and lateral extent of foraminifera as well as other fossils of marine origin, and in many cases coarse calcarenite derived from carbonate banks, suggests that they were in reality deposited under marine conditions. Coarse well-rounded cobble and boulder conglomerate were generally deposited under marine conditions and are not indicative of unconformities or disconformities in the rock sequence, although they may suggest subaerial erosion in the source area. Sediments were probably derived chiefly from local volcanic centers, including some, commonly subordinate, materials received from explosive eruptions of ash from more distant subaerial volcanic centers. Subvolcanic intrusive igneous rocks were emplaced at about the same time as eruptions were in progress. Coarse crystalline batholithic masses in the San Lorenzo and Utuado areas were emplaced at greater depth. The whole of the volcanic-intrusive pile was deeply eroded and locally covered by epiclastic rocks and carbonate bank deposits. In the southwest, oceanic rocks largely covered by rocks identical to those in the island-arc proper, were thrust over the island-arc volcanic pile. The initiation of this thrusting presumably postdates the Kimmeridgian and continued to some unknown time after the early Eocene. The volcanic pile was eroded sufficiently deeply so as to expose rocks of the San Lorenzo and Utuado batholiths. Margins of the eroded pile were submerged and covered with basal clastic debris as well as mixtures of epiclastic and carbonate deposits.

Geologic Map of Puerto Rico With Correlation Chart And Map Unit Descriptions

by

Richard D. Krushensky

Broad scale geologic studies of the island of Puerto Rico were first published by the New York Academy of Science in the first 2 decades of the 20th century. Interest in the geology of the island was revived in the 1950s and 1960s by the publication of studies by students of Professor Harry Hess, Princeton University. Geologic maps resulting from the USGS mapping program were published from the 1960s through the present. The island includes 64 topographic quadrangles, scale, 1:20,000. Some published maps have been mapped at a reconnaissance scale. Geology of the Sabana Grande map has been done at reconnaissance scale by the author but not previously published. The Rincon quadrangle is largely unmapped, therefore the geology presented for that quadrangle is highly interpretative. The geologic map is presented here in three sections: West, Central, and East.

The basic objective of the USGS geologic mapping program was to produce a series of geologic maps which could be used in the economic development of Puerto Rico. Similarly, this publication is directed to making the latest information on the geology of the island available to local governments and to industry. The geologic map was compiled from all studies available. Interpretation, at times at variance with the original author's work, was needed as the geologic mapping and therefore the understanding of the geology of the island progressed.

The digitized geologic map of Puerto Rico, scale (1:100,000) includes 151 map units. Descriptions of the map units are in stratigraphic order and grouped under the general terms, southwest, central, and northeastern.

Digitization of the geologic map allows for the manipulation of data with greater economy of time than through use of paper copy alone. Maps at various scales and projections can be produced without difficulty, and various map units can be grouped and manipulated with relative ease.

Associated Thematic Data For The Geologic Map for Puerto Rico

By

Walter J Bawiec

The geologic map of Puerto Rico for this study consists of a main island and the three largest surrounding islands of Isla de Vieques, Isla de Culebra, and Isla Mona.

The geologic map of the Commonwealth of Puerto Rico (west; central; east) is based upon a compilation by R.D. Krushensky at 1:100,000 scale of sixty-seven geologic quadrangles, sixty-two of which were mapped at a scale of 1:20,000 (fig. 1). Compilation of the geologic map for the main island of Puerto Rico was initiated in order to produce a more recent and useful geologic map to be used by both government and industry. Because of the length of time over which these geologic quadrangles were mapped and the large number of individuals involved in the mapping, reinterpretation of the original data for some quadrangles was necessary to resolve map-edge inconsistencies, which became apparent in this compilation. Table 1 lists the quadrangle name, mapper, scale, and date of publication for each of the quadrangles. The geologic maps for the above-mentioned three surrounding islands are not included in the 1:100,000 scale compilation, but reflect the general geologic features as presented in Cox and Briggs, 1973.

The geologic map used in this study of the mineral resources of Puerto Rico is presented at a scale of 1:100,000. This geologic map (west; central; east) consists of 151 map units for the main island, descriptions of which can be found on in Appendix A. These map units descriptioms are listed in alphabetical order by map unit mnemonic.

The geologic legend is presented in several different formats. The basic legend has map units grouped into twelve terranes based upon lithologic rock type, depositional environment, and(or) age of deposition. These terranes were designed with consideration of how the mineral resource assessment would be conducted and what logical groupings made the most sense in Puerto Rico. Colors and patterns are combined to have each map unit unique, with patterns used to distinguish discrete columns of map units in the legend, and colors are used to differentiate map units within columns. For example, all nonvolcaniclastic map units of Pliocene through Oligocene age are overprinted with black vertical lines, and all nonvolcaniclastic map units which are Eocene through Cretaceous in age have blue vertical lines. The Stratigraphic Correllation Chart is another format of the map units. The correllation chart is designed to show which map units are in contact and which map units in different parts of the island were forming at the same time. The basic legend is displayed with terrane colors to show what map units are included in each terrane. The stratigraphic correllation chart is displayed with terrane colors to show how each terrane is distributed through time.

The 1:100,000 scale geologic map as represented in this study was optically scanned on a drum scanner and transformed into a digital map coverage. Each closed map area (polygon) was identified and tagged with the appropriate map unit attributes of mnemonic (which includes formation name and age), polygon color, polygon pattern and geologic terrane. The purpose in creating this digital map was to enable the combination, analysis and manipulation of other digital thematic data (geochemistry, geophysics) relevant to the mineral resource assessment, and to provide a useful product to an ever-growing Geographic Information System (GIS) community.

The digital geologic map of Puerto Rico allows for the analysis and manipulation of information which is impossible with hard copy (paper). Maps can be reproduced at varying scales and at different projections without a great deal of difficulty. Derivative maps can also be produced by combining map units (i.e., all intrusive map units), or selecting only combinations of map units for which there is an interest. An example of the statistics which can be generated from digital maps can be found in table 1 of the geologic terrane section, this report.

Table 1. List of 1:20,000 scale geologic maps.

Quadrangle name	Reference
Adjuntas	Mattson, P.H., 1968, Geologic map of the Adjuntas Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-519, scale 1:20,000.
Aguadilla	Monroe, W.H., 1969a, Geologic map of the Aguadilla Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigation Map I-569, scale 1:20,000.
Aguas Buenas	Pease, M.H., Jr., 1968b, Geologic map of the Aguas Buenas Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-479, scale 1:20,000.
Arecibo	Briggs, R.P., 1968c, Geologic map of the Arecibo Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-551, Scale 1:20,000.
Barceloneta	Briggs, R.P., 1965, Geologic map of the Barceloneta Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-421, scale 1:20,000.
Barranquitas	Briggs, R.P., and Gelabert, P.A., 1962, Preliminary report of the geology of the Barranquitas Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-336, scale 1:20,000, 2 sheets.
Bayamon	Monroe, W.H., and Pease, M.H., 1962, Preliminary geologic map of the Bayamon Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-347, scale 1:20,000.

	Monroe, W.H., 1973, Geologic map of the Bayamon Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-751, scale 1:20,000.
Bayaney	Nelson, A.E., and Tobisch, Q.T., 1968, Geologic map of the Bayaney quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-525, scale 1:20,000.
Cabo Rojo	Volckmann, R.P., 1984a, Geologic map of the Cabo Rojo-Parguera Quadrangle, southwest Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1557, scale 1:20,000.
Caguas	Rogers, C.L., 1979, Geologic map of the Caguas Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1152, scale 1:20,000.
Camuy	Monroe, W.H., 1963b, Geology of the Camuy Quadrangle, Puerto Rico: U.S. Geological Survey Geologic Quadrangle GQ-197, scale 1:20,000.
Carolina	Monroe, W.H., 1977, Geologic map of the Carolina quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1054, scale 1:20,000.
Cayey	Berryhill, H.L., and Glover, Lynn, 1960, Geology of the Cayey Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-319, scale 1:20,000.
Cayo Icacos	Briggs, R.P., and Aguilar-Cortes, E., 1980, Geologic map of the Fajardo and Cayo Icacos Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1153, scale 1:20,000.

Central Aguirre	Berryhill, H.L., Jr., 1960, Geology of the Central Aguirre Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-318, scale 1:20,000.
Central La Plata	McIntyre, D.H., 1971, Geologic map of the Central La Plata Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-660, scale 1:20,000.
Ciales	Berryhill, H.L., Jr., 1965, Geology of the Ciales quadrangle, Puerto Rico: U.S. Geological Survey Bulletin 1184, scale 1:20,000.
Coamo	Glover, III, Lynn, 1961a, Preliminary report on the geology of the Coamo Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-335, scale 1:20,000.
Comerio	Pease, M.H., and Briggs, R.P., 1960, Geology of the Comerio Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-320, scale 1:20,000.
Corozal	Nelson, A.E., 1967a, Geologic Map of the Corozal Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-473, scale 1:20,000.
El Yunque	Seiders, V.M., 1971a, Geologic map of the El Yunque quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-658.
Fajardo	Briggs, R.P., and Aguilar-Cortes, E., 1980, Geologic map of the Fajardo and Cayo Icacos Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1153, scale 1:20,000.

Guanica	Monroe, W.H., 1972, Geology of the middle Tertiary rock in the Ponce-Guanica area, Puerto Rico: U.S. Geological Survey Open-File Report Series no. 1712.
Florida	Nelson, A.E., and Monroe, W.H., 1966, Geology of the Florida quadrangle, Puerto Rico: U.S. Geological Survey Bulletin 1221-C, scale 1:20,000.
Guayama	Glover, Lynn, 1982, Preliminary geologic map of the Patillas and Guayama Quadrangles, Puerto Rico: U.S. Geological Survey Open-File Report 82-1097, scale 1:20,000.
Gurabo	Seiders, V.M., 1971c, Geologic map of the Gurabo Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-657, scale 1:20,000.
Humacao	M'Gonigle, J.W., 1978a, Geologic map of the Humacao Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1070, scale 1:20,000.
Isabela	Monroe, W.H., 1969b, Geologic map of the Moca and Isabela Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-565, scale 1:20,000.
Isla de Mona	Briggs, R.P., and Seiders, V.M., 1972, Geologic map of the Isla de Mona Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-718, 1 sheet, scale 1:20,000.
Isla Descheo	Seiders, V.M., Briggs, R.P., and Gover, L., III, 1972, Geology of Isla Descheo, Puerto Rico, with notes on the great southern Puerto Rico fault zone and quaternary stillstands of the sea: U.S. Geological Survey Professional Paper 739, Washington, D.C., scale 1:9,500.

Jayaya	Mattson, P.H., 1986b, Geologic map of the Jayaya quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-520.
Juncos	Broedal, C.H., 1961, Preliminary geologic map showing iron and copper prospects in the Juncos Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-326, scale 1:20,000.
Manati	Monroe, W.H., 1971, Geology of the Manati Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-671, scale 1:20,000.
Maricao	McIntyre, D.H., 1976, Geologic map of the Maricao quadrangle, western Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-918, scale 1:20,000.
Mayaguez	Curet, A.F., 1986, Geologic map of the Mayaguez and Rosario Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1657, scale 1:20,000.
Moca	Monroe, W.H., 1969b, Geologic map of the Moca and Isabela Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-565, scale 1:20,000.
Monte Guilarte	Krushensky, R.D., and Curet, A.F., 1984, Geologic map of the Monte Guilarte quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1556, scale 1:20,000.
Naguabo	M'Gonigle, J.W., 1979, Geologic map of the Naguabo and part of the Punta Puerca Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1099, scale 1:20,000.

Naranjito	Pease, M.H., 1968c, Geologic map of the Naranjito Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-508, scale 1:20,000.
Orocovis	Briggs, R.P., 1971a, Geologic map of the Orocovis Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-615, 1 sheet, scale 1:20,000.
Parguera	Volckman, R.P., 1984a, Geologic map of the Cabo Rojo-Paguera quadrangles, southwest Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1557, scale 1:20,000.
Patillas	Glover, Lynn, 1982, Preliminary geologic map of the Patillas and Guayama Quadrangles, Puerto Rico: U.S. Geological Survey Open-File Report 82-1097, scale 1:20,000.
Peñuelas	Krushensky, R.D., and Monroe, W.H., 1978, Geologic map of the Peñuelas and Punta Cuchara Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1042, scale 1:20,000.
Playa de Ponce	Glover, L., Pease, M.H., and Arnow, T., 1977, Surficial geologic map of the Playa de Ponce and Santa Isabel Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Field Studies Map MF-886, scale 1:20,00.
Ponce	Krushensky, R.D., and Monroe, W.H., 1975, Geologic map of the Ponce Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-863, scale 1:20,000.
Puerto Real	Volckmann, R.P., 1984b, Geologic map of the Puerto Real Quadrangle, southwest Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-559, scale 1:20,000.

Punta Cuchara	Krushensky, R.D., and Monroe, W.H., 1978, Geologic map of the Peñuelas and Punta Cuchara Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1042, scale 1:20,000.
Punta Guayanes	Rogers, C.L., 1977, Geologic map of the Punta Guayanes Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-998, scale 1:20,000.
Punta Puerca	M'Gonigle, J.W., 1979, Geologic map of the Naguabo and part of the Punta Puerca Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1099, scale 1:20,000.
Punta Tuna	Rogers, C.L., Cram, C.M., Pease, M.H., and Tischler, M.S., 1979, Geologic map of the Yabucoa and Punta Tuna Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1086, scale 1:20,000.
Punta Verraco	Krushensky, R.D., and Monroe, W.H., 1979, Geologic map of the Yauco and Punta Verraco Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1147, scale 1:20,000.
Quebradillas	Monroe, W.H., 1967a, Geologic map of the Quebradillas Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-498, scale 1:20,000.
Rio Descalabrado	Glover, Lynn, III, and Matson, P.H., 1973, Geologic map of the Rio Descalabrado Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-735, scale 1:20,000.
Rincon	Aaron, J.M., 1968, Geology of the Rincon Quadrangle, a preliminary report: Washington, D.C., U.S. Geological Survey

Rio Grande	Pease, M.H., 1972, Geologic map of the Rio Grande quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-733, scale 1:20,000.
Rosario	Curet, A.F., 1986, Geologic map of the Mayaguez and Rosario Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1657, scale 1:20,000.
Salinas	Glover, Lynn, III, 1961b, Preliminary geologic map of the Salinas Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-337, scale 1:20,000.
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San German	Volckmann, R.P., 1984c, Geologic map of the San German Quadrangle, southwest Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-558, scale 1:20,000.
San Juan	Pease, M.H., and Monroe, W.H., 1977, Geologic map of the San Juan Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1010, scale 1:20,000.
San Sebastian	Tobisch, Q.T., and Turner, M.D., 1971, Geologic map of the San Sebastian quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-661, scale 1:20,000.
Santa Isabel	Glover, L., Pease, M.H., and Arnow, T., 1977, Surficial geologic map of the Playa de Ponce and Santa Isabel Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Field Studies Map MF-886, scale 1:20,00.
Utuado	Nelson, A.E., 1967b, Geologic map of the Utuado Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-480, scale 1:20,000.

Vega Alta	Monroe, W.H., 1963a, Geology of the Vega Alta Quadrangle, Puerto Rico: U.S. Geological Survey Geologic Quadrangle Map GQ-191, scale 1:20,000.
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Yauco	Krushensky, R.D., and Monroe, W.H., 1979, Geologic map of the Yauco and Punta Verraco Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1147, scale 1:20,000.

Geologic Terranes of Puerto Rico

by

Walter J. Bawiec

terrane 1. A formation or group of formations,

2. The area or surface over which a particular rock or group of rocks is prevalent, or

3. An area or region considered in relation to its fitness or suitability for some specific purpose.

Dictionary of Geological Terms-AGI

INTRODUCTION

The Commonwealth of Puerto Rico can be partitioned into several subtle but distinct 'packages' of rocks (terrane map) as a consequence of the tectonic setting and geologic history of the Caribbean region. These packages of associated map units are treated as geologic terranes having affinities based upon lithologic rock type, depositional environment, and (or) age of deposition. Terranes are used to reconstruct and understand the large-scale geologic history of Puerto Rico. Also of use to economic geologists is the knowledge that each terrane, which hosts distinct types of mineral occurrences, requires different exploration techniques.

Puerto Rico is part of an island-arc complex on the northern edge of the Caribbean plate; the geology is described in detail by Krushensky and Schellekens (geology). The exposed part of the island arc which comprises Puerto Rico is divided into three major structural blocks (Garrison and others, 1972; Cox and Briggs, 1973, Cox and others, 1977), due to left-lateral strike-slip faulting along two northwest-southeast-trending fault zones, the South fault zone (Seiders et.al., 1972) , which coincides with the northern boundary of the Eocene Belt and the North fault zone in which the San Francisco – Cerro Mula Fault is the most important (Briggs and Pease, 1968). These structural blocks are referred to as the Northeast Igneous Province, Central Igneous Province, and Southwest Igneous Province (Schellekens, 1991, 1998). Within each of these provinces, the faults appear to be predominantly normal.

The geologic history of Puerto Rico can be summarized into several broad and general phases of development as extracted from Cox (1985):

1. Early sedimentary volcanic, and tectonic events in southwestern Puerto Rico are recorded in rocks of the Bermeja Complex of Mattson (1958, 1960a), which include radiolarian chert containing fossils of Jurassic age, serpentine, and amphibolite having a metamorphic age of 126 Ma.

2. The Bermeja Complex is overlain by volcanic and sedimentary rocks as old as Cenomanian that are part of a thick sequence of basalt, andesite, and breccia, and conglomerate, sandstone, and shale derived from volcanic rocks, which were deposited from Albian time to the end of the Cretaceous Period. Volcanism was associated with left-lateral strike-slip displacement along major northwest-striking faults that were active from Cenomanian to Eocene time.

3. This pile of volcanic rocks was intruded by plutons of tonalitic and granodioritic composition beginning in the Aptian and culminating in the Maastrichtian. Two batholiths were emplaced during Maastrichtian time: the San Lorenzo in the eastern part of Puerto Rico and the Utuado in the west-central part.

4. After emplacement of these batholiths, parts of the region were uplifted and eroded, and during the middle to late Eocene, basaltic to dacitic lava, tuff, and volcaniclastic sediment were deposited in west-central Puerto Rico, mainly along a northwest-trending trough, 100 km long by 10 km wide. This trough may have resulted from rifting.

5. During late Eocene time, small stocks of tonalite were emplaced along the boundary between the Eocene trough and the Utuado batholith as well as in other parts of central and northeastern Puerto Rico. These intrusions, which were the latest igneous events in the history of Puerto Rico, were accompanied by hydrothermal alteration and copper mineralization in the Tanamá and Río Viví areas.

6. Uplift, erosion, and formation of extensive areas of low relief followed the termination of igneous activity in Puerto Rico. Clastic sediment interbedded with thin coal seams (San Sebastian Formation) of middle Oligocene age was overlain by thick marine limestone deposits during the Oligocene and Miocene (Lares Limestone and overlying units).

7. Renewed erosion followed arching and uplift of the island, and the present topography began to develop. A regional saprolite weathering zone was created by intense tropical weathering.

GEOLOGIC TERRANES

A total of 151 map units, identified on the geologic map of Puerto Rico (west, central, east), are combined into twelve associated terranes for the main island (terrane map). The surface area covered by each of these terranes is shown in table 1 as a percentage of the total landmass and square kilometers. The map units that make up each of the twelve terranes are listed in table 2. Map unit descriptions can be found in Appendix A. The geology of the islands of Mona, Culebra, and Vieques has not been reexamined in detail in this study, and the terranes for these islands have been extrapolated from the previously published maps of Cox and Briggs (1973).

Ultramafic rocks in Puerto Rico are igneous rocks composed chiefly of mafic minerals, and amphibolite is a metamorphic rock consisting mainly of amphibole and plagioclase, containing little or no quartz. Ultramafic rocks and amphibolite, which are the oldest rocks found in Puerto Rico, are Jurassic and Cretaceous in age. They occur in the southwest corner of the island, as part of an obducted oceanic plate. These rocks have potential as hosts of podiform chromite deposits, and erode to form remnant sedimentary nickel laterite deposits. They make up approximately 87km^2 , or 1 percent of the surface area.

Basalt in Puerto Rico is dark- to medium-dark, commonly extrusive, mafic igneous rock composed chiefly of calcic plagioclase and clinopyroxene in a glassy or fine-grained groundmass. Chert is found in association with basalt in Puerto Rico. It is hard, extremely dense, or cryptocrystalline sedimentary rock. The basalts are typified by pillow structures, interbedded limestone, or related calcareous sediments. Mineral occurrences observed in basalt include vein deposits of barite. The basalt has been quarried as traprock, an industrial product.

Puerto Rico's intrusive rocks have been separated into two classes; Cretaceous, and Tertiary through Cretaceous, based upon the age of intrusion. Intrusive rock types include diorite, gabbro, granodiorite, quartz monzonite, and syenite, as well as others.

Cretaceous intrusive rocks are the largest plutonic units known in Puerto Rico and cover approximately 600 km^2, or 7 percent, of the land area. They are typified by the San Lorenzo batholith of southeastern Puerto Rico and the Utuado batholith of central Puerto Rico. Porphyry copper deposits found in these areas are thought to be related to the younger Eocene intrusions, and the older Cretaceous rocks have associated mineral deposits such as magnetite skarns.

The Tertiary and Cretaceous intrusive terrane includes known Tertiary rocks and those rocks for which age is uncertain. Although some of these rocks have not been dated, they are included in this terrane because of their stratigraphic relationship with surrounding rocks. The age of these intrusive rocks is important, because the present potentially economic metallic mineralization of Puerto Rico has been identified with the Eocene intrusive rocks. Most important are porphyry copper systems bearing copper, molybdenum, and gold. Associated with these intrusive rocks are skarn deposits within adjacent calcareous rocks, and vein deposits in fractures and faults.

Concurrent with these two periods of intrusion was the synchronous deposition of related marine volcaniclastic rocks, which cover a substantial area of Puerto Rico. Volcaniclastic rocks are defined as any rock containing volcanic material without regard to origin or environment. Rock types that make up this terrane include volcaniclastic sandstone and siltstone, ash-flow tuff, volcanic breccia, laharic breccia, and volcaniclastic conglomerate. This terrane constitutes approximately 3,100 km^2, or 36 percent, of the surficial Puerto Rican landmass. Most of the volcaniclastic terrane was deposited in a marine environment of Cretaceous age (20 percent of the surface). Marine volcaniclastic rocks are commonly transitional or interfinger with rock types. Subaerial volcaniclastic rocks are also present in Puerto Rico, but are limited in extent.

Rocks described as alteration on the terrane map are metavolcanic rocks or hydrothermally altered rocks for which the protolith is uncertain (R. Krushensky, oral communications; 1994). Alteration is an important indicator for locating many types of mineral deposits. However, altered rocks are widespread and represent many different levels of alteration intensity throughout Puerto Rico. Only the most intensely altered rocks are identified on the 1:20,000 geologic quadrangle maps that were used to compile the 1:200,000 geologic map.

Nonvolcaniclastic terranes are composed of biogenic or clastic map units devoid of volcanic material and cover approximately 3,900 km^2 or 45 percent of the surface area of Puerto Rico. Sedimentary or epiclastic processes including weathering, erosion, transport, and deposition form these nonvolcaniclastic rocks by consolidating fragments of preexisting rocks.

Eocene through Cretaceous nonvolcaniclastic terranes were intruded by Eocene igneous rocks. These nonvolcaniclastic rocks are dominantly limestone and calcareous clastic rocks. An understanding of the vertical and horizontal dimensions of these terranes is important because they host intrusion-related deposits, such as skarns and vein deposits.

Pliocene through Oligocene nonvolcaniclastic terranes comprise approximately 1,500 square kilometers, or 17 percent, of the surface area and consist of limestone and calcareous clastic rock. These rocks cover older rocks present during the intrusion of metalliferous Eocene igneous rocks. This terrane is an important source for industrial minerals, including limestone and sand and gravel.

Quaternary nonvolcaniclastic terranes consist of surficial deposits of alluvium, beach and swamp deposits, identified landslide areas, artificial fill, and fault breccia. Quaternary nonvolcaniclastic terranes comprise approximately 2,100 km^2, or 24 percent, of the total surface area and cover underlying rocks that have a potential for economic mineral deposits. Quaternary rocks are a major source for industrial minerals.

PATTERN OF GEOLOGIC TERRANES

The terrane map, which was generated by grouping geologically similar rock types, depositional environments, and (or) ages, displays twelve distinct terranes. Rocks of similar age and similar lithologic character tend to occur together. However, it must be remembered that because many of the lithologies are transitional or interfingering, they may logically be placed in more than one terrane. Terrane type was determined by the depositional environment and age of the predominant rock type for that particular map unit. Some assignments are likely ambiguous.

An obducted plate of Jurassic age ultramafic and amphibolite rocks is found in the southwest quadrant of the island.

The volcaniclastic rocks are intruded by Cretaceous and Cretaceous through Tertiary intrusive rocks, and submarine basalts and cherts occur throughout.

The marine Cretaceous volcaniclastic sediments dominate the east and interior of Puerto Rico, and Tertiary volcaniclastic rocks are mostly restricted to a linear belt in the west. There is a broad, mixed-age, Cretaceous and Tertiary transitional volcaniclastic terrane lying between.

Eocene and older nonvolcaniclastic rocks are sporadically distributed throughout the western and central parts of the island.

The Oligocene and younger nonvolcaniclastic terrane consists of sandstone and limestone that form a well-developed transgressive carbonate wedge on the north shore of the island, and a less well-developed, limited carbonate cover on the south side of the island.

The Quarternary nonvolcaniclastic terrane forms the blanket sand deposits, beaches, and Quaternary alluvium deposits that fill the river valleys and lowlands.

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Table 1. Twelve identified geologic terranes of Puerto Rico, shown as the percentage of surface area and areal extent square kilometers. [Total adds to 98 percent due to presence of surficial water bodies and rounding error.]

Geologic Terrane	Percent of island surface area	Areal extent (km^2)
Nonvolcaniclastic Terranes:		
Quaternary	24	2,088
Pliocene through Oligocene	17	1,479
Eocene through Cretaceous	4	348
Subtotal	45	3,915
Intrusive Terranes:		
Tertiary and Cretaceous	1	87
Cretaceous	7	609
Subtotal	8	696
Volcaniclastic Terranes:		
Subaerial	1	87
Marine	9	783
Tertiary		
Tertiary and Cretaceous	6	522
Cretaceous	20	1,740
Subtotal	36	3,132
Alteration	1	87
Seafloor Basalts and Cherts	7	609
Ultramafic Rocks and Amphibolites	1	87
Total land area	98	8,526
Surface water	2	174
Grand Total	100	8,700

Table 2. Puerto Rico geologic map units by geologic terranes
[Stratigraphic units listed alphabetically]

Map unit symbol	Map unit
NONVOLCANICLASTIC TERRANES	
Quaternary:	
Qa	Alluvium
Qb	Beach deposits
QTs	Blanket sand deposits
Ql	Landslide deposits
Qs	Swamp deposits
af	Artificial fill
Pliocene through Oligocene:	
Tcbga	Almirante Sur Sand Lentil of Cibao Formation
Ta	Aguada Limestone
Tay	Aymamon Limestone
Tcm	Camuy Formation
Tcb	Cibao Formation
Tcbg	Guajataca Member of Cibao Formation
Tgua	Guanajibo Formation
Tjd	Juana Diaz Formation
Tla	Lares Limestone
Tcbmi	Miranda Sand Member of Cibao Formation
Tcbm	Montebello Limestone Member of Cibao Formation
Tmu	Mucarabones Sand
Tpo	Ponce Limestone
Tcbq	Quebrada Arenas Limstone Member of Cibao Formation
Tcbr	Rio Indio Limstone Member of Cibao Fomation
Ts	San Sebastian Formation
Tfb	Fault breccia
Eocene through Cretaceous:	
Tco	Corozal Limestone
Kcot	Cotui Limestone
Tc	Cuevas Limstone
Tg	Guayo Formation
Klm	La Muda Formation
Kp	Parguera Limestone
Kpe	Penones Limestone

INTRUSIVE TERRANES

Tertiary through Cretaceous:

TKas	Alkali syenite
TKap	Augite andesite porphyry
TKahp	Augite-hornblende porphyry
TKat	Augite trachybasalt
Td	Porphyritic dacite
TKda	Amygdaloidal dacite
TKg	Diabasic gabbro
Tga	Gabbro
TKgm	Granodiorite quartz monzonite
TKhda	Hornblende dacite
TKh	Porphyry Hornblende quartz-diorite
Thp	Hornblende quartz diorite porphyry
TKdi	Diorite
TKqd	Quartz diorite-granodiorite
TKk	Quartz keratophyre
Trhp	Rhyodacite porphyry

Cretaceous:

Kdi	Diorite
Kdh	Diorite-hornblende gabbro
Kcag	Granodiorite of the Caguas pluton
Kmc	Granodiorite of Morovis and Ciales stocks
Kpgq	Quartz diorite - plutonic complex of Punta Guayanes
Kpsg	Granodiorite of the plutonic complex of Punta Guayanes and the granodiorite of San Lorenzo batholith, undivided
Ksl	Granodiorite-quartz diorite of San Lorenzo batholith
Ku	Granodiorite-quartz diorite of the Utuado batholith
Kib	Intrusive breccia of the Daguao Formation
Kslg	Mixed granodiorite-diorite of the San Lorenzo batholith
Kpgg	Granodiorite of plutonic complex of Punta Guayanes
Kpsq	Quartz diorite of plutonic complex of Punta Guayanes and of the Granodiorite of San Lorenzo batholith
Kslq	Quartz diorite facies of Granodiorite of San Lorenzo batholith and diorite-hornblende gabbro
Kpgqm	Quartz monzonite of plutonic complex of Punta Guayanes
Kpob	Two pyroxene olivine basalt

VOLCANICLASTIC TERRANES

SUBAERIAL:

Kcb	Cambalache Formation
Kpo	Pozas Formation

MARINE:

Tertiary

Tca	Carreras Siltstone
Tj	Jicara Formation
Tjo	Jobos Formation
Tl	Los Puertos Formation
Tm	Monserrate Formation
Tor	Ortiz Formation
Tpa	Palmarejo Formation
Tra	Raspaldo Formation
Tr	Rio Culebrinas Formation
Trd	Rio Descalabrado Formation
Trp	Rio Piedras Siltstone
Ty	Yunes Formation

Tertiary and Cretaceous:

TKa	Anon Formation
TKamo	Anon-Monserrate Formations, undivided
TKay	Anon and Yauco Formations, undivided
TKam	Anon and Maricao Formations, undivided
TKci	Cibuco Formation
TKgu	Guaracanal Formation
TKl	Lago Garzas Formation
TKaym	Anon, Yauco, and Maricao Formations, undivided
TKlam	Lago Garzas, Anon, and Maricao Formations, undivided
TKly	Lago Garzas and Yauco Formations, undivided
TKal	Anon Formations and Lago Garzas, undivided
TKm	Maricao Formation
TKmy	Maricao and Yauco Formations, undivided
TKmly	Maricao, Lago Garzas, and Yauco Formations, undivided
TKn	Naranjito Formation
TKy	Yauco Formation

Cretaceous:

Kac	Achiote Conglomerate
Kal	Alonso Formation
Kba	Barrazas Formation
Kcam	Camarones Sandstone
Kcn	Canovanas Formation
Kca	Cariblanco Formation
Kcan	Cancel Breccia
Kcar	Carraizo Breccia
Kcoa	Coamo Formation
Keo	El Ocho Formation
Kfa	Fajardo Formation
Kfr	Frailes Formation
Kg	Guaynabo Formation
Kh	Hato Puerco Formation
Kja	Jayuya Tuff
Kln	Los Negros Formation
Kma	Magueyes Formation
Kmal	Malo Breccia
Kman	Manicaboa Formation
Kmar	Maravillas Formation
Kmag	Martin Gonzalez Lava
Km	Melones Limestone
Kmo	Monacillo Formation
Kpa	Pajaros Tuff
Kpi	Pitahaya Formation
Kra	Rio Abajo Formation
Krp	Rio de la Plata Sandstone
Kr	Robles Formation
Ks	Sabana Grande Formation
Kta	Tabonuco Formation
Kte	Tetuan Formation
Kt	Torrecilla Breccia
Kto	Tortuga Andesite
Kv	Vista Alegre Formation

ALTERATION TERRANE

TKmv	Metavolcanic rock
TKha	Hydrothermally altered rock

SUBMARINE BASALT AND CHERT TERRANE

Kabcj	Formations A, B, C, & J
Kav	Avispa Formation
Kap	Avispa and Perchas Formations, undivided
Kbo	Boqueron Basalt
KJc	Cajul Basalt
Kce	Celada Formation
Kcg	Cerro Gordo Lava
Kco	Concepcion Formation
Kctt	Cotorra Tuff
Kd	Daguao Formation
Ke	El Rayo Formation
Kf	Figuera Lava
Kfd	Figuera and Daguao Formations, undivided
Ki	Infierno Formation
Kl	Lajas Formation
Klo	Lomas Formation
Kmam	Mameyes Formation
KJm	Mariquita Chert
Kper	Perchas Formation
Kso	Santa Olaya Lava

ULTRAMAFIC ROCK AND AMPHIBOLITE TERRANE

KJa	Amphibolite
KJas	Amphibolite-Serpentinite
KJs	Serpentinite
KJb	Spillitized Basalt

Geochemistry of Puerto Rico

STREAM-SEDIMENT GEOCHEMISTRY OF PUERTO RICO,
ISLA DE VIEQUES, AND ISLA DE CULEBRA

By
Sherman P. Marsh

GEOCHEMISTRY OF PUERTO RICO

INTRODUCTION

A regional stream-sediment geochemical survey of the Commonwealth of Puerto Rico began in the early 1970's as an outgrowth of the cooperative exploration geochemical studies by the Department of Natural Resources of Puerto Rico (DNR) and the United States Geological Survey (USGS) on the Río Tanamá and Río Viví copper deposits. From the early 1970's through the mid 1980's stream-sediment sampling continued over a large part of the island. In 1980 a cooperative project between the DNR and the USGS was started to continue the regional stream-sediment sampling program, and this project continued for several years. A total of 2,493 stream-sediment samples were collected during this phase of the project.

In 1990 a systematic search of USGS computer records and records in the DNR chemistry laboratory yielded a geochemical data set for the stream sediments that indicated that the regional geochemical sample net for the island was incomplete. In 1991 we made two field trips to Puerto Rico and an additional 292 stream-sediment samples were collected and analyzed in order to complete the regional geochemical survey.

The total number of stream-sediment samples used in this report is 2,785. Because of the lengthy period of time between the original stream-sediment survey and the survey completed in 1991, and because analytical techniques and procedures have changed somewhat over the years, the two resulting geochemical data sets have generally been kept separate for interpretive and statistical purposes. The two data sets are referred to as the "old" and the "new" in this report. All geochemical data from the regional stream-sediment geochemical surveys are published in USGS Open-File Reports 92-353A and 92-353B (Marsh, 1992) and are included in appendix D.

Sample collection and processing

During the cooperative project between the DNR and the USGS, stream-sediment samples were taken from first-order streams that drained basins from less than 1 square kilometer to as much as 3 square kilometers. Most of the sediment samples were collected from the main channel of active streams. Due to time and budget constraints the sediment samples collected in 1991 were from first- and second-order streams and represented drainage basins as large as 10 square kilometers. These samples were also collected from the main channel of active streams.

Sediment samples were screened through a 2-mm-mesh stainless-steel screen in the field, and a 4 X 6-in. sample bag of the resulting material was collected for further processing. The samples were air dried and sieved through a 250-m (U.S. Standard Sieve #60 mesh) stainless-steel sieve for the "old" samples and through a 177-m (U.S. Standard Sieve #80 mesh) stainless steel sieve for the "new" samples. The -250-m and -177-m fractions respectively were then pulverized for analysis.

Contamination

Due to the high population density on the island of Puerto Rico, most of the streams sampled for the regional geochemical survey were contaminated in some manner. Contamination ranged from refuse from nearby habitation to large objects such as car bodies, refrigerators, construction materials, and such. The results of the geochemical survey do not seem to reflect any abnormal anomalies at the 1:200,000 scale of these maps that can be directly attributable to contamination. It is possible, however, that at larger scales, where the details of individual streams would be shown, some single-point anomalies might prove to be the result of contamination.

Statistical methods

Univariate statistics, correlation coefficient tables, cumulative frequency plots, factor analysis, factor-score plots, and single-element distribution plots were used to evaluate the stream-sediment geochemical data. The geochemical data were examined and basic statistics were generated for both the "old" and the "new" data (table 1; table 2). From the basic statistics, cumulative frequency plots (figs. 1-22) were generated for the 11 elements utilized in the geochemical interpretation in this report for the "old" and "new" data.

For the purposes of this study, geochemical values in the 90th percentile or above (figs. 1-22) were considered to be anomalous. For most of the 11 elements plotted, the 90th percentile was well above the crustal abundance for the individual elements (table 3).

Some of the lower detection limits of the semiquantitative spectrographic data for individual elements are above crustal abundances, making the analyses less useful for interpretation. Because of this, the only reported values for some elements (such as gold silver, and zinc) are in the highly anomalous range. When an element has a very restricted number of valid determinations that represent only a small part of the distribution, the data is considered to be highly "censored." For the Puerto Rico geochemical data sets, any elements that had less than 38-43 percent valid determinations were considered to be censored.

Although statistically somewhat difficult to deal with, many of these highly "censored" data are important in the interpretation of the geochemistry, especially in determining suites of elements related to mineralization. When using this highly "censored" data, as in the case of gold and silver, any reported value is usually at or above the 90th percentile of the distribution and was considered anomalous for this interpretation.

Correlation - In addition to the above statistics, tables of correlation coefficients were generated (table 4; table 5). These tables show three different things; (1) correlations between elements, (2) the standard deviation for each element, and (3) the number of samples involved in making the correlation. Correlations are shown in the upper half of the tables. Those in **bold** and **bold shaded** typeface are statistically significant and correlate at the 99 percent confidence level (99 percent of the time the correlation is significant and not the result of a random event) for the elements shown. The correlations indicate lithogeochemical associations as well as associations related to mineralization. The number of samples involved in each correlation is shown in the lower half of the tables. The standard deviations for each element are shown in the middle of the tables. To read the tables, find the element of interest (either vertically or horizontally), move across or down to the other element of interest and note the number. If you are in the upper half of the table the number will be the correlation coefficient and if you are in the lower half of the table the number will be the number of samples involved in the correlation calculation. If you look at the same element along both the vertical and horizontal axes, the resulting number will be the standard deviation for that element (shown in UNDERLINE typeface).

Multivariate analysis

Analysis of multivariate data allows consideration of changes in several properties simultaneously. Multivariate analysis used in geologic studies includes multiple regression, discriminate functions, cluster analysis, and factor analysis. Factor analysis is a method for identifying common factors (or, in the case of the Puerto Rico geochemical data, suites of elements) in the variables of a data set and is useful in interpretation when the number of factors is less than the number of variables or number of elements analyzed. The method involves interpreting the structure within a variance-covariance matrix of a multivariate data set and assigning the various elements of the matrix to groups (factors) on the basis of a common variability of these elements. A factor is a vector that is weighted proportionally to the amount of the total variance that it represents.

There are two methods of factor analysis, R-mode and Q-mode. Q-mode factor analysis investigates the interrelationships between individual samples, whereas R-mode factor analysis investigates the interrelationships in a matrix of correlations between variables. R-mode factor analysis can be used to identify groups of elements (variables) that have common associations, for example, a group of elements that represents a certain rock type (a lithologic factor), or a group that represents a type of- or model for-mineralization (a mineralizing factor).

R-mode factor analysis (Koch and Link, 1971) was used on the Puerto Rico geochemical stream sediment data to identify associations as geochemically related groups of elements. These groups or "factors" were based on the correlation coefficients of the elements (table 4; table 5). Individual factors show predominant lithologies and mineral associations.

Factor analysis cannot be performed on data that contains nonnumeric or qualified values. The geochemical data sets for Puerto Rico, Appendix D, contain many analyses that are qualified. Qualified values are indicated as follows: "N," not detected at the lower limit of analytical determination, "L," detected, but below the lower limit of determination, or "G," detected at greater than the upper limit of determination. In order to resolve problems with qualified data, a computer program was run on each data set to replace the qualified data with numeric data. The qualified data were replaced as follows:

N: All values of an element qualified with a "N" were replaced with 0.3 times the lower limit of determination for that element.

L: All values of an element qualified with a "L" were replaced with 0.7 times the lower limit of determination for that element.

G: All values of an element qualified with a "G" were replaced with 1.5 times the upper limit of determination for that element.

For semiquantitative spectrographic data these replacement values correspond to approximately three reporting steps lower than the lower limit of determination for "N"' values, One step below the lower limit of determination for "L"' values, and one step above the upper limit of determination for "G" values.

Factor analyses - A number of R-mode factor analyses using varimax factor rotation were run on the combined "old" and "new" data sets. One series of R-mode factor analyses included the censored data, and another series had the censored data removed. Individual factor analyses were run using from 7 to 12 factors. The factor analyses generated from data sets that excluded censored data gave somewhat similar results to the factor analyses generated from data sets that included censored data, the difference being that when the highly censored data were included, the elements Ag, As, Bi, Cd, Mo, and Sb, in general, were added to the factors related to mineralization. The individual factor analyses selected for interpretation were based on the ability to explain the individual factors in geologic terms and on the total percent of variance within the data set that was resolved. For the Puerto Rican data sets, 9- 12 factors were geologically significant and explained approximately 70 percent of the variance (Marsh, 1993). Comparison of the factor analyses for the "old" and "new" data sets indicates that the individual factors are comparable and in many cases identical. Because of these similarities a new data set called "all" was generated by combining the "old" and "new" data sets. To make the "all" data set, many element analyses were deleted from the "new" data set, including most of the inductively coupled plasma-atomic emission spectrophotometry (ICP-AES) analyses (Appendix D). Also, variations in analytical techniques were ignored because most of the samples (both "old" and "new") were analyzed by the standard semiquantitative spectrographic method. The resulting "all" data set showed analytical data for 23 elements in 2,785 samples. Basic statistics (table 6) and a table of correlation coefficients (Table 7) were generated for the "all" data set, similar to those for the "old" and "new" data sets.

A series of R-mode factor analyses were run on both the "all" data set containing the censored data and on the "all" data set from which the censored data were removed, using from 7 to 11 factors (Marsh, 1993). For interpretation of the "all" data set containing the censored data, a ten-factor model was chosen that accounted for 69 percent of the variance (table 8). For interpretation of the "all" data set from which the highly censored data were removed, a nine-factor model was chosen that accounted for 71 percent of the variance (table 9). In the following discussion of the individual factors the nine-factor model, which excludes the censored data, is used. The ten-factor model, which includes the censored data, is referred to where the additional elements aid in the interpretation (table 8). These two factor models are generally equivalent, but the individual factors do not necessarily correspond. Where differences occur, they are noted.

The R-mode factor analysis program also creates a data file that contains a factor "score" for each sample in the data set. A score is calculated for each factor of each sample, and a high positive score indicates that the factor is dominant in that sample. A high negative score indicates that the factor is not representative for that sample. For this interpretation a positive score of +1 and a negative score of -1 were considered to be anomalous. These scores were plotted on a map of geologic terranes and (or) the permissive mineral deposit terranes, depending on whether the factors were related to lithology or mineralization, respectively. These factor score-plots are shown in figures 23 - 35 and are discussed in the geochemical interpretation of the factors and in the interpretation of individual deposit types.

Discussion of factors - The following is a discussion of the individual factors generated from the R-mode factor analysis of the "all" geochemical data set.

<u>Factor 1.</u> -- This factor has high positive loadings for Fe, Ti, V, Y, and Zr which make up a suite of elements that characterizes igneous rocks. When the highly censored data are included there are no changes and this factor becomes factor 7 (table 8). The factor score plot (fig. 23) shows anomalous sample localities that define the major intrusive bodies on the island including the San Lorenzo and Utuado batholiths. A clustering of anomalous sample localities occurs in the northwestern part of the island, northeast of Mayaguez, probably represents a more dominant acid to intermediate intrusive component of the volcaniclastic rocks in this area.

<u>Factor 2.</u> - This factor has high positive loadings for magnesium, cobalt, chromium, and nickel, which make up a suite of elements that can represent both lithology and mineralization. Lithologies represented are mafic to ultramafic rocks and laterite and include ophiolite sequences. Podiform chromite, nickel laterite, and platinum-group elements all can occur in these rock types. When the highly censored data are included there are no changes and this factor remains factor 2 (table 8). The factor-score plot (fig. 24) shows a clustering of anomalous sample localities around the known areas of ultramafic rocks in the southwestern part of the island. Another area of anomalous sample localities in the north-central part of the island, in the volcaniclastic terrane, corresponds, approximately, to the areas of anomalous sample localities shown for factors 3 and 6. These three factors combined would be consistent with a mafic rock terrane, but none is known to exist. Analytical values for samples from this area, although anomalous, are significantly lower than those for samples from the ultramafic rocks in the southwestern part of the island (Appendix D) and may indicate the presence of basalt that contains mafic minerals such as chromian diopside, which would account for elevated values of magnesium and chromium.

<u>Factor 3.</u> - This factor has high positive loadings for calcium and strontium and a high negative loading for zinc. These elements are characteristic of a lithologic factor, mainly limestone and calcium bearing sedimentary rocks. When censored data are included (factor 5,table 8) the moderately positive factor loading for lead is added and the negative loading for zinc disappears.

The factor-score plot (fig. 25) shows clusters of anomalous sample localities in the non volcaniclastic units that include the limestone terrane in the northern part of the island and the alluvial plains around the edge of the island. Some anomalous sample localities scattered throughout the rest of the island probably represent small limestone units in the volcaniclastic and basalt and chert terranes. A cluster of anomalous sample localities in and near the Utuado batholith (Intrusive and Structural Map), in the north-central part of the island, probably represent calcite veining, altered rock, and minor lead-zinc minerals because much of this terrane is mineralized. Another group of anomalous sample localities partially coincides with anomalous sample localities for factor 2 in the north-central part of the island and may represent either altered rock or calcite veining.

Factor 4. - This factor has high positive loadings for Ti, Mn, Sc, V, and Y, which make up a suite of elements characteristic of a lithologic factor, mainly mafic volcanic, volcaniclastic, and metavolcanic rocks and submarine basalt and chert. Factor 4 also has moderately positive factor loadings for iron, magnesium, and zinc, elements that are indicative of volcanic terrane. When the highly censored data are included, this factor becomes equivalent to factor 1 (table 8) and the moderately positive loading for barium is substituted for the moderately positive loading for zinc. The factor-score plot on the generalized geologic map (fig. 26) shows the preponderance of anomalous sample localities for factor 4 in the volcaniclastic rocks in the western third of the island, many clustered north of Mayaguez. The remainder is scattered throughout this rock type with an additional clustering of anomalous sample localities in the submarine basalt and chert west of the San Lorenzo batholith. The area of high negative loadings for factor 4 covering the entire area of the Utuado batholith in the west-central part of the island and part of the San Lorenzo batholith in the southeastern part of the island indicates that the chemical composition of these intrusive rocks is completely different from that of the surrounding volcaniclastic host rocks and, in the case of the Utuado Batholith, may be indicative of alteration and mineralization.

Factor 5. - This factor has high positive loadings for lead and zinc and a moderately positive loading for manganese. These elements are characteristic of base-metal mineralization as veins and possible elemental zoning around porphyry copper-molybdenum-gold deposits, of volcanogenic manganese deposits, and of Kuroko-type massive sulfide deposits (figs. 27 and 28). When the highly censored data are included, this factor becomes equivalent to factor 3 (table 8) and the factor loading for manganese becomes highly positive with a moderately positive factor loading for Fe added. The factor-score plot on a base map showing the igneous rocks and the porphyry copper terrane (fig. 29) show three clusters of anomalous sample localities: (1) around the known porphyry copper-gold deposits adjacent to the Utuado batholith in the west-central part of the island, (2) around the known porphyry-molybdenum occurrences in the northeastern part of the island, and (3) around the copper skarn occurrences in the east-central part of the island. Many of the anomalous sample localities in the western part of the island coincide with the margins of the volcanogenic manganese and Kuroko-type massive sulfide terrane (fig. 28). Other scattered anomalous sample localities in the volcaniclastic and basalt and chert terranes probably represent polymetallic vein occurrences.

Factor 6. - This factor has a high positive loading for barium, and, although no other loadings are listed, a moderately positive loading of .1933 for Magnesium is present, just below the cut off value of .2000. Factor 6 also has a moderately negative loading for zinc. When highly censored data are included, the barium-magnesium factor 6 (table 9) is no longer present and barium is associated with gold and lead (factor 6, table 8) and with tin (factor 10, table 8), both of these factors representing mineralization. The factor-score plot for the uncensored data shows several areas of anomalous sample localities, most of which are in the volcaniclastic terrane (f ig. 30). Two exceptions to this relationship are the cluster of anomalous sample localities in granodiorite of the San Lorenzo batholith in the southeastern part of the island and the small cluster of anomalous sample localities around a small pluton in the north-central part of the island (fig. 31). These samples may represent a barium-rich phase of the plutons or may represent hydrothermal barite veins. The four other clusters of anomalous sample localities all occur in the volcaniclastic terrane (fig. 30). One cluster, in the northeastern part of the island, approximately corresponds to an area of anomalous sample localities shown for factors 2 and 3. These three factors combined would be consistent with a mafic rock terrane, but none is known to exist in this area. If, however, the actual anomalous values of these samples are examined (Appendix D) they appear to mostly be of lesser magnitude than those found in the other anomalous areas. Mafic minerals in the volcaniclastic rocks in this part of the northeastern part of the island could be causing this area of anomalies. For example, chromium diopside in basalt would account for the higher than normal concentrations of chromium and magnesium in these rocks. Factor 6 anomalies also occur around the ultramafic terrane in the southwestern part of the island and in three areas in the central part of the island. These areas do not relate to any known mineral occurrences (Metallic Mineral Occurrences Map) and may be related to chloritic alteration and barite around a Kuroko-type massive sulfide or exhalative type deposit (Cox and Singer, 1986).

Factor 7. - This factor has high positive loadings for iron and copper and moderately positive loadings for magnesium, vanadium, and zinc. These elements represent porphyry copper-gold and porphyry copper mineralization. The factor score plot (fig. 32) shows most of the anomalous sample localities around the western part of the porphyry copper terrane, where there are known porphyry copper-gold deposits. An additional cluster of anomalous sample localities occurs near some small intrusive bodies in the north-central part of the island, and a small cluster of anomalous sample localities lies just northeast of Mayaguez, in the volcaniclastic terrane. When the highly censored data are included copper is present in two mineralization factors (factors 4 and 8, table 8) that represent porphyry copper deposits. In factor 4 has high positive loadings for copper and silver and represents mineralization. Factor 8 has a high positive loading for iron and molybdenum and the loading for copper becomes only moderately positive along with magnesium, lead, vanadium, and zinc.

Factor 8. - This factor is a single-element factor showing a high positive loading for boron. When the highly censored data are included boron is in factor 9 and the moderately positive loading for Pb is added (table 8). The factor-score plot (fig. 33) shows that most of the anomalous sample localities are lithologically related, in or adjacent to areas of the submarine basalt and chert terrane. Exceptions to this relationship are the cluster of anomalous sample localities at the north end of a pluton in the south-central part of the island and a cluster along the contact of the volcaniclastic terrane with the non-volcaniclastic terrane in the northwestern part of the island. Anomalies related to the pluton may represent mineralization or they may be related to alteration of the volcaniclastic rocks nearby. The anomalous sample localities in the northwestern part of the island appear to be lithologically related and may represent tourmaline bearing metavolcanic rocks or, where they coincide with anomalous sample localities for factor 9 (gold), may represent low-sulfide gold-quartz veins (Cox and Singer, 1984).

Factor 9. - This factor is also a single-element factor and shows a high positive loading for gold. In an eight factor model this factor (gold) is included in factor 6, the porphyry copper factor. Indeed, trace gold in soils has been used as an indicator element for the porphyry copper-gold deposits in the west-central part of the island (Learned and Boissen, 1973). When the highly censored data are included gold is in factor 6 (table 8). This factor also contains a high positive loading for barium and a moderately positive loading for lead. The factor-score plot (figure 34; figure 35) shows that the anomalous sample localities for the gold factor are related to the permissive mineral deposit terranes (map 1; map 2). Anomalous sample localities are clustered around the known porphyry copper-gold deposits in the west-central part of the island, related to placer deposits in the northeastern part of the island, and near the areas of epithermal quartz-alunite-gold. Anomalous sample localities are also clustered in the drainage basin of the Río Cibuco and may represent a placer potential downstream (fig. 34). The anomalous concentration of gold in this area is also reflected in 'Silt heavy-mineral distributions in the Rio Cibuco system and adjacent rivers of north-central Puerto Rico' by Poppe and others, contained within this publication.

Geochemical interpretation

Mineral resource terranes

The analytical results for the stream sediments reveal complex patterns of anomalously high values for many elements, and many of these anomalies can be attributed to various hydrothermal mineralization processes on the island. On the basis of these data and data from geophysics and geology, terranes permissive for mineral resources have been identified on the island of Puerto Rico (Permissive terrane map 1 and map 2). In addition, there is a possibility of a zircon placer terrane around the San Lorenzo batholith in the southeastern part of the island and of shoreline titanium placers around the island.

Geochemical maps

Cumulative frequency plots for elements (figs. 1 - 22) were used to determine the 90th percentile of the data. All values above the 90th percentile were plotted on the maps and ranges of values were used as noted.

Deposit models

The following discussion focuses on the geochemical data derived from stream-sediment samples and interpretation of anomaly patterns in relation to permissive terranes, known occurrences, and depositional terranes. The individual deposit models discussed below are described in detail in the Mineral Deposit Summary Sheet.

Podiform chromite and nickel laterite

Although no podiform chromite deposits are known to occur in Puerto Rico, an area of permissive terrane has been delineated. The geochemical suite of chromium, cobalt, and nickel (figure 24) characterizes this terrane, and most of the anomalous values for these elements are for samples from localities clustered around the mapped outcrops of mafic and ultramafic rocks in southwestern Puerto Rico; the factor plot for the Mg, Co, Cr, and Ni factor (fig. 24) closely corresponds to the geologic map of these rocks. There is another population of anomalies hosted mostly in marine Cretaceous volcaniclastic rocks in the north-central part of the island, in the Corozal and Naranjito quadrangles. There are 34 geologic units in the marine Cretaceous volcaniclastic terrane, but the anomalous area is confined mostly to the following map units; Kcam, Kcan, Keo, Kln, Kmag, Kman, Kpa, Krf, and Kv. The most common rock type in these formations is andesitic and basaltic lava followed by volcanic siltstone, sandstone, and breccia. Crustal abundances for Co, Cr, and Ni are approximately 50, 170, and 140 parts per million (ppm) (table 3). Anomalies for these elements in this area are somewhat above these values and represent either unmapped more mafic lithologies, mafic minerals in the andesitic and basaltic lava, or possible mineralized rock. The map of nickel-cobalt anomalies show a broader distribution of cobalt throughout the marine Cretaceous volcaniclastic terrane and generally represents the lower range (50-150 ppm) of cobalt. This range is just slightly higher than crustal abundance and is considered within normal range for these rock types.

There are known nickel laterite deposits and located in the mafic and amphibolite terrane in southwestern Puerto Rico. The terrane favorable for this deposit type is the same as that favorable for podiform chromite and the related geochemical suite is similar. Although the Mg, Co, Cr, and Ni geochemical suite is present at anomalous sample localities the north-central part of the island, the volcaniclastic marine Cretaceous rocks are not conducive to the formation of nickel laterites.

Porphyry copper and porphyry copper-gold

These two deposit types are closely related, and the porphyry copper terrane is favorable for deposits fitting both these models. There are seven known deposits and ten occurrences of porphyry copper and porphyry copper-gold on the island. All but five occurrences fall inside this terrane. Copper anomalies are scattered throughout the porphyry copper terrane, and most are related to Cretaceous and Tertiary intrusive rocks, the most intense anomalies being in the area of porphyry copper-gold deposits in the west-central part of the island. This is also reflected in factor 7 of the R-mode factor analysis (table 9) and the factor-score plot for factor 7 (fig. 32). This area also has the most intense anomalies for gold and molybdenum, and minor anomalies for tin. Some of the known occurrences are not defined by anomalous concentrations of copper in stream-sediment samples, especially those occurrences outside the porphyry copper terrane. This may be due to low sampling density and the fact that all these occurrences may be rather small and poorly exposed. More detailed sampling in specific areas of known occurrences would probably give additional copper anomalies. There are two areas that contain anomalous concentrations for copper, gold, molybdenum, and tin that do not contain known mineral occurrences and may warrant further investigation. One is an area approximately 20 km east of the known porphyry copper-gold deposits. Anomalies in this area are centered on a cluster of small Tertiary plutons along the east margin of the Utuado batholith. This area also contains the localities of several anomalous samples on the factor score plot for factor 7 (fig. 32). A northwest-trending zone of copper-tin anomalies in the south-central part of the island contains a known porphyry copper deposit and three polymetallic vein occurrences, but it is mostly devoid of known mineral occurrences.

Copper and iron skarns

Terranes favorable for copper and iron skarn deposits were identified around the Río Blanco stock and San Lorenzo batholith. Of all the elements analyzed in the geochemical survey, only some scattered tin anomalies appear to be associated with the skarn terrane. There are scattered anomalies for copper, zinc, lead, and gold but no definite pattern or grouping of anomalies. Most of the known skarn occurrences are in marine Cretaceous volcaniclastic rocks to the north of the San Lorenzo batholith. There may be fewer anomalies in this terrane due to the lower sample density, because skarn deposits tend to be rather small and irregular. The preponderance of the tin anomalies are on the west side of the San Lorenzo batholith in Cretaceous and Tertiary extrusive rocks and may suggest unidentified skarn deposits or pegmatite. Scattered gold, copper, molybdenum anomalies and the only tungsten anomaly occur in drainage basins around the Río Blanco stock and may indicate a potential for tungsten-bearing skarn.

Polymetallic veins

By far the most numerous metallic mineral occurrences are polymetallic veins, 59 occurrences and 2 deposits being scattered throughout the island. Geochemical anomalies related to this deposit type are also scattered throughout the island and samples anomalous in factor 4, which is indicative of intermediate to acid igneous rocks, show a similar island-wide distribution. One area containing 16 of the known occurrences is also within the porphyry copper terrane, related to the known porphyry copper-gold deposits in the west-central part of the island. Copper, lead, zinc, and silver anomalies group in this area and probably represent polymetallic vein occurrences peripheral to the porphyry copper-gold deposits. Another grouping of nine occurrences in the south-central part of the island in marine Tertiary volcaniclastic rocks is not geochemically defined because of low sample density.

Volcanogenic manganese and Kuroko-type massive sulfide

These two deposit types are outlined by one terrane in volcaniclastic rocks in the west and west - central part of the island. The geochemical signature for volcanogenic manganese is Mn, Cu, Pb, Zn, and Ba and for Kuroko massive sulfide is Cu, Zn, Pb, Ba, As, Ag, Au, Se, Sn, Bi, and Fe. Co, Pb, Zn, Sn, Au, and Ag occur as scattered anomalies in this terrane, in which Cu and Zn anomalies predominant, especially in the western part. Anomalous sample localities for the factor-score plot of factor 5 (Pb, Zn, and Mn; fig. 28) are also common in this part of the terrane.

Epithermal quartz-alunite gold

Most of the known terranes for this model are represented by anomalies for Au, Ag, Cu, Pb, and Zn, but especially for Cu and Au. Since the geochemical signature for this model can include almost any combination of base and precious metals, depending on the level of the mineralized system exposed at the surface, it is very difficult to establish geochemical anomaly patterns for this model.

Placer gold and platinum-group elements

The factor score plot for factor 9 Au (fig. 34; fig.35) shows potential gold placer terranes and localities for samples containing gold. Some gold anomalies define drainage basins that are permissive for placer deposits in the northwestern and north-central part of the island. Some of these drainage basins contain areas of past production or contain known deposits and the mineralogy from one, Río Cibuco, has been studied in detail (see Poppe, and others,'Silt heavy-mineral distributions in the Rio Cibuco system..., this volume).

Shoreline placer titanium

Although the four known placer titanium occurrences are all along the north coast of the island, the bulk of the titanium anomalies in stream sediments occur in the volcaniclastic rocks in the western part of the island. The mineralogy of the titanium in these samples is unknown, but if sufficient ilmenite ($FeTiO_3$) is present there may be potential for placer deposits along the west shoreline. There are also a number of large titanium anomalies (1,000-2,000 PPM) surrounding the San Lorenzo batholith in the southeastern part of the island, and there is a shoreline titanium placer potential in this area. This area is also characterized by zirconium anomalies, indicating that the San Lorenzo batholith may be a more felsic intrusion than others on the island. If this is the case, then shoreline placers may also contain zircon and possibly other rare-earth minerals.

Copper Manto

The area of copper Manto terrane is in the north-central part of the island, is confined to the Pozas Formation, and is relatively small. Although there are three known occurrences near the northeast border of this terrane, there is little geochemical evidence for this model except for a few copper anomalies in the central part and a few anomalous sample localities for factor 7 on the factor score plot for copper (fig. 32).

Summary

The geochemical data for the stream-sediment samples from Puerto Rico generally supports and helps define the mineral deposit models and permissive terranes on the island as well as identifying possible additional areas of presently unknown mineralization. The geochemistry and factor analysis also help differentiate lithology from mineralization.

GEOCHEMISTRY OF ISLA DE VIEQUES AND ISLA DE CULEBRA

Isla de Vieques

Introduction -- Isla de Vieques was geochemically sampled in 1972, and Learned and others (1973) published a report describing the results. A soil-sample survey of the island was conducted, rather than a stream-sediment survey, because drainage basins are poorly developed and commonly filled with colluvium and, where near populated areas, highly contaminated. A total of 421 soil samples were taken of the "C" horizon (weathered bedrock) at 0.5-km intervals on northwest-trending traverses spaced approximately 1 km apart. The soil samples were analyzed for 30 elements by semiquantitative emission spectroscopy (Grimes and Marranzino, 1968). Gold and zinc were also determined by atomic-absorption methods (Ward and others, 1969 and Thompson and others, 1968). All geochemical data from the regional soil geochemical survey are published in USGS Open-File Reports 73-1866, 92-353-A and 92-353-B (Learned and others, 1973 and Marsh, 1992) and are included in Appendix D, this report.

Geology -- The geology of the island is dominated by Late Cretaceous intrusions (quartz-diorite, diorite, and granodiorite) that have intruded a thick (greater than 700 m) section of Upper Cretaceous andesite, tuff, breccia, and limestone (G.R. Grove, unpub. data, 1972). These rocks all exhibit some degree of propylitization and have been contact metamorphosed to hornblende-hornfels facies near the contact with the intrusions. A zone of intense hydrothermal alteration extends along the northeast coast from just east of Santa Maria to 2 km east of Punta Goleta. This area is characterized by severe bleaching and oxidation and by numerous quartz veins. The quartz veins range in size from 1 to 2 mm to more than 0.5 m and contain magnetite, pyrite, chalcopyrite, and molybdenite. Late, fine-grained diorite dikes intrude both the plutonic and volcanic rocks.

Statistical methods -- The soil geochemical data for Isla de Vieques were examined and univariate statistics were generated (table 10). From the univariate statistics, cumulative frequency plots were generated for 11 elements (figs. 36 - 46). For the purposes of this study geochemical values in the 90th percentile or above were considered to be anomalous. Where feasible, arbitrary ranges of values were used in the element plots. In the case of highly censored data, as for gold, any reported value was generally at or above the 90th percentile and was used in the element plot.

Correlation - In addition to the above statistics, a table of correlation coefficients was generated (table 11). This table shows three different things; (1) correlations between elements, (2) the standard deviation for each element, and (3) the number of samples involved in making the correlation. Correlations are shown in the upper half of the tables. Those in **bold** and **bold shaded** typeface are statistically significant and correlate at the 99 percent confidence level (99 percent of the time the correlation is significant and not the result of a random event) for the elements shown. The correlations indicate lithogeochemical associations as well as associations related to mineralization. The number of samples involved in each correlation is shown in the lower half of the tables. The standard deviations for each element are shown in the middle of the tables. To read the tables, find the element of interest (either vertically or horizontally), move across or down to the other element of interest and note the number. If you are in the upper half of the table the number will be the correlation coefficient and if you are in the lower half of the table the number will be the number of samples involved in the correlation calculation. If you look at the same element along both the vertical and horizontal axes, the resulting number will be the standard deviation for that element (shown in UNDERLINE typeface).

R-mode factor analysis -- In order to help sort the lithogeochemical associations from those related to possible mineralization, an R-mode factor analysis was run initially on the entire soil geochemical data set, including highly censored elements (elements for which there were less than 38% valid determinations) (table 12). As with the stream-sediment geochemical data for Puerto Rico, qualified data were replaced with numeric data (see previous discussion of multivariate analyses). A second factor analysis was run on a modified data set from which the highly censored elements removed (table 13). A six-factor model was selected for both the entire soil geochemical data set and for the data set with the highly censored data removed that accounted for 61 percent and 73 percent of the total variance in the data, respectively. Factor loadings for each element, both positive and negative, are shown in table 11 and table 12. Both factor models gave somewhat similar results, the difference being that with the entire data set the censored elements Ag, Au, Bi, and Mo were added to the factors related to mineralization.

Factor 1. -- In both factor analyses, factor 1 has high positive loadings for Fe, Mg, Ti, Mn, Co, Sc, V, and Y which make up a suite of elements characteristic of a lithologic factor. With the entire data set factor 1 also has high positive factor loadings fro chromium and nickel and a moderate positive loading for copper. When highly censored data are removed (table 13) factor 1 has a high positive loading for copper and a moderately positive loading for chromium and nickel. Factor 1 can be interpreted to represent ferromagnesian-bearing rocks, which would include the igneous intrusive, volcanic, and volcaniclastic rocks of the island.

Factor 2. -- When all the data are included, factor 2 has moderately positive loadings for B, Co, Mo, Sc, Y, and Zn, and high negative loadings for Mn, Ba, and Sr (table 12). Factor 2 can be interpreted to represent the diorite-granodiorite pluton that is mineralized in some areas. The high negative loadings for barium and strontium indicate that the large barium anomaly in the southwestern part of the island probably is not related to the mafic chemistry of the pluton and indicates an alteration phenomenon. With the highly censored data removed, factor 2 is simpler, having high positive loadings for manganese, barium, and strontium (table 13). This geochemical suite could indicate either a given rock type and (or) alteration. Barium and strontium are commonly associated with limestone, and although uncommon, there is a small area of limestone at the eastern end of the island. Significantly, however, all the anomalous barium values are for samples in the southwestern part of the island, mostly in the diorite-granodiorite intrusive rocks. This is interpreted to represent a secondary alteration phenomenon.

Factor 3 -- Factor 3 for the entire soil data set (table 12) is equivalent to factor 4 in the modified data set from which the highly censored elements have been removed (table 13). Factor 3 for the entire data set is a mineralization factor and has high positive loadings for Pb and Zn and moderately positive loadings for Au, Ag, and Mn (table 12). The suite of elements in factor 3 can be interpreted to represent base- and precious-metal deposit types related to the intrusive rocks on the island. Factor 3 for the modified data set has high positive loadings for yttrium and zirconium, moderately positive loadings for manganese, and a high negative loading for calcium; it can be interpreted to represent a given rock type and (or) alteration (table 13). These elements probably represent a geochemical contribution from the diorite-granodiorite pluton, and the high negative factor for calcium probably indicates a more sodic feldspar composition.

Factor 4. -- Factor 4 for the entire soil data set is equivalent to factor 3 in the modified data set, from which the highly censored elements have been removed. Factor 4 for the entire data set is a lithologic and (or) alteration factor having high positive loadings for Mn, Ba, Y and Zr, moderately positive loading for Ti, and high negative loadings for Ca, Cr, and Ni (table 12). This is interpreted to represent the diorite-granodiorite intrusive rocks and alteration at the contact with the volcanic and volcaniclastic rocks. The high negative loadings indicate that the mafic volcanic rocks are not contributing to this factor. Factor 4 for the modified data set has high positive loadings for lead and zinc and a moderately positive loading for manganese and is interpreted to represent base- and precious-metal mineralization (table 13). With the censored data removed, especially gold and silver, the suite of elements representing base- and precious-metals is somewhat simplified but still significant.

Factor 5. -- For the entire data set (table 12), factor 5 is interpreted to represent a given rock type; it has high positive loadings for beryllium and lanthanum and moderately positive loadings for boron and zirconium. This factor probably represents the diorite-granodiorite intrusive rocks. For the modified data set factor 5 (table 13) is interpreted to also represent a given rock type; it has high positive loadings for Cr and Ni and moderate positive loadings for Co, Sc, and Zn. This elemental suite probably represents the mafic volcanic (hornblende andesite) and volcaniclastic rocks of the island that are intruded by the diorite-granodiorite pluton.

Factor 6. -- Factor 6 for the entire data (table 12) set is another mineralization factor having high positive loadings for Ag, Cu, and Mo, and moderate positive loadings for Bi, Pb, and Au. This suite of elements is interpreted to represent a porphyry copper deposit type, model 17 from Cox and Singer (1986). Factor 6 for the modified data (table 13) is another lithologic factor having a high positive loading for boron, moderately positive loadings for calcium and yttrium, and a high negative loading for copper. This factor is interpreted to represent the non-altered and non-mineralized diorite-granodiorite igneous rocks.

Geochemical interpretation -- Results from the geochemical soil sampling indicate three areas on Isla de Vieques that are of potential economic interest: area 1: the east end of the zone of intensive alteration in Cretaceous volcanic rocks along the northeast coast; area 2: a central zone of propylitized rocks trending northwest in the center of the island along the contact between plutonic and volcanic rocks; and area 3: an area in the northwestern part of the island spatially related to the contact of the western pluton and Upper Cretaceous andesite and tuff units. Cerro El Buey, immediately south of this area, is a coarse-grained hornblende gabbro that intrudes the western pluton. Gravity data suggest that Cerro El Buey may be the southern tip of a much larger feature. Cerro El Buey may be contributing to the geochemical anomalies in this area. All three areas are anomalous in iron (greater than 7 percent) and titanium (greater than 0.7 percent)

Area 1. -- Area 1 is the east end of the zone of intense hydrothermal alteration along the northeast coast. Analysis of geochemical soil samples indicated anomalies in Fe, Ti, Cu, Zn, Mo, Sn, Ag, and Au. This geochemical suite of elements is indicative of copper skarn mineralization related to a porphyry copper system (model 18b, Cox and Singer, 1986). The anomalous concentrations of iron and titanium in the area, along with anomalous concentrations of magnesium are probably the result of the intense hydrothermal alteration of the Upper Cretaceous volcanic rocks (andesite, tuff, and breccia). The geochemical anomalies combined with the geologic observations of the intense hydrothermal alteration and iron- and manganese-stained boxwork quartz veins containing chalcopyrite and pyrite make area 1 the most significant zone of mineralization on the island.

Area 2. -- Area 2 is along the eastern contact of the western quartz-diorite pluton with Upper Cretaceous metavolcanic rocks south of Isabele Segunda and east of Destino (G.R. Grove, unpub. data, 1972). Here, copper occurs as chalcopyrite in quartz veins in the quartz-diorite pluton. Geochemical soil samples show anomalies in copper, gold, and molybdenum indicative again of copper-skarn mineralization. Anomalies of iron, titanium, and magnesium are probably the result of contact metamorphism and hydrothermal alteration. Area 2 contains anomalies of fewer elements in the geochemical suite related to copper skarns, is smaller in areal extent, and apparently has less potential for copper skarn deposits than does Area 1.

Area 3. -- Area 3 is at the west end of the western pluton and is along its contact with Upper Cretaceous metavolcanic rocks. This area contains anomalous amounts of iron, titanium, copper, and gold. As with the other two areas, area 3 shows some evidence of hydrothermal alteration and copper-skarn mineralization. Area 3 also is just north of Cerro El Buey, an area of copper anomalies.

Additional single-point anomalies in the geochemical suite related to copper-skarn - copper-porphyry mineralization are scattered throughout the area of Late Cretaceous diorite and probably reflect small mineralized siliceous zones and veins. Lithogeochemical anomalies of chromium, nickel, and cobalt occur throughout the areas of volcanic and metavolcanic rocks on the island and represent the mafic nature of these units. An area of intense barium anomalies (see appendix D) occurs at the southwestern end of the island and is partially coincident with a small grouping of manganese anomalies. The area is mapped as part of the western diorite pluton (G.R. Grove, unpub. data, 1972), and there are no reported occurrences of barite or barite veins. These anomalies are probably due to alteration.

Isla de Culebra

Introduction -- The small island of Culebra was geochemically sampled in late 1970 as part of a study to determine the island's natural resources, development potential, and socio-economic aspects (Commonwealth of Puerto Rico, 1970). Because of the lack of active streams on the island, geochemical samples of dry streambed material were collected. This material included pebbles and cobbles showing the most intense iron staining and any material showing traces of mineralization. A total of 41 samples were collected and analyzed for 30 elements by emission spectrography (Grimes and Maranzino, 1968). Gold was also determined by an atomic-absorption method (Ward and others, 1969).

Geology -- Most of the island is composed of andesite lava of probable Cretaceous age showing pillow structures. These are overlain by andesite tuff along the northeast coast. The tuff and lava have been intruded by diorite in the north-central part of the island.

Geochemistry -- Of the 41 samples analyzed, only nine contained anomalous concentrations of any elements commonly associated with mineralization and these were only weakly anomalous for one element, copper (100-150 PPM) (see Appendix D). Since this is only slightly above crustal abundance (table 3) and since the semiquantitative spectrographic method was used for analysis, these numbers are probably within normal range for these rocks. None of the samples contained any other elements of interest above crustal abundance. Since no anomalous samples were identified from the geochemical data and because of the small number of samples, no statistics were run on the geochemical data from Isla de Culebra. There are no identified deposit types on the island, and no mineral deposit terranes were established. All geochemical data from the regional stream-sediment geochemical survey are published as Open-File Reports 92-353-A and 92-353-B (Marsh, 1992) and are included in Appendix D, this report.

Geophysical Maps of Puerto Rico

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 inBromery 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-mGalcontour 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 mapof 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 305rn 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 user should keep in mind the local distribution of gravity stations when evaluating the 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 massivemafic 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 theMayaguez 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°12' W. and long 66°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°07' N., long 66°.15' W.) produces a magnetic anomaly. At least two plutons, the Cuyon and the Morovis stock (lat 18°20' N., long 66°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°12' N., long 66°14' W.) and the north side of the Coamo Arriba stock (lat 18°08' N., long 66°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°07' N., long 66°15' W.) and of the Cedro Abajo stock (lat 18°17' N., long 66°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 nearlat 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 alsocan 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 magneticlows. 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 thatpotassium 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

Andrew Griscom and Nami E. Kitchen

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° 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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METALLIC AND INDUSTRIAL MINERAL MINES, PROSPECTS, AND OCCURRENCES IN PUERTO RICO, AS RECORDED IN THE MINERAL RESOURCES DATA SYSTEM (MRDS)

by Walter J. Bawiec, Dennis P. Cox, Gregg E. McKelvey, Matthew E Paidakovich, Andrea Handler, and Johannes H. Schellekens

INTRODUCTION

This compilation summarizes the metallic and industrial mineral mines, prospects, and occurrences of Puerto Rico. The metallic and industrial mineral data discussed here have been complied and entered, in support of the mineral resource assessment of Puerto Rico, into the U.S. Geological Survey's (USGS) Mineral Resources Data System (MRDS), a database for worldwide mineral deposits and occurrences.

Metallic mines and mineral occurrences for Puerto Rico are listed in Appendix B. This table of selected MRDS data fields was extracted from MRDS records compiled from previous mineral occurrence maps (Cox and Briggs, 1973), literature searches, and public company records on file at the Puerto Rico Department of Natural Resources, San Juan. A complete listing of the MRDS records for metallic minerals in Puerto Rico can be found in Appendix E.

The fields for the Puerto Rico industrial mineral sites listed in Appendix C, were extracted from U.S. Geological Survey Open-File Report 92-244 (Center for Inter-American Mineral Resource Investigations (CIMRI) and Puerto Rico Department of Natural Resources, 1992). These records describe sites with active extraction permits in 1991, as recorded by the Corteza Terrestre/Surface Mining Permits Office of the Puerto Rico Department of Natural Resources, and previous sites displayed on 1:20,000-scale geologic maps published by the USGS during the last 30 years. The complete MRDS records for industrial minerals in Puerto Rico can be found in Appendix E.

MRDS

MRDS, originally named the Computerized Resource Information Bank (CRIB), is a database of mineral deposits and occurrences. Information on mineral deposits in MRDS includes commodity and descriptive geologic data useful for regional mineral resource assessments and reconnaissance exploration. In-depth site descriptions for some well-studied mines and deposits are also available. MRDS containes approximately 110,000 records, 76,000 of which are for deposits and occurrences in the United States.

A primary goal of MRDS is to ensure that each record faithfully reproduces the data source(s); this assumes that the data source is accurate and contains valid information. Where there are inconsistencies or questionable quality, the data have been interpreted and reflect the opinions of the record contributors and file editors. The user, therefore, is advised to check the original data source materials, as referenced in the MRDS records, whenever questions arise. Also, no claim is made for completeness of this compilation and users of the data should bear in mind that some published and unpublished sources may have been missed.

Additions and corrections to the information in this report are welcomed. Data changes or additions may be submitted to:

Mineral Resources Data Systems
U.S. Geological Survey, Mail Stop 954
12201 Sunrise Valley Drive
Reston, VA 22092 USA

MINES, PROSPECTS, AND OCCURRENCES

An inventory of known mineral deposits and less-understood mineral occurrences is essential in the evaluation of the potential mineral resource endowment of an area. For this reason, great care was used to identify and document metallic and nonmetallic industrial mineral occurrences of Puerto Rico.

Previous studies of Puerto Rico, many of which were conducted on specific commodities or in restricted areas, examined known mineral deposits and occurrences. The "Metallogenic Map of Puerto Rico" (Cox and Briggs, 1973) combined mineral sites from these studies into a comprehensive compilation. In this study, deposits and occurrences described in Cox and Briggs were augmented with additional published and unpublished information by reviewing the original literature and other sources. New MRDS records were prepared to incorporate data found in the files available at the Department of Natural Resources in San Juan, Puerto Rico.

The occurrences of metallic minerals, shows an association of mineral deposit types by spatial distribution. Each deposit type is represented by a unique symbol accompanied by a site number. Those occurrences for which a deposit type could not be determined due to lack of information are represented by the abbreviation of an element known to occur at this site. Certain mineral deposit types tend to be found in proximity to one another. If geology, geologic terrane, and metallic mineral occurrences are considered, it can be seen that granitic intrusive rocks tend to be associated with skarn and vein deposits. Gold placer deposits can be found in sediments downstream in drainage basins crossing areas that contain gold-bearing porphyry, skarn, and vein systems. Nickel laterite deposits are concentrated in southwestern Puerto Rico, where they have developed on weathered serpentinite. Volcanogenic manganese deposits display a northwest-southeast trend that corresponds to outcrops of Tertiary volcaniclastic rocks.

Industrial mineral commodities of Puerto Rico have not received the attention they deserve. No published comprehensive compilation of industrial mineral mines and occurrences was found to exist previous to this mineral resource assessment. Because of their low unit value, high transportation costs, and perception of not being "glamorous," the characteristics of formation and mode of occurrence of industrial minerals have not been very well documented. Of the industrial commodity occurrences, approximately 120 have permits active in 1991, as reported by the Corteza Terrestre Surface Mining Permits Office of the Puerto Rico Department of Natural

Resources, San Juan. Additional records for 300 occurrences were collected by the USGS from more than 40 geologic maps at a scale of 1:20,000. This compilation resulted in more than 450 industrial mineral mines and occurrences being documented for Puerto Rico. A complete listing of all industrial mineral occurrences documented in MRDS is found in Appendix E.

Patterns of occurrence for the industrial minerals show most permit sites located proximal to the coastline and, more importantly, within short distances of modern highways. Sand deposits, important to the construction industry, are contained in recent surficial sediments that blanket much of the north and south coasts.

The largest mineral production in Puerto Rico is related to the manufacture of cement, and more than 140 of the MRDS records are for limestone and limestone aggregate quarries. Most of the limestone and limestone aggregate quarries mine material from the Miocene Aymamón Limestone, but at least four other formations have significant limestone production (Center for Inter-American Mineral Resources Investigation (CIMRI) and Puerto Rico Department of Natural Resources, 1992). Other industrial minerals produced in Puerto Rico include dimension stone, silica sand, sand and gravel, aggregate and road metal, gypsum, barite, phosphate, clay, and dolomite.

EXPLANATION OF DATA FIELDS

A complete MRDS record contains as many as 240 fields for recording a wide range of attributes (U.S. Geological Survey, 1993). Selected fields from the metallic and nonmetallic MRDS records are listed in Appendix B and Appendix C, respectively. Appendix E contains the complete MRDS records for Puerto Rico, with ‘Help’ files to describe indexed fields.

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Puerto Rico Mineral Resource Assessment

OUTLINE

May 4, 1999

MINERAL RESOURCE ASSESSMENT OF PUERTO RICO

by

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METHOD OF RESOURCE ASSESSMENT

The mineral resource assessment of Puerto Rico is the culmination of the collection, examination, interpretation, and evaluation of geological, geochemical, geophysical and mineral occurrence data of the island. Information discussed in this text is summarized in the Mineral Deposit-type Summary Table and is self-explanatory. However, the distinction between "mineral occurrence" and "mineral deposit" is important. A "mineral occurrence" is a concentration of a mineral (usually, but not necessarily, considered in terms of some commodity, such as copper, barite, or gold) that is considered valuable by someone somewhere, or that is of scientific or technical interest (Cox and Singer, 1986). A "mineral deposit" is a mineral occurrence of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have economic potential (Cox and Singer, 1986). Therefore, mineral deposits, as discussed here, have two more qualifiers than do mineral occurrences: they have been investigated in sufficient detail so as to provide a sense of the size and grade, with the size large enough and the grade high enough to be of economic interest.

INTRODUCTION

Mineral resource assessment methodology is a continually evolving process, and the tools for mineral resource assessment are constantly being improved. Unlike the oil and gas industry, which has relatively well-documented exploration and production statistics and a much longer history of petroleum-related resource assessment, the minerals industry is less well documented, subject to more variables, and has more complexities. The products from mineral resource assessments are also more diversified (Singer and Mosier, 1981).

Initially, mineral assessments attempted only to highlight areas of potential exploration having suitable geologic characteristics. Qualitative assessments, delineating areas and characterizing them as to high, medium, or low potential on the basis of the favorability of geologic characteristics, were provided as mineral resource assessments, but were not found to be very useful when integrating information from other disciplines. With the development of new assessment tools, such as descriptive models and grade and tonnage models (Cox and Singer, 1986; Bliss, 1992), the quantitative mineral resource assessment method of estimating probabilistically the number of undiscovered deposits became possible. Mineral resource assessment has evolved to a point where government officials, policymakers, and managers of private enterprise can now integrate mineral resource potential with information from other disciplines.

STEPS IN MINERAL RESOURCE ASSESSMENT

The process of performing a quantitative mineral resource assessment, as developed by the U.S. Geological Survey, consists of a series of preliminary, but necessary, steps (Singer and Ovenshine, 1979; Singer and Cox, 1988; Menzie and Singer, 1990; Root and others, 1992). The first step is the identification of mineral deposit types and delineation of tracts having geologic characteristics permissive to the occurrence of each identified deposit type. The second step is a probabilistic estimate of the number of undiscovered deposits expected to occur for each deposit type within each tract. Knowing the permissive terranes for each mineral deposit type and the probabilistic estimate of undiscovered occurrences, the third step of computation of the metallic endowment for each tract for discrete probabilities is possible. The expected metal endowment is calculated with MARK3, a USGS-developed Monte Carlo simulation model that combines grade and tonnage models with probabilistic estimates of the number of undiscovered deposits (Root and others, 1992).

Identifying mineral deposit models

Documenting the known mineral occurrences and classifying them into mineral deposit models is a fundamental and important step in the assessment process. Identifying which deposit models are represented and which are most likely to be represented, even if corollaries are not yet identified, is based upon descriptive and genetic models unique to each deposit type. Descriptive and genetic models describe the geologic environment, including rock types, textures, ages, depositional environment, tectonic setting and associated deposit types. Descriptive deposit models also include mineralogy, texture and structure, alteration, ore controls, weathering, and geochemical and geophysical signatures (Cox and Singer, 1986).

Grade and tonnage models

Grade and tonnage models have been developed for many of the mineral deposit models. This is an ongoing activity through which more and more models are being added to those initially included in USGS Bulletin 1693 (Cox and Singer, 1986; Orris and Bliss, 1991; Bliss, 1992). These grade and tonnage models document the historical grades and tonnages of both economic and noneconomic deposits for which sufficient grade and tonnage data has been collected to be included in the model. It is from these grade and tonnage models that a probabilistic estimate of the size and grade of undiscovered deposits could be projected.

Delineation of permissive tracts

The delineation of tracts that are permissive for undiscovered mineral deposits of a specific type requires the input and assimilation of geologic information from multiple earth-science disciplines. The preliminary tracts are usually based upon the distribution of permissive host rocks, which may contain known occurrences. Host rocks are assembled into favorable geologic terranes based upon rock type, age, and (or) depositional environment. Geochemical and geophysical data (magnetism, gravity) can be used to either extend or delete parts of these terranes, especially with respect to surficial cover. Geochemical data show the presence of anomalous metallic elements, or indicative pathfinder elements, which provide circumstantial evidence for the presence of metallic minerals. Gravity and magnetism are important in understanding the geometry and extent of subsurface geology. The degree of known exploration is then examined to determine which areas could be considered as having been explored and (or) exhausted on the basis of previous investigations for each deposit type.

The resultant permissive tract is the area that remains after elimination of all areas in which the deposit type could not possibly occur.

Estimation of the number of deposits

The estimation of the number of undiscovered mineral deposits thought to occur within the delineated tracts is conditional upon a number of separate, but related, factors. Limitations considered by the assessment team include the size and depth for each deposit type considered, the extent of previous exploration for that or similar deposits, and the distribution of undiscovered deposits, which must fit the grade and tonnage distributions such that they are centered on the median. For this reason, estimated undiscovered mineral deposits are not necessarily large, nor economic, but have grade and size distributions like the models. These numbers are subjective and were determined by a team of earth scientists knowledgeable about the area. In the case for Puerto Rico, a team representing the disciplines of economic geology, geochemistry, geophysics, marine geology, coal geology, resource analysis, and field geology met twice to identify and to estimate the number of probable undiscovered deposits. They estimated numbers only for those deposit types for which the assessment team felt sufficient information was available. This group was knowledgeable about ore deposits, in general, and about the geology of Puerto Rico, specifically. After examination of all data available for the resource assessment, individual team members estimated numbers for each deposit type at the 90th, 50th and 10th percentile probability levels. If there was disagreement as to the number of undiscovered deposits, individuals who estimated high or low numbers were asked to justify these estimates with relevant evidence, and discussion ensued until consensus was reached. The probabilistic number of undiscovered deposits by mineral deposit type thought to be found in Puerto Rico can be found in table 1.

As stated previously, the field of mineral resource assessment is still evolving. As knowledge of mineral deposits grows and experience is gained, the assessing of undiscovered mineral deposits will have additional and better tools available. As these lessons are learned, each step of the three-step assessment method may be adjusted to improve and upgrade the estimates of the affected deposit types.

The mineral resources of Puerto Rico will be discussed by mineral deposit type (for example, podiform chromite, porphyry copper).

DEPOSITS RELATED TO MAFIC-ULTRAMAFIC ROCKS IN UNSTABLE AREAS

PODIFORM CHROMITE

The model

The podiform chromite deposit type consists of irregular masses of chromite in ultramafic parts of ophiolite complexes. The deposits are restricted to dunite bodies within tectonized harzburgite and (or) the lower portions of ultramafic cumulates, both of which are commonly serpentinized (Albers, 1986). While geologically similar, podiform chromite deposits have been subdivided into two grade and tonnage models on the basis of significant differences in tonnages. Median tonnage of minor podiform chromite deposits is 130 mt in California and Oregon (Singer and Page, 1986) having a median Cr_2O_3 grade of 44 percent; median tonnage of major podiform chromite deposits is 20,000 mt in Turkey and the Philippines (Singer and others, 1986), having a median Cr_2O_3 grade of 46 percent.

Examples in Puerto Rico

There are no known examples of podiform chromite occurrences in Puerto Rico.

Permissive tracts

Tract delineation for podiform chromite deposits is based primarily upon the outcrop pattern of the exposed serpentinite, which occurs only within the southwestern part of Puerto Rico. Areas considered permissive for the occurrence of podiform chromite are restricted to surficial exposures of serpentinite. This map unit is included within the ultramafic rocks and amphibolite terrane.

Stream-sediment geochemical patterns, which for southwestern Puerto Rico include anomalies of nickel (150-10,000 PPM), cobalt (50-2,000 PPM), and chromium (2000-10,000 PPM)(figure 24).

Geophysical patterns displayed on the "Gravity Boundary Map of Puerto Rico", "Filtered Bouguer Gravity Map of Puerto Rico", and the "Complete Bouguer Gravity Map of Puerto Rico" show lows that are mainly associated with serpentinite (KJs), which is interpreted to be generally antiformal in shape and to have outward-dipping contacts. Tracts that are permissive for podiform chromite deposits are restricted to areas of gravity lows. Locally, the serpentinite is overlain with a thin layer of a two-pyroxene olivine basalt unit, Kpob, which is not included in the delineated tract.

Detailed contoured aeromagnetic surveys are not available for much of southwestern Puerto Rico. For this reason, magnetism has been of little help in describing this terrane. However, the serpentinites have been investigated for their magnetic susceptibilities and are described elsewhere (see "Magnetic Map of Puerto Rico").

Undiscovered deposits

Due to the limited areal extent of permissive map units and the likelihood that a deposit having tonnage equal to the median for the minor podiform chromite deposit model would have been found, the assessment team determined that the probability of occurrence of one or more undiscovered deposits consistent with the grade and tonnage model is very low. No probabilistic estimate of undiscovered deposits was made.

DEPOSITS RELATED TO FELSIC INTRUSIONS

COPPER SKARN

The model

Copper skarn deposits are irregularly shaped or tabular ore bodies formed in carbonate or calcareous rocks near igneous contacts or in xenoliths in igneous stocks (Cox and Theodore, 1986). These deposits can be extremely irregular in shape, tongues of ore projecting along any available planar structure. The intrusive igneous rocks usually range from tonalite to monzogranite in composition, and the carbonate country rock is commonly altered to marble and calc-silicate hornfels. Primary ore minerals consist of chalcopyrite and minor bornite, along with hematite, magnetite, pyrite, and pyrrhotite. The median tonnage of copper skarn deposits is 560,000 Mt, and 10 percent of the deposits contain 9.2 million Mt or more. The median copper grade is 0.7 percent, and 10 percent of the deposits also contain more than 2.8 g/Mt Au (Jones and Menzie, 1986).

Examples in Puerto Rico

There are twelve known occurrences of copper skarn in Puerto Rico. Two of these occurrences, Island Queen Mine (site 92) and La Mina (site 164)are classified as mineral deposits and has been the subject of active exploration and production. The Island Queen Mine consists of two 20-to 30-ft -wide bands of carbonate-bearing rocks, altered to skarn, and separated by andesite flows. Ore materials include magnetite, hematite, and chalcopyrite, with secondary malachite, azurite, and chalcocite. One 2-m interval contains 2.83 percent copper and more than 60 percent iron oxide. Production from the Island Queen Mine, during 1951-53, unfortunately was included with production from the Keystone Mine (site 85) and from an iron skarn deposit (Vazquez, 1960).

La Mina (site 164), also known as Río Blanco and Spanish Adit, is a copper deposit formed in a limestone bed that has been metamorphosed to a calc-silicate rock along its contact with a tonalite intrusion. Considerable chalcopyrite is present in the limestone near the border of the intrusive mass, and pyrrhotite is the principle sulfide in other areas. At La Mina (site 164), economically important amounts of gold and silver occur in the copper-rich zones (Pease, 1966). Chalcopyrite, pyrrhotite, and pyrite occur with skarn minerals wollastonite, garnet, diopside, and epidote.

Permissive tracts

Terrane delineation for copper skarn deposits is based primarily on the juxtaposition of tonalite to monzogranite intrusions with carbonate-bearing rocks and the distribution of known copper skarn occurrences. On the basis of surface evidence and subsurface geophysics, three areas were identified as having potential for undiscovered copper skarn deposits: peripheral to (1) the San Lorenzo Batholith, (2) the Río Blanco stock, and (3) the Barranquitas and Piñas stocks ("Intrusive and Structural Map").

The San Lorenzo batholith (unit Ksl) and adjoining quartz diorite (unit Kpgq) complex have known associated copper skarn occurrences, altered metavolcanic rocks (unit TKmv), and calcareous rocks including the Pitahaya Formation (unit Kpi), Torrecilla breccia (unit Kt), and the Robles Formation (unit Kr).

The "Magnetic Boundary Map of Puerto Rico" shows intense local magnetic highs around the perimeter of the San Lorenzo batholith and indicates favorable locations for magnetite bearing skarn deposits at the contacts of the San Lorenzo batholith. This map also shows a northeastern limiting boundary of nonmagnetic altered rocks that was used to constrain this permissive tract.

The "Filtered Bouguer Gravity Map" and the "Gravity Boundary Map of Puerto Rico" shows the San Lorenzo batholith as a gravity low surrounded by more dense rocks, possibly the result of contact metamorphism. An exception to this halo of gravity-high rocks is near the southeast shoreline where plutonic rocks of Punta Guayanes (unit Kpgg) appear as low-density rocks.

The tract that is permissive for copper skarn deposits around the San Lorenzo batholith shows an interior boundary following the surficial outcrop pattern of the plutonic rocks. The exterior boundary of the permissive tract was restrained in the northeast by the Northern fault zone (La Muda?) ("Intrusive and Structural Map") and the inflection point of low magnetic rocks. On the north and west sides, the fault contact between the carbonate-bearing Torrecilla breccia (unit Kt) and the Los Negros Formation (unit Kln). Through Formation A of Berryhill and Glover (1960) (unit Kabcj) approximately a 2-km distance was maintained from the outside edge of the batholith.

Tract delineation for copper skarn deposits in the Rio Blanco stock area was based upon mapped altered rock and pyrite occurrences from the 1:20,000-scale mapping, known occurrences, and geologically favorable map units.

The "Magnetic Boundary Map of Puerto Rico" shows the Rio Blanco stock as a highly magnetic pluton that may have magnetite-bearing skarn deposits at contacts with carbonate rocks. The "Gravity Boundary Map of Puerto Rico" shows the Rio Blanco stock as a relative low.

The permissive tract drawn around the Rio Blanco stock shows an interior limit based upon the outcrop pattern of plutonic rock and an exterior limit based upon a distance of approximately 2 km from the edge of the pluton.

Just north of the Barranquitas stock and the Piñas stock ("Intrusive and Structural Map") are seven copper skarn occurrences concentrated within a fault-bounded area. The Torrecilla Breccia (unit Kt) hosts these occurrences, which consists of lava flows, volcanic sandstone, and limestone.

The gravity and magnetic patterns in this area are inconclusive due to the small size of the tract and the resolution of the geophysical data.

The copper skarn tract is delineated in the area of the Barranquitas stock and the Pinas stock on the basis of known occurrences and the surface exposure of the Torrecilla Breccia (unit Kt).

Undiscovered deposits

There are 12 known occurrences of copper skarn in Puerto Rico. Due to the low level of prospecting for this deposit type, the assessment team has estimated that there is a 90 percent chance of one or more deposits, a 50 percent chance of four or more deposits, and a 10 percent chance of 8 or more deposits. These deposits are expected to have grades and tonnages consistent with the grade-tonnage model of Jones and Menzie (1986).

IRON SKARN

The model

Iron skarn deposits are irregularly shaped or tabular masses of iron oxides formed in carbonate or calcareous rocks near igneous contacts. As with all skarn deposits, iron skarn deposits are extremely irregular in shape, their morphology being determined by the extent to which fluids can be introduced to the surrounding carbonate-bearing lithologies. Carbonate rocks, calcareous rocks, igneous contacts, and fracture zones near contacts all affect the shape of these ore bodies.

Iron skarns consist of magnetite or hematite, and minor chalcopyrite, pyrite and pyrrhotite in calc-silicate contact metasomatic rocks. Intrusive rock types include gabbro, diorite, diabase, syenite, tonalite, granodiorite, and granite. Weathering usually results in magnetite occurring as float.

The median grade and tonnage for iron skarn deposits is a size of 7.2 million tonnes and 50 percent iron grade (Mosier and Menzie, 1986).

Examples in Puerto Rico

There is 1 major mine and 16 known occurrences of this mineral deposit type in Puerto Rico. Iron and copper skarn deposits occur in the same environments of formation. TheKeystone Mine (site 85) was developed as an open pit, which, in combination with theIsland Queen Mine (site 92), produced approximately 220,000 tons of ore having an iron content greater than 60 percent in the years 1951-53 (Vazquez, 1960). The Keystone mine consisted of magnetite and hematite, and minor chalcopyrite, malachite and other ore minerals concentrated in two lenticular layers approximately 15 m wide. This is believed to be the largest iron ore deposit in Puerto Rico (Broedel, 1961).

Permissive tracts

Copper skarn deposits and iron skarn deposits of Puerto Rico appear in similar settings and, more likely than not, are co-mingled. Much of what has been stated with respect to defining tracts for the copper skarn mineral deposit type may also be applied to the iron skarn mineral deposit type. The reader is referred to the copper skarn tract delineation section for more discussion on how permissive tracts were delineated.

The area around the intrusion at Los Panes ("Intrusive and Structural Map") is considered permissive for the occurrence of iron skarn deposits, in addition to those already mentioned. The intrusion of diorite (unit Kdi) into the Robles Formation (unit Kr), a chiefly calcareous volcaniclastic sandstone and siltstone, resulted in the development of magnetite. However, the richest iron concentrations have not yet been found to be above 10 percent.

Undiscovered deposits

There are seventeen known occurrences and deposits of iron skarn in Puerto Rico. Because of the moderate to high level of exploration, the assessment team determined that there is only a 10 percent chance of one or more undiscovered iron skarn deposits, a 5 percent chance of two or more, and a 1 percent chance of three or more undiscovered deposits.

PORPHYRY COPPER DEPOSITS

The model

Porphyry copper deposits consist of a stockwork of veinlets of quartz, chalcopyrite, and molybdenite in or near a porphyritic intrusion (Cox, 1986a). Rock types include tonalite to monzogranite stocks and breccia pipes intrusive into batholithic, volcanic, or sedimentary rocks. The ore grade is, in general, positively correlated with the density of veinlets and mineralized fractures. Minerals include chalcopyrite, pyrite and molybdenite, and peripheral vein or replacement deposits contain chalcopyrite, pyrite, galena, and (or) gold. The outermost deposits may have veins of copper, silver, and antimony sulfides, barite, and gold. The median tonnage of 208 porphyry copper deposits worldwide is 140 million mt, and 10 percent have tonnages of 1.1 billion mt or more. Median copper grade is 0.54 percent, and 10 percent of the deposits have molybdenum grades of 0.03 percent or more (Singer and others, 1986).

Porphyry copper deposits have been described by a generalized model (Cox 1986b) that includes several subtypes. The model has been subdivided into a porphyry copper-gold model (Cox, 1986b) and a porphyry copper-molybdenum model (Cox, 1986c), but for the assessment of undiscovered deposits of Puerto Rico, there is insufficient information to prepare separate tracts for these two deposit types. In the Lares-Adjuntas area, however, an estimate of undiscovered deposits of the porphyry copper-gold type was made.

Examples In Puerto Rico

Four porphyry copper-gold deposits have been discovered in the Lares- Adjuntas region: Tanamá (site 161), Helecho (site 179), Cala Abajo (site 75), and Piedra Hueca (site 71). The last two may be segments of the same deposit and are commonly referred to as the Río Viví deposits. These deposits have been explored by drilling and, with the exception of Helecho, their grades and tonnages have been announced. In addition, several occurrences of this type are known, including Laundry Creek (site 158), Copper Creek (site 159), and Sapo Allegre (site 73). These deposits and occurrences are discussed in a subsequent section.

There are eight porphyry copper occurrences outside of the Lares-Adjuntas region for which there is insufficient information to classify them by subtype. Three of these have been partially explored: the Barranquitas Prospect (site 203), Rio Cuyon (site 52), and La Muda (site 114).

About 40 km east of the Río Viví area is the Barranquitas Prospect (site 203), a porphyry stock weakly mineralized with copper (Pease, 1966). The prospect has some characteristics of a porphyry copper-gold system; soil samples from near the stock contain as much as 0.2 ounces per ton (6 PPM) Au. Drilling during the 1950's did not encounter economic concentration of copper mineralization and the gold grade of the mineralized rock was not known.

Río Cuyon (site 52) consists of a surface oxide zone enriched in copper, which was measured to be 1,500 PPM Cu and 4,000 PPM Mo. Drilling during exploration demonstrated that rock characterized by these analytical data did not continue at depth. Drilling offered little encouragement for copper porphyry mineralization at depth, and potential for gold, while untested, was not considered high.

La Muda (site 114) is an inactive prospect that occurs, in addition to other porphyry copper occurrences, along the La Muda Fault Zone. Of the seven drill holes that were drilled, the best analytical data from core data show 0.18 percent Cu and 0.28 percent Mo (Bergey, 1967). This deposit is considered well explored and of limited potential (Bergey, 1967).

The remaining identified occurrences appear to be small, but are unexplored in the subsurface.

Permissive tracts

Tract delineation for undiscovered porphyry copper deposits is dependent upon the distribution of intrusive rocks, geophysical patterns, known occurrences, and geochemical signature. Unlike tracts defined for other mineral deposit types in this study, large areas of Puerto Rico are considered to be permissive for this deposit type. In order to be more discriminating and restrictive in applying this information, only areas that had the strongest supporting evidence for the occurrence of this deposit type are considered favorable.

The tract that is permissive for undiscovered porphyry copper deposits is limited in the north by a carbonate wedge that increases in thickness to the north. This boundary line is located to approximate the gravity gradient. A combination of the "Gravity Boundary Map" and the geologic terrane map were used to delineate the remaining boundaries of the permissive tract. Within this permissive tract, we have delineated an area favorable for porphyry copper-gold deposits as discussed in the following section.

Undiscovered deposits

Consideration of the high level of exploration for these deposits in Puerto Rico, the tendency to find the larger deposits first, and the small size and low grade of the known occurrences, led the assessment team to assign a low probability to the existence of undiscovered deposits near the surface consistent with the porphyry copper grade and tonnage model of Singer and others (1986). Probabilistic estimates of the number of undiscovered deposits of this general porphyry copper type were not made. However, an estimate of undiscovered porphyry copper-gold deposits, for which estimates of numbers of undiscovered deposits was possible, is given in the following section.

PORPHYRY COPPER-GOLD

The model

Porphyry copper-gold deposits consist of stockwork veinlets of chalcopyrite, bornite, and magnetite in porphyritic igneous stocks or dikes that intrude coeval volcanic rocks (Cox, 1986b). Rock types include tonalite, monzogranite, and, less commonly, syenite and monzonite intrusive rocks, and comagmatic volcanic flows and tuffs. Typical tectonic settings include the late stages of the volcanic cycle in an island-arc environment. Alteration is abundant and extensive, and is commonly associated with intrusive and hydrothermal breccias (Cox and others, 1973). The ratio of gold (in PPM) to molybdenum (in percent) is greater than 30. Median tonnage of deposits is 100 million Mt, and 10 percent of deposits contain 400 million Mt or more. Median copper and gold grades are 0.5 percent, and 0.38 grams per Mt, respectively (Singer and Cox, 1986).

Examples In Puerto Rico

There are four known mineral deposits and three mineral occurrences that have the characteristics of the porphyry copper-gold deposit model. The most important of these, from northwest to southeast are the occurrence at the Laundry Creek Prospect (site 158), the Tanamá Deposit (site 161), the Helecho Deposit (site 179) and the Río Viví deposits (the Píedra Hueca Deposit (site 71) and the Cala Abajo Deposit (site 75).

At Laundry Creek(site 158), a steeply dipping east-west tabular zone of mineralized quartz diorite was found in an otherwise unmineralized quartz diorite stock. This prospect was found on drilling to be smaller in tonnage than the smallest members of the tonnage and grade model of Singer and Cox (1986).

The Tanamá Deposit (site 161) is a gold-bearing porphyry system in a low-potassium island-arc environment. The stock intrudes metabasalt of Cretaceous age and felsic volcanic and sedimentary rocks of early Eocene age. There are three alteration zones present, consisting of an inner amphibole-dominated assemblage, an outer chlorite-dominated assemblage, and an upper sericite-clay-calcite-pyrite zone. The deposit, which consists of two ore bodies separated by a fault, contains abundant quartz veins with disseminated chalcopyrite. The south orebody has a secondary enrichment-blanket containing chalcocite and other copper sulfide minerals (Cox, 1985). The two parts of the Tanamá Deposit together contain 139 million Mt of ore having a grade of 0.64 percent Cu (Lutjen, 1971) and 0.2-0.4 g/Mt Au.

The Helecho deposit (site 179) is similar to the Tanamá Deposit and is coextensive with a tonalite porphyry stock that intrudes volcanic and sedimentary rocks of early Eocene age. The deposit was explored by 31 vertical diamond-drill holes and found to contain a slightly smaller amount of ore than the Tanamá Deposit, but of about the same grade (Cox, 1985).

Southeast of Tanamá, 13 km, is the Río Viví area, which contains two deposits in close proximity, the Piedra Hueca Deposit (site 71) and the Cala Abajo Deposit (site 75). The deposits are within Eocene tonalite stocks that intrude Cretaceous metabasalt (Barabas, 1971; 1977) and may be faulted segments of a single deposit having a combined tonnage of 104 million tonnes (Lutjen, 1971). Close to these two copper-gold deposits is the occurrence of the Sapo Alegre Prospect (site 73), a small porphyry copper-molybdenum body that contains a high concentration of gold (Cox and others, 1975).

Delineation of favorable tracts

Favorable exploration areas are those parts of the tract permissive for porphyry copper-gold deposits, which contain a more confident degree of information favorable to the occurrence of mineral deposits. New exploration technology and new genetic models may suggest areas within the permissive tract, but outside the promising target areas.

Promising exploration areas for porphyry copper-gold within the tract permissive for porphyry copper were delineated from the mapped distribution of Tertiary intrusions along the south flank of the Cretaceous Utuado batholith, aeromagnetic anomalies indicating concealed intrusions, and the distribution of known deposits and occurrences.

Undiscovered deposits

Because of the detailed information available for the porphyry copper-gold permissive area and because of the confidence in the deposit model, an estimate of undiscovered porphyry copper-gold deposits was made. The estimates are based on analysis of 1:20,000-scale geologic maps by Mattson (1968), Nelson and Tobisch (1968), Cox (1985), and R. Krushensky, (unpub. data, 1994); aeromagnetic maps provided by Kennecott Exploration, Inc.; and geochemical maps prepared by Sherman Marsh from unpublished data of Robert Learned (1994).

Porphyry copper-gold deposits in the promising target areas have a characteristic set of features:

1. An Eocene tonalite porphyry stock having a quartz-rich aplitic groundmass intrudes Cretaceous metabasalt or volcanic and sedimentary rocks.
2. Hydrothermally altered rock is prominent, potassic in the central part, and grading outward to propyllitic. Some deposits have a cap and (or) an outer zone of phyllic or argillic altered rock.
3. Chalcopyrite and either magnetite or pyrite occurs with quartz in stockwork veinlets. Molybdenite-bearing stockworks are rare.
4. Peripheral polymetallic veins that contain chalcopyrite, sphalerite, and galena occur several kilometers from the porphyry deposit.
5. An aeromagnetic high is associated with the stock and is accentuated by magnetite minerals in the orebodies.
6. In some areas (Helecho), the central magnetic high is surrounded by a low that results from the replacement of magnetic iron minerals by pyrite in the peripheral phyllic and argillic altered zones.
7. Chemical analysis of sediments from streams draining areas that contain deposits shows anomalous concentrations of copper and gold associated with more weakly anomalous concentrations of molybdenum. Peripherally, weak anomalies, of zinc, silver, and manganese are present. Some deposits do not produce geochemical anomalies, probably because of dilution in active streams. The strongest anomalies were found near a relatively small deposit (Laundry Creek).

Twenty-four areas within the favorable tract were selected on the basis of geology, mineral occurrences, stream-sediment geochemistry, and aeromagnetic anomalies. They are summarized in Table 2 and shown in figure 1.

To each target, we assigned a probability that it contains an undiscovered deposit having a tonnage and grade consistent with the grade and tonnage model of Singer and Cox (1986). This assignment was made subjectively on the basis of the degree to which the area exhibited the seven features listed above or otherwise matched areas of known deposits in the permissive tract.

Tanamá (area 11) and Río Viví (area 22), which contain deposits having published tonnages and grades consistent with the model, were assigned zero probabilities because it is not possible for an additional undiscovered deposit to exist there. Helecho (area 12) was assigned a high probability because, although a tonnage and grade has not been published, maps based on

Kennecott data (Cox, 1985) show that the deposit almost certainly belongs to the model. Laundry Creek (area 4) is given a low probability because of its low tonnage and resulting uncertainty about whether or not it fits the model.

A high probability was assigned to East Criminales (area 9), where a breccia body containing pervasive sericite-pyrite altered rock (Cox, 1985, p. 10) suggests the existence of a large porphyry system at depth. The second highest probability was assigned to Piletas (area 2), which is covered by about 300 m of Oligocene sedimentary rocks. This area includes aeromagnetic anomalies that are similar in form to highs associated with porphyry systems to the southeast--that is, on strike with the Río Viví, Tanamá-Laundry Creek trend, and is situated 11-12 km NW of Tanamá. This distance is similar to the distance between Tanamá and Río Viví, a fact that supports the probability of a deposit at Piletas. A periodic 15- km spacing of deposits of this type along the Quesnel structural trends has been noted in British Coumbia, Canada (D. G. Bailey, Bailey Geological Consultants (Canada), Ltd., oral commun., 1992).

The sum of the probabilities shown in table 2 is 3.5. This is the expected number of deposits for all promising target areas. A probability density function of the number of undiscovered deposits, table 1, that most closely approximates this expected number is as follows: a 90 percent chance of two or more deposits, a 50 percent chance of three or more, a 10 percent chance of five or more, a 5 percent chance of eight or more, and a 1 percent chance of ten or more deposits. These undiscovered deposits would have a median tonnage of 100 million Mt and would have copper and gold grades consistent with the grade and tonnage model of Singer and Cox (1986).

POLYMETALLIC VEINS

The model

The polymetallic vein model consists of quartz-carbonate veins containing gold and (or) silver and associated with base-metal sulfides related to hypabyssal intrusions in sedimentary and metamorphic terranes (Cox, 1986d). These veins occur in near-surface fractures and breccias within the thermal aureole of clusters of small intrusions or peripheral to porphyry systems. Minerals contained within the veins include native gold, electrum, sphalerite, chalcopyrite, galena, and a variety of others. Median tonnage of ore in polymetallic veins is 7,600 Mt, 10 percent of the deposits containing 200,000 Mt of ore. Median grades are 820 g/Mt Ag; 0.13 g/mt Au; 9.0 percent Pb; and 2.1 percent Zn (Bliss and Cox, 1986).

Examples in Puerto Rico

There are 61 known occurrences in Puerto Rico, and 2 of these known occurrences are likely mineral deposits. The Constancia Mine (site 66) consists of a 120-ft-long tunnel with a 60-ft drift constructed to access a sulfide-bearing vein assayed as 27 percent Cu and 2 percent Sn. This mine has no known reported production.

A mineral deposit at Cerro Avispa (site 88), was discovered in 1956 after investigation of a geochemical anomaly. Chalcopyrite and pyrite were found to be the predominant ore minerals, and minor galena, sphalerite, and chalcocite are also present. Chemical analysis of this vein indicated a Au content of 2.81 ounces per ton and Ag of 21.04 ounces per ton. This deposit has no known production. The grade and tonnage in these veins are probably not sufficient to represent a copper deposit that could be mined, but gold and silver values are high, and copper is a potential byproduct of the ore (Pease, 1966).

Permissive tracts

Due to the large number of map units of intrusive igneous rocks and because of their dispersed pattern, no permissive tract was drawn for the polymetallic vein deposit type. Instead, the entire island was considered to be permissive, with the exclusion of all map units that represent cover rocks, post-metalliferous (Eocene), or plutonic rocks.

Geochemical sampling throughout the island provides more localized information with respect to anomalous elements indicative of the presence of polymetallic veins. Zinc, copper, lead, gold, and silver are considered good pathfinder elements for these deposits, and areas in which these elements are anomalous have a greater likelihood for undiscovered deposits.

Undiscovered deposits

Due to the large area that is permissive for polymetallic vein deposits, the large number of known occurrences, and what is considered to be only a moderate level of exploration, the mineral resource assessment has determined that there is a 90 percent chance of one or more deposits, a 50 percent chance of four or more deposits, and a 10 percent chance of fifteen or more undiscovered deposits.

During the early years of exploration, veins were a very important source of metals. However, due to increased efficiencies in the mining, milling, and beneficiation of the ore, veins have lost much of their economic importance in current mining around the world and the bulk mining of lower-graded larger-tonnage ores has become more important.

DEPOSITS RELATED TO SUBAERIAL MAFIC EXTRUSIVE ROCKS

COPPER-SILVER MANTO DEPOSITS

Small lenses and veins of native copper, chalcocite, and bornite (sites 15, 16, and 17) are found in the Blacho Tuff Member of the Pozas Formation 3-4 km southwest of Ciales. The low sulfur content of this mineralized rock suggests that it is not derived from hydrothermal fluids emanating from plutonic sources, as are most vein deposits in Puerto Rico. Their occurrence in subaerial volcanic rocks including red-hued dacite tuff and minor fluvial sedimentary rock suggests an affinity with the copper-silver manto deposits of Chile, of which El Jardin Deposit (Mayer and Fontboté, 1990) is a good example. The known deposits near Ciales are small, but there is a chance of medium-size, high-grade copper-silver deposits in this subaerial volcanic environment. The permissive area includes the Pozas Formation. Because no grade and tonnage model is available, we do not estimate a specific number of undiscovered deposits.

DEPOSITS RELATED TO MARINE MAFIC EXTRUSIVE ROCKS

VOLCANOGENIC MANGANESE

The model

The descriptive model for the volcanogenic manganese deposit type includes lenses and stratiform bodies of manganese oxide, carbonate, and silicate in volcanic-sedimentary sequences (Koski, 1986). Median tonnage of ore in volcanogenic manganese deposits is 47,000 mt and median grade 42 percent manganese (Mosier, 1986).

Manganese deposits in Puerto Rico are in the form of pockets of the minerals pyrolusite and psilomelane that fill irregular chambers within Tertiary limestone units (Meyerhoff, 1933). The limestone units, which are fractured due to faulting, dissolved as ground water and surface water percolated through the fractures. These percolating waters not only dissolved the calcium carbonate of the limestone, but also precipitated highly concentrated bodies of manganese oxide.

Examples in Puerto Rico

In 1915, in the barrios of Tijeras and Guayabal of Juana Diaz, the Atlantic Ore Company initiated the production of manganese oxide to be used in the manufacture of dry batteries (Pico, 1974). Besides gold and a small amount of iron from the Keystone Mine, manganese is the only metal ever to be exploited commercially in Puerto Rico.

There are 14 known occurrences of volcanogenic manganese in Puerto Rico, and three of these occurrences have been upgraded to known deposits. The Juana Diaz Mine (site 2), was an active mine from 1915 to 1939, producing an estimated 80,000 tons of manganese ore at an average grade of 60 percent manganese (Mitchell, 1954).

The Gatti Prospect (site 128) was developed in 1932 with the digging of a 35-ft shaft and a 109-ft drift. A vein, varying in thickness from 2 to 6 ft and containing rhodonite and psilomelane, produced about 120 tons of manganese ore that assayed as 52 percent Mn, 0.25 percent Fe, and 6.75 percent silica. The mine work was stopped due to flooding and transportation problems.

Aguada (site 115) has manganese ore present as a vein and as float, covering five-acres in area. The ore assayed at 54 percent Mn and occurs in conjunction with deeply weathered bentonite clay.

Permissive tracts

Tract delineation of permissive areas for volcanogenic manganese deposit types is based primarily upon known occurrences, Cretaceous and Tertiary marine volcaniclastic map units, Tertiary marine volcaniclastic map units, Tertiary basalts and cherts, and the geochemical signature associated with these deposits of Mn, Zn, Pb, Cu, and Ba.

Undiscovered deposits

Given the presence of 14 known volcanogenic manganese occurrences, including 3 mineral deposits, the large size of the permissive area, the small size of the deposits, and the moderate level of exploration, the mineral resource assessment team estimated that there is a 90 percent chance of one or more undiscovered deposits, a 50 percent chance of three or more undiscovered deposits, and a 10 percent chance of eight or more undiscovered deposits.

DEPOSITS RELATED TO SUBAERIAL FELSIC TO MAFIC EXTRUSIVE ROCKS

EPITHERMAL QUARTZ-ALUNITE GOLD

The model

These deposits occur in island arcs and back-arc spreading centers and within vuggy veins and breccias in zones of high-alumina altered rock. Gold, pyrite, and enargite mineralized rock is related to felsic volcanism (Berger, 1986).

Associated hydrothermally altered rock is predominantly argillic, the advanced argillic zones surrounding the former feeder conduits for the hydrothermal solutions. The orebodies are always located in or adjacent to the advanced argillic zones (Ashley, 1982). Median tonnage for epithermal quartz-alunite-gold vein deposits is 1.6 million Mt (Mosier and Menzie, 1986).

Examples in Puerto Rico

There are five mineral occurrences in Puerto Rico that are classified as being of the epithermal quartz-alunite-gold deposit type, and two of these occurrences are mineral deposits. Cerro La Tiza (site 160), consists of alternating bands of quartz and alunite covering a 556-acre area. The ore material of interest is alunite, kaolinite, halloysite, and pyrophyllite, which is the result of hydrothermal (acidic) alteration. Some small-scale sporadic mining of kaolin clays may have been tried locally with the development of pits approximately 200 ft long, but there is no documented production. General analytical data shows zinc (5,000 ppm) and gold (160 ppb) to be present.

The city of Cidra is located in a valley underlain by a zone of hydrothermally altered volcanic rock (site 35). The major alteration zone has been poorly prospected, but there is little indication of near-surface economic mineralized rock for either precious metals or copper. The alteration zone is poorly exposed and covered by farms and houses. However, analytical data for soils were 1,400 PPM Zn, 600 PPM Cu, and 3000 PPM Pb.

Permissive tracts

Tract delineation for the epithermal quartz-alunite gold deposit type is based primarily on permissive rock types identified from known mineral deposits and occurrences, advanced argillic altered rocks associated with plutons, recognized hydrothermally altered rocks, and meta-volcanic rocks.

Undiscovered deposits

The mineral resource assessment team estimated a 90 percent chance of one or more undiscovered deposits, 50 percent chance of two or more deposits and 10 percent chance of four or more undiscovered epithermal quartz-alunite gold type deposits.

DEPOSITS RELATED TO MARINE FELSIC TO MAFIC EXTRUSIVE ROCKS

KUROKO-TYPE MASSIVE SULFIDE

The model

The Kuroko-type massive sulfide deposit contains copper- and zinc bearing massive sulfide deposits in marine volcanic rocks of intermediate to felsic composition (Singer, 1986). Rock types permissive for Kuroko-type massive sulfide deposits include marine rhyolite, dacite, and subordinate basalt and associated sediments, principally organic-rich mudstone and shale. The tectonic environment is an island arc characterized by extensional faulting and fractures. Median tonnage for Kuroko-type massive sulfide deposits is 1.5 million Mt; 90 percent of the deposits are larger than 120,000 mt; and 10 percent of the deposits are larger than 18 million Mt (Singer and Mosier, 1986).

Examples in Puerto Rico

There are no examples of the Kuroko-type massive sulfide deposits known to occur in Puerto Rico.

Permissive tracts

While there are no known occurrences of Kuroko-type massive sulfide deposits in Puerto Rico, the area delineated as permissive for volcanogenic manganese deposits is also a suitable environment for Kuroko-type massive sulfide deposits.

The permissive features include marine volcanic rocks of intermediate to felsic composition; marine rhyolite, dacite, subordinate basalt and associated sediments; hot springs related to marine volcanism; island arc tectonic setting; and evidence of associated deposits (volcanogenic manganese).

Undiscovered deposits

While no Kuroko-type massive sulfide deposits are known to be present in Puerto Rico, the mineral resource assessment team felt that their occurrence was possible on the basis of the above mentioned evidence. It is estimated that there is a 10 percent chance of one or more undiscovered deposits being present.

DEPOSITS RELATED TO SURFICIAL PROCESSES AND UNCONFORMITIES

LATERITIC NICKEL

The model

Nickel-rich, laterites develop from weathering of peridotites (Singer, 1986b), with nickel-rich iron oxides the most common types of minerals. Relatively high rates of chemical weathering with warm and humid climates, in conjunction with relatively low rates of physical erosion, are necessary to create the requisite depositional environment.

Examples in Puerto Rico

There are seven lateritic nickel mineral deposits known in southwestern Puerto Rico. These deposits have been explored and examined in great detail, including definition drilling of the resource.

Tract delineation

Areas delineated as permissible for nickel laterites were identified primarily on the basis of permissible lithologic units from known occurrences, the exposure of serpentinite (KJs), and the previous work of others (Heidenreich and Reynolds, 1959).

Undiscovered deposits

Because of the limited exposure of favorable map units, requirements of formation, and the high level of exploration for this deposit type, the mineral resource assessment team concluded that the probability of undiscovered lateritic nickel deposits is near zero.

KARST-TYPE BAUXITE

The model

Karst-type bauxite deposits develop through the surficial weathering in wet tropical climates of aluminous sediments (Patterson, 1986). These sediments may be residual or transported material, such as felsic volcanic ash on carbonate rocks. Deposits tend to be concentrated in depressions on karst surfaces.

Within Puerto Rico, three kinds of karst topography have developed, related to the limestone-bearing units involved (St. Claire, 1962): tower karst is prominent in areas of the Lares Limestone; gently rolling hills are typical in areas of the Cibao Formation; and mature sinkhole karst is typical in areas of the Aguada Limestone.

Examples in Puerto Rico

There are no documented occurrences of karst-type bauxite deposits shown, "Metallic Mineral Occurrences in Puerto Rico." However, bauxite as much as 80-ft thick is known to occur in sinkholes within the bauxitic clay belt (Hildebrand, 1960). The mineral assemblage found in these sinkholes includes boehmite, quartz, goethite, hematite, kaolinite, halloysite, anatase, oligoclase, sanidine, and organic matter.

In 1961 a Kennedy Bauxite Concession was granted to investigate the development of these sinkhole deposits. No aluminum has yet been reported to have been commercially produced in Puerto Rico.

Permissive tract

The source of the clays found in sinkholes of the karst topography is postulated to be weathered Cretaceous andesitic volcanics that lie to the south. This is also the case in Jamaica, which has karst and blanket deposits. The bauxitic clay belt runs east-west along the unconformable contact between Tertiary sedimentary rocks and the underlying Cretaceous complex on the north side of the island. Preliminary sampling across the karst belt south of Florida, Puerto Rico, shows that the bauxitic clays are confined largely to the Lares Limestone along a 3-mi wide strip at the south edge of the karst belt (Hildebrand, 1960). The terrane considered permissive for bauxitic clay is delineated by the surface exposure of the Lares Limestone.

Undiscovered deposits

The bauxite sampled in sinkholes and analyzed for contaminant material showed the presence of silica, largely attributable to the presence of free quartz. The quartz can be removed through a process of pulping, spiraling, thickening, and dewatering. However, because bauxite is a low-priced commodity, the economic feasibility of the above process would require extensive laboratory testing (Hildebrand, 1960).

The mineral resource assessment team felt there is a potential for karst-type bauxite deposits in Puerto Rico. However, because of the large size of deposits in the grade and tonnage model (the smallest deposit is approximately one million tonnes), the assessment team did not estimate the probability of numbers of undiscovered deposits. Any undiscovered deposits present in Puerto Rico would be smaller than those in the grade and tonnage model of Mosier (1986), a conclusion based on the geologic and geomorphic style of occurrence, and the improbability that a large surface deposit of this type would be missed.

PLACER GOLD-PLATINUM-GROUP ELEMENTS

The model

The descriptive model for the placer gold-platinum-group-elements (PGE) deposit type includes detrital elemental gold and alloys of platinum-group elements in grains and (rarely) nuggets in gravel, sand, silt, clay, and their consolidated equivalents, in alluvial, beach, eolian, and (rarely) glacial deposits (Yeend, 1986).

The depositional environment for placer gold-PGE includes transitional areas where streams loose energy and cannot carry the sediment load carried by a higher energy stream, such as entering lower stream gradients, the inside point bars of stream meanders, below rapids and falls, beneath boulders, and in vegetation mats.

Examples in Puerto Rico

Production of gold within Puerto Rico was first reported during its early years of settlement, when gold-bearing sands of river systems were exploited by the early settlers during the years 1509-36 (Picó, 1974).

There are three placer gold-PGE deposits and one unclassified occurrence of gold. Río Caliente (site 200) was reportedly mined in the late 1930's at about the same time the Barranquitas stock area was being prospected for gold (Briggs and Gelabert, 1962). Small dams were built on the southern headwaters of the Río Caliente north of the Barranquitas stock to store water for sluicing operations. The Luquillo Mountains gold placers (site 100) are represented by this one occurrence. Placer mining was conducted on the Ríos Fajardo, Luquillo, Mameyes, Rio Grande, and Sabana, which drain the El Yunque forest. Palos Blancos (site 72) is recorded by Cox and Briggs (1972) to be a former placer site; site 140 contains anomalous gold within chert of the Bermeja complex.

Permissive tracts

Tract delineation for placer Au-PGE is based primarily on known historical river placer sites and drainage patterns that are downstream from these known occurrences.

Undiscovered deposits

Due to the high degree of exploration onshore, but relatively little knowledge of offshore sediments, other than surficial sediment types, the assessment team agreed that there was a one percent chance of one or more undiscovered deposits, most likely in the offshore area. There is a documented occurrence of a gold grain being found offshore (Grosz, personnel commun., 1992).

SHORELINE PLACER TITANIUM

The model

Shoreline placer titanium deposit types consist of ilmenite and other heavy minerals concentrated by beach processes and enriched by weathering (Force, 1986). These deposits typically occur in stable coastal regions receiving sediment from deeply weathered metamorphic terranes of sillimanite or higher grade. The heavy minerals include ilmenite, rutile, and zircon, which occur in deposits in the shape of elongate 'shoestring' ore bodies parallel to coastal dunes and beaches.

Examples in Puerto Rico

There are four known occurrences in Puerto Rico of shoreline placer titanium. The occurrence near the town of Hatillo (site 105) is found at the mouth of the Río Camuy. Two channel samples from a dune more than 1,800 ft long have a magnetite content of 20 percent. An estimate of the magnetite content of this occurrence is 27,000 tons, based on this reconnaissance data (Guillou and Glass, 1957).

La Marina (site 106) is in the barrio La Marina, an island at the mouth of the Rio Grande de Aricibo. Estimates of 25,000 tons of magnetite have been reported for this occurrence (Guillou and Glass, 1957).

Thirteen shallow drill holes were used to estimate the occurrence of 62,000 tons of magnetite for La Boca (site 107) and 90,000 tons of magnetite were estimated to be at Río Cocal (site 111).

Permissive tracts

No permissive tract was drawn for the occurrence of shoreline placer titanium deposits in Puerto Rico. Due to their limited size and dimensions, only their occurrence is noted.

Undiscovered deposits

There was no estimate made for the occurrence of undiscovered shoreline titanium deposits. This is due to the lack of sufficient information to make a credible estimate.

Industrial mineral deposits

Industrial mineral mines, deposits, and occurrences of Puerto Rico are not all inclusive of historical mining pits and quarries, but they do represent the locations of 1991 mining permits and the sources of some historical production of industrial minerals. Puerto Rico's recent mineral industry consists entirely of the production of industrial minerals, such as cement, clays, sand and gravel, lime, volcanic rocks, granodiorite, serpentinite, marble, limestone, and stone that is mostly consumed domestically and not exported from Puerto Rico.

Permissive tracts were not delineated in this study for industrial minerals. This is due mainly to the high variability of the characteristics and qualities that make industrial commodities most valuable and the lack of detailed geologic criteria upon which determinations relating to permissive tracts could be made.

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Mineral Deposit Summary Sheets

by

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The mineral resource assessment of Puerto Rico requires the consideration of a wide spectrum of potential mineral deposit types. These deposit types vary widely in many of their physical attributes including their geology and geologic setting, genesis, mineralogy, and structure. Deposit types also display a unique array of circumstantial evidence, including geochemical anomalies, geophysical signatures, and alteration patterns, which are used to aid in their detection and identification.

Because of the complexity in the description of mineral deposits and their mode of formation, characteristics of the deposits have been summarized on Mineral Deposit Summary Sheets. The Mineral Deposit Summary Sheets are divided into several sections. These sections include:

Deposit type;

Description of deposit type;

Rock units and structures permissive for deposit type;

Example of deposit type;

Known occurrences;

Geophysical signature;

Geochemical signature;

Tract delineation;

Comments

These data sheets provide the physical and circumstantial evidence for the mineral deposit types for Puerto Rico and serve as a quick reference source and comparison guide.

These summary sheets use deposit type numbers and models, and mineral deposit descriptive information from USGS Bulletin 1693, Mineral deposit models (Cox and Singer, 1986). Other information collected on the deposits and occurrences of Puerto Rico is also incorporated into these summaries. From these lines of evidence, the expected patterns of deposits from USGS Bulletin 1693 and recorded characteristics from known Puerto Rico occurrences are compared.

Most of the sections and data are self explanatory. However, the distinction made between "mineral occurrence" and "mineral deposit" is as follows. A "mineral occurrence" is a concentration of mineral (usually, but not necessarily, considered in terms of some commodity, such as copper, barite, or gold) that is considered valuable by someone somewhere, or that is of scientific or technical interest (Cox and Singer, 1986). A "mineral deposit" is a mineral occurrence of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have economic potential (Cox and Singer, 1986).

After discussion of the mineral deposit types and their characteristics, an explanation as to how permissive mineral deposit tracts were delineated is explained. This includes favorable geology, geochemistry, geophysics, and known occurrences.

DEPOSIT TYPE

8A Podiform chromite

DESCRIPTION OF DEPOSIT TYPE

Irregular masses of chromite in ultramafic parts of ophiolite (Albers, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Deposits are restricted to dunite bodies within tectonized harzburgite and (or) the lower portions of ultramafic cumulates. These rocks are commonly serpentinized.

Within Puerto Rico, outline of serpentinite (KJs) defines host rocks. These map units are massive, but previously sheared and internally slickensided. Serpentinite is chiefly altered harzburgite. There is no evidence that serpentine extends very deep.

EXAMPLE OF DEPOSIT TYPE

None

KNOWN OCCURRENCE

None

GEOPHYSICAL SIGNATURE

Magnetic Map - serpentinite antiforms of southwestern Puerto Rico produce large anomalies.

Gravity Map - serpentinite antiforms of southwestern Puerto Rico show gravity lows. Imply extension of serpentinite below Quaternary alluvium into the Valle de Guanajibo.

GEOCHEMICAL SIGNATURE

Within USGS Bulletin 1693, no geochemical signature is recognized for this model.

Our stream sediment geochemical samples show: a suite of element anomalies related to podiform chromite terrane in southwest Puerto Rico.

Nickel anomalies (150-10,000 PPM) present in podiform chromite terrane.

Chrome values (2,000-10,000 PPM) occur in podiform chromite terrane.

Cobalt values (50 - 2,000 PPM).

TRACT DELINEATION

Tract delineation based on outcrop pattern of known serpentinite map units.

DEPOSIT TYPE

17 Porphyry Cu

DESCRIPTION OF DEPOSIT TYPE

Stockwork veinlets of quartz, chalcopyrite, and molybdenite in or near a porphyritic intrusion. The model name and number porphyry copper (17) is used when it is believed the mineral occurrence is part of a Cu porphyry system, but not enough information is available to discriminate between porphyry Cu-Au (20c) or porphyry Cu-Mo (21A).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Tonalite to monzogranite stocks and breccia pipes intrusive into batholiths, volcanic or sedimentary rocks.

Within Puerto Rico, these igneous rocks intrude rocks of older age (not comagmatic).

Molybdenum increases with depth of system, which indicates a deeper seated porphyry system.

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name
52	W701159	Rio Cuyon
114	W701043	La Muda

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
98	W701166	Cacao
116	W701044	La Muda
117	W701045	La Muda
119	W701046	La Muda
176	W701091	Quebrada de la Mina
188	WALT003	Rio Santiago copper prospect
189	WALT004	Humaco copper prospect
203	W701109	Barranquitas prospect

GEOPHYSICAL SIGNATURE

Aeromagnetics - linear features and dominantly aeromagnetic high reflect the subsurface.

Bouguer gravity - Utuado and San Lorenzo batholiths reflect lows.

GEOCHEMICAL SIGNATURE

The porphyry Cu model described in USGS Bulletin 1693 contains a geochemical signature of Cu, Mo, Au, Ag, W, B, Sr towards center; Pb, Zn, Au, As, Sb, Se, Te, Mn, Co, Ba, and Rb towards periphery.

Geochemical analysis of Puerto Rico samples show anomalies for Cu, Au, Mo and Sn, contained mostly within the permissive terrain.

TRACT DELINEATION

Known occurrences identify permissive lithologies.

South of Utuado batholith - track delineated based on a combination of known occurrences, linear aeromagnetic signature, and geologic terrane. Aeromagnetics can be either high or low, depending on composition of surrounding lithologies.

COMMENTS

The permissive area for porphyry deposits is very large, containing most of the Tertiary and mixed Cretaceous and Tertiary volcanoclastic lithologies. Within this area of permissive terranes, promising areas are delineated with respect to known occurrences.

DEPOSIT TYPE

18B Cu skarn deposits

DESCRIPTION OF DEPOSIT TYPE

Chalcopyrite in calc-silicate contact metasomatic rocks (Cox and Theodore, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Tonalite to monzogranite plutons intrude carbonate rocks or calcareous clastic rocks.

In Puerto Rico:

Rio Blanco stock (TKh) - intrudes calcareous Tabonuco Formation (Kta) and Hato Puerco Formation (Kh), Fajardo Formation (Kfa), Lomas Formation (Klo).

San Lorenzo batholith (Ksl) and quartz diorite (Kpgq) complex intrudes metavolcanic rocks (TKmv), lava flows and breccias (Kabcj), and calcareous Pitahaya Formation (Kpi), Torrecilla breccia (Kt) and Robles Formation (Kr).

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name
92	W701128	Island Queen (Las Torres)
164	W701050	La Mine, Rio Blanca (Spanish adit)

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
34	W701112	Rio Hondo (36-2)
37	W701115	Escuela prospect (Jaguar vein, Mamey vein)
51	GEM1111	Borinquen
126	W7011049	El Yunque
191	W701101	Rio Hondo (35-1)
192	W701102	Rio Hondo (35-2)
193	W701103	Rio Hondo (35-3)
194	W701104	Rio Hondo (35-4)
195	W701105	Rio Hondo (35-5)
196	W701106	Rio Hondo (35-6)

GEOPHYSICAL SIGNATURE

Rio Blanco area

Magnetics - no coverage in Rio Blanco area.

Gravity - Rio Blanco alteration too small to be seen.

San Lorenzo batholith

Aeromagnetics - only partial coverage of area, therefore, inconclusive.

Gravity - there appears to be a halo (145-155mGal) around batholith, but it is unclear if this is an artifact of the batholith or mineralization.

GEOCHEMICAL SIGNATURE

USGS Bulletin 1693 shows geochemical signatures of Cu, Au, Ag, Pb, Zn, and Co for this model type. In Puerto Rico, geochemical sampling does not show major groupings of the signature elements around the Cu-skarn terrane.

TRACT DELINEATION

Rio Blanco area - tract delineation based on 1:20,000 mapped alteration and pyrite occurrences.

Known Cu skarn occurrences.

Kfa (Fajardo Fm.) & Klo (Lomas Fm.) have very little carbonate material.

Delineated area to northwest of stock based on mapped copper occurrences and implied buried pluton based on 1:20,000 scale mapping.

San Lorenzo batholith - interior boundary at edge of plutonic rocks.

Exterior boundary - on northeast side - fault contact buried under Quaternary alluvium (Qa), contact between carbonate bearing Torrecilla Breccia (Kt) and Los Negros Formation (Kln).

Approximately 2 kilometers from plutonic rocks through Kabcj unit.

Barranquitas stock - Pinas stock area - Tract delineated based upon known occurrences, fault-bounded Torrecilla Breccia (Kt)

COMMENTS

Cu and Fe skarn - both deposits usually contain both Fe and Cu, assignment between these two models was based on what was perceived to be dominant metal.

DEPOSIT TYPE

18D Iron skarn deposits

DESCRIPTION OF DEPOSIT TYPE

Magnetite in calc-silicate contact metasomatic rocks (Cox, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

For this deposit type, contacts of gabbro, diorite, diabase, syenite, tonalite, granodiorite or granite intrusions and carbonate rocks or calcareous clastic rocks

In Puerto Rico:

Rio Blanco stock unit (TKh) - intrudes calcareous Tabonuco Formation (KTa) and Hato Puerco Formation (Kh), Fajardo Formation (Kfa), Lomas Formation (Klo).

San Lorenzo batholith (Ksl) and quartz diorite (Kpgq) complex intrudes metavolcanic rocks (TKmv), lava flows and breccias (Kgbcj), and calcareous Pitahaya Formation (Kpi), Torrecilla Breccia (Kt) and Robles Formation (Kr).

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name
85	W701123	Keystone mine (La Mina, La Esperanza, Juncos mine)

KNOWN OCURRENCES

Site no.	MRDS no.	Name
39	W701116	Aguayo prospect
41	W701117	Cane Field and Pastor prospects
43	W701118	Santiago and Pastor prospects
45	W701119	Suiza prospect
82	W701120	Mamey limestone deposits
83	W701121	Buen Suceso
84	W701122	La Caridad prospect
87	W701125	Deposit no. 5
89	W701126	Deposit no. 2
91	W701127	Deposit no. 3
94	W701129	Deposit no. 4
96	W701164	Yaurel (Los Cocaos)
97	W701165	Emajagua
143	W701136	Tibes
147	W701138	Barrio Tibes, Rio Portuges
197	W701140	Unnamed (47-1)

GEOPHYSICAL SIGNATURE

Rio Blanco area

Magnetics - no coverage in Rio Blanco area.

Gravity - Rio Blanco alteration too small to be seen.

San Lorenzo batholith

Aeromagnetics - only partial coverage of area, therefore, inconclusive.

Gravity - there appears to be a halo (145-155mGal) around batholith, but it is unclear if this is an artifact of the batholith or mineralization.

GEOCHEMICAL SIGNATURE

USGS Bulletin 1693 shows a geochemical signature of Fe, Cu, Co, Au and possibly Sn for this model.

In Puerto Rico, the geochemical analyses do not show anomalous patterns for these elements.

TRACT DELINEATION

Rio Blanco area - known Fe skarn occurrence.

Tract delineation based on known alteration and pyrite at 1:20,000 scale mapping.

San Lorenzo batholith - coincident tract with Cu skarn.

Mix of both Cu skarn and Fe skarn occurrences.

See Cu skarn for tract delineation description.

Los Panes intrusion - magnetite, resulting from partial replacement of hornblende; occurs along contact of Los Panes intrusion.

Richest concentrations do not exceed 10 percent of rock.

A.D. Frazer aeromagnetic map shows pronounced magnetic anomaly along southeast portion of intrusion (map I-335).

Cerro el Gato - quartz diorite-grandiorite (TKqd) intrudes.

Yauco Formation (TKy) - calcareous.

Lago Garzas (TKl) - calcareous.

Yauco Formation interbedded with Lago Garzas (TKly).

Known Cu and Fe skarn occurrences.

COMMENTS

Cu and Fe skarn - both deposits usually contain both Fe and Cu, assignment between these two models was based on what was perceived to be dominant metal.

DEPOSIT TYPE

20C Porphyry Cu-Au

DESCRIPTION OF DEPOSIT TYPE

Stockwork veinlets of chalcopyrite, bornite, and magnetite in porphyritic intrusions and coeval volcanic rocks. Ratio of Au (in PPM) to Mo (in percent) is greater than 30 (Cox, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Within Puerto Rico, porphyry Cu-Au deposits are associated with Eocene porphyry intrusions, which are mostly quartz bearing and tonalite in composition.

These Eocene porphyries intrude rocks of same age (comagmatic).

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name
71	W701071	Piedra Hueca deposit
75	W701073	Cala Abajo deposit
161	W701014	Tanama Deposit
179	W701059	Helecho Deposit

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
73	W701072	Sapo Alegre
158	W701012	Laundry Creek Prospect
159	W701013	Copper Creek

GEOPHYSICAL SIGNATURE

Aeromagnetics - linear features and dominantly aeromagnetic highs reflect the subsurface.

Bouguer gravity - Utuado and San Lorenzo batholiths reflect lows.

GEOCHEMICAL SIGNATURE

USGS Bulletin 1693 describes the geochemical signature for the porphyry Cu-Au model as Cu, Au, Ag central to deposit, and Mo, Pb, Zn, Mn peripheral to these models.

Geochemical analyses for Puerto Rico show:

Molybdenum and tin anomalies contained within the permissive areas.
Gold occurs both within and outside of permissive terranes.
Anomalous copper values occur within permissive terranes.

TRACT DELINEATION

Delineated by extent of volcanic clastic belt and known occurrences.

South of Utuado batholith - Track delineated based on a combination of known occurrences, linear aeromagnetic signature, and geologic terrane. Aeromagnetics can be either high or low, depending on composition of surrounding lithologies.

COMMENTS

The model name and number porphyry copper (17) is used when it is believed the mineral occurrence is part of a Cu porphyry system, but not enough information is available to discriminate between porphyry Cu-Au (20c) or porphyry Cu-Mo (21A).

The permissive area for porphyry deposits is very large, containing most of the Tertiary and mixed Cretaceous and Tertiary volcanoclastic lithologies. Within this area of permissive terranes, favorable areas are delineated with respect to known occurrences.

DEPOSIT TYPE

22C Polymetallic veins

DESCRIPTION OF DEPOSIT TYPE

Quartz-carbonate veins with Au and Ag associated with base metal sulfides related to hypabyssal intrusions in sedimentary and metamorphic terranes (Cox, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Near surface fractures and breccias within thermal aureal of clusters of small intrusions. In some areas peripheral to porphyry systems.

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name
66	W701034	Constancia mine
88	W701160	Cerro Avispa

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
4	W701146	Unnamed (48-4)
8	W701148	Unnamed (48-6)
14	W701022	Unnamed (20-3)
25	W701029	Barrio Pasto deposits
26	W701064	Unnamed (32-1)
27	W701065	Unnamed (32-2)
28	W701066	Unnamed (32-3)
29	W701067	Unnamed (32-4)
31	W701069	Unnamed (32-6)
32	W701110	Unnamed (32-10)
36	W701114	Unnamed (37-1)
38	W701150	Unnamed (48-8)
42	W701152	Unnamed (48-10)
44	W701153	Unnamed (48-11)
46	W701154	Unnamed (48-12)
47	W701155	Unnamed (48-13)
49	W701157	Unnamed (48-15)
58	GEM1117	Rio Jajome
63	W701031	Unnamed (20-12)
64	W701032	Unnamed (20-13)
68	W701036	Cuchillos
69	W701070	Pellejas
70	W701037	Collcuchi, Sayre
74	W701039	Unnamed (21-7)
76	W701074	Unnamed (32-11)
77	W701075	Unnamed (32-12)

78	W701076	Unnamed (32-13)
79	W701077	Unnamed (32-14)
80	W701078	Unnamed (32-15)
81	W701079	Unnamed (32-56)
90	W701161	Carmen (50-3)
93	W701162	Carmen (50-4)
95	W701163	Carmen (50-5)
110	W701041	Unnamed (22-2)
118	W701080	Unnamed (32-17)
121	W701081	Unnamed (32-18)
123	W701082	Unnamed (32-19)
125	W701083	Unnamed (32-20)
127	W701084	Unnamed (32-21)
129	WALT001	Monte El Gato
130	W701086	Unnamed (33-1)
131	W701087	Unnamed (33-2)
132	W701088	Unnamed (33-3)
139	W701133	Palmarejo
141	W701135	Minillas, San German
149	W701139	Unnamed (46-2)
156	W701010	Unnamed (14-2)
157	W701011	Unnamed (15-1)
163	W701016	Unnamed (18-1)
178	W701092	Unnamed (33-7)
180	W701093	Unnamed (33-8)
181	W701094	Unnamed (33-9)
182	W701095	Unnamed (33-10)
184	W701097	Unnamed (33-12)
185	W701098	Unnamed (33-13)
186	W701099	Unnamed (33-14)
190	W701100	Unnamed (34-1)
198	W701107	Unnamed (35-7)
204	W701143	Unnamed (48-1)

GEOPHYSICAL SIGNATURE

None

GEOCHEMICAL SIGNATURE

The element Zn, Cu, Pb, Au and Ag are characteristic of this deposit type. These elements are present in the geochemical samples taken throughout the island.

TRACT DELINEATION

No terrane drawn.

The entire island is permissible for polymetallic veins, except the San Lorenzo and Utuado batholiths, and Oligocene or younger sediments.

COMMENTS

The depositional environment for this deposit type is within near-surface fractures and breccias within thermal aureoles of small intrusions or peripheral to porphyry systems.

Due to the high degree of faulting and the abundance of intrusions, most of the island is permissive except for the large batholiths and the Oligocene and younger sediments.

All of these occurrences were identified in Cox and Briggs (1973), and their descriptions used to classify as polymetallic veins.

DEPOSIT TYPE

24C Volcanogenic manganese

DESCRIPTION OF DEPOSIT TYPE

Lenses and stratiform bodies of manganese oxide, carbonate, and silicate in volcanic-sedimentary sequences (Koski, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

The marine Tertiary volcaniclastics with carbonates were found to contain all occurrences of manganese

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name
2	W701145	Juana Diaz mine
115	W701009	Aguada
128	W701085	Gatti prospect

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
1	W701144	Unnamed (48-2)
6	W701147	Unnamed (48-5)
10	W701149	Unnamed (48-7)
18	W701060	Unnamed (31-2)
20	W701061	Unnamed (31-3)
22	W701062	Unnamed (31-4)
24	W701063	Monte Guilarte
48	W701156	Santiago
65	W701033	Mayaguez
67	W701035	Corazal
173	W701056	Unnamed (30-1)

GEOPHYSICAL SIGNATURE

Aeromagnetics - incomplete or no coverage over permissive terrane.

Gravity - no detectable pattern over permissive terranes.

GEOCHEMICAL SIGNATURE

The geochemical signature for volcanogenic Mn deposits contained in USGS Bulletin 1693 is Mn, Zn, Pb, Cu and Ba.

These elements do not show related patterns for Puerto Rico samples.

TRACT DELINEATION

Manganese occurrences and deposits.

Area permissive - contains volcaniclastic marine Tertiary lithologies.

COMMENTS

Volcanogenic manganese deposits form most often when there is sufficient structure and porosity to permit subsea-floor hydrothermal circulation and sea floor venting.

The Juana Diaz mine produced manganese oxide from irregular chambers of limestone of the Juana Diaz Formation. Meyerhoff (1933) believes this manganese ore was deposited by meteoric waters that dissolved calcium carbonate and also precipitated manganese oxide.

DEPOSIT TYPE

25E Epithermal quartz-alunite Au

DESCRIPTION OF DEPOSIT TYPE

Gold, pyrite, and enargite in craggy veins and breccias in zones of high-alumina alteration related to felsic volcanism (Berger, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Through going fractures, centers of intrusive activity.

Upper and peripheral parts of porphyry copper systems.

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name
35	W701113	Cidra
160	D002191	Cerro la Tiza

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
86	W701124	Unnamed (39-1)
124	W701048	Unnamed (23-7)
187	WALT002	Rio Anasco

GEOPHYSICAL SIGNATURE

Aeromagnetics - coverage not available for large units.

Gravity - inconclusive.

GEOCHEMICAL SIGNATURE

The USGS Model book, Bulletin 1693, shows geochemical presence of Au, Ag, and Cu higher in the system, and base metals increasing with depth.

These elements did not define the permissive area for this deposit type.

TRACT DELINEATION

Terranes drawn based on known 1:20,000 alteration.

Called advanced argillic alteration associated with plutons.

Known occurrences in most tracts.

All hydrothermal alteration (TKha) and meta-volcanic rocks (TKmv) included that are related to dacite, quartz latite, rhyodacite or rhyolite.

DEPOSIT TYPE

28A Kuroko massive sulfide

DESCRIPTION OF DEPOSIT TYPE

Copper- and zinc-bearing massive sulfide deposits in marine volcanic rocks of intermediate to felsic composition (Singer, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Eocene island arc volcanics
Cherts present
Dacitic domes

EXAMPLE OF DEPOSIT TYPE

None

KNOWN OCCURRENCES

None

GEOPHYSICAL SIGNATURE

Aeromagnetics - incomplete or no coverage over permissive terrane.
Gravity - no detectable pattern over permissive terrane.

GEOCHEMICAL SIGNATURE

Copper and zinc anomalies with scattered gold anomalies occur in the western part of the massive sulfide terrane.

TRACT DELINEATION

Area permissive delineated by intermediate to felsic marine Tertiary volcano-clastic lithologies.

Associated occurrences of volcanogenic Mn.

COMMENTS

While no known occurrences of Kuroko massive sulfide deposits have been described, there is a high probability that they are present in Puerto Rico. The permissive features include: marine volcanic rocks of intermediate to felsic composition; marine rhyolite, dacite, subordinate basalt and associated sediments; hot springs related to marine volcanism; island arc tectonic setting; evidence of associated deposits (volcanogenic Mn).

DEPOSIT TYPE

38A Lateritic Ni

DESCRIPTION OF DEPOSIT TYPE

Nickel-rich, in situ lateritic weathering products developed from dunites and peridotites. Ni-rich iron oxides are most common (Singer, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Relatively high rates of chemical weathering (warm-humid climate) of ultramafic rocks and relatively low rates of physical erosion.

KJs - serpentinite is host rock

Dunite source = good chrome resource

Harzburgite source = poor chrome resource

Host lithology is outline of laterite accumulation.

EXAMPLE OF DEPOSIT TYPE

Site no.	MRDS no.	Name	Reserves and Grades
166	W701051	Punta Guanajibo	1.03% Ni, 0.07% Co, .63% Cr, 2,100,000 ST, 19.03% Fe
201	W701052	Guanajibo	0.08% Co, 20.54% Fe, 0.51% Cr, 46,800,000 ST, .88% Ni
169	W701053	Las Mesas deposit	28.39% FE, 0.75% Cr, 25,000,000 ST, .81% Ni, .12% Co
171	W701054	Rosario north deposit	20.76% Fe, .58% Cr 4,800,000 ST, .85% Ni, .07% Co
172	W701055	Rosario south deposit	12.47% Fe, .34 Cr, 1,100,000 ST, .71% Ni, .06% Co
175	W701057	Maricao west	22.05% Fe, .59% Cr, 5,000,000 ST, .98% Ni, .10% Co
177	W701058	Maricao east	29.45% Fe, .67% Cr 5,600,000 ST, 1.08% Ni, .11% Co

KNOWN OCCURRENCES

None

GEOPHYSICAL SIGNATURE

Gravity - serpentinite antiforms produce large anomalies.

Aeromagnetics - coverage incomplete.

GEOCHEMICAL SIGNATURE

Enriched Ni, Cr, and Co represent geochemical signatures for this model.

These elements and Mg are anomalous in the permissive terrane for this deposit type.

TRACT DELINEATION

Known occurrences.
All laterites contained within Serpentinite (KJs).
Ni laterites mapped at 1:20,000.

COMMENTS

Laterite accumulation is restricted to the outcrop pattern of the serpentinite (KJs) zone.

This area is believed to have been exhaustively explored for this type of deposit.

DEPOSIT TYPE

38C Karst Type Bauxite

DESCRIPTION OF DEPOSIT TYPE

Residual and transported material on carbonate rocks. Transported material may be felsic volcanic ash from distant source or any aluminous sediments washed into the basin of deposition (Patterson, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

EXAMPLE OF DEPOSIT TYPE

Kennedy bauxite concession.

KNOWN OCCURRENCES

Not plotted.

GEOPHYSICAL SIGNATURE

None

GEOCHEMICAL SIGNATURE

Aluminum and Ga not examined.

TRACT DELINEATION

Based on Kennedy bauxite concession granted in 1961. Tract extends farther east and west and is restricted to the Lares Limestone. Bauxite sampled from sinkholes.

DEPOSIT TYPE

39A Placer AU-PGE

DESCRIPTION OF DEPOSIT TYPE

Elemental gold and platinum-group alloys in grains and (rarely) nuggets in gravel, sand, silt, and clay, and their consolidated equivalents, in alluvial, beach, and eolian deposits (Yeend, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Oligocene and Quaternary sedimentary clastic deposits which have drained gold bearing lithologies and alteration.

EXAMPLE OF DEPOSIT TYPE

None

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
72	W701038	Palos Blancos
100	GEM1120	Luquillo Mountains gold placers
200	W701108	Rio Caliente

GEOPHYSICAL SIGNATURE

None

GEOCHEMICAL SIGNATURE

Some Au anomalies define drainage permissive for placer Au-PGE mineralization in the northeast part of the island.

TRACT DELINEATION

Known occurrences.

High-energy drainage areas below known gold occurrences.

COMMENTS

Gold placers were exploited by both the Indian and then Spanish colonists during colonization. Gold placers were also exploited during the 1900's to 1930's.

Remaining gold resources lie both in undiscovered remnant placer deposits, veins of gold-bearing quartz, and placers offshore are possible.

DEPOSIT TYPE

39C Shoreline Placer Ti

DESCRIPTION OF DEPOSIT TYPE

Ilmenite and other heavy minerals concentrated by beach processes and enriched by weathering (Force, 1986).

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Rock types included in this deposit type consist of well-sorted medium-to fine-grained sand in dune, beach, and inlet deposits commonly overlying shallow-marine deposits.

These deposit types typically are elongated 'shoestring' ore bodies parallel to coastal dunes and beaches.

EXAMPLE OF DEPOSIT TYPE

None

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
105	W701003	Hatillo
106	W701004	La Marina
107	W701005	La Boca
111	W701007	Rio Cocal

GEOPHYSICAL SIGNATURE

None

GEOCHEMICAL SIGNATURE

Ti anomalies in the volcaniclastic rocks in the western part of the island may indicate the possibility of placer Ti deposits along the west coast.

TRACT DELINEATION

Occurrences are restricted to individual beach dunes that are not visible at 1:200,000 scale.

DEPOSIT TYPE

Copper Manto

DESCRIPTION OF DEPOSIT TYPE

Mantos (horizontal) and pipes (vertical) found in association as brecciated areas, small in two dimensions and long in the third dimension. Brecciation allows the flow of fluids and deposition of minerals.

ROCK UNITS AND STRUCTURES PERMISSIVE FOR DEPOSIT TYPE

Small lenses and veins found in the Blacho Tuff Member of the Pozas Formation. Subaerial volcanic lithologies are preferred host lithologies.

EXAMPLE OF DEPOSIT TYPE

None

KNOWN OCCURRENCES

Site no.	MRDS no.	Name
15	W701023	Unnamed (20-4)
16	W701024	Unnamed (20-5)
17	W701025	Unnamed (20-6)

GEOPHYSICAL SIGNATURE

A few scattered anomalies for Cu occur in this terrane.

GEOCHEMICAL SIGNATURE

TRACT DELINEATION

Tract delineated for copper-silver Manto deposits of Puerto Rico is controlled by surface exposure of subaerial volcanic rocks of the Pozas Formation (Kpo).

QUANTITATIVE MINERAL RESOURCE ASSESSMENT OF PUERTO RICO

by

Walter J. Bawiec

Tracts permissible (Map 1, Map 2) for the occurrence of undiscovered metallic mineral deposits were delineated on the basis of the integration and interpretation of geology, geochemistry, geophysics, exploration history, and known metallic mineral occurrences of Puerto Rico. The geology provided permissive rock types and ages necessary for deposit formation; geochemistry indicated areas of anomalous values for both metallic and pathfinder elements; geophysics inferred subsurface extensions and structure of map units; exploration history allowed exclusion of deposit types or areas on the basis of previous exploration experience; and known mineral occurrences permitted investigation into the conditions of ore formation and the genesis of deposits.

A computer program, Mark3, combines subjective estimates of numbers of undiscovered mineral deposits at specified probability levels with documented distributions of grade and tonnage models (Cox and Singer, 1986; Drew and others, 1986; Bliss, 1992). Mark3 combines these values using Monte Carlo simulation to produce a probability distribution of quantities of ore and contained metal (Root and others, 1992; Root and Scott, 1988).

Estimates of numbers of undiscovered mineral deposits at specified probability levels can be found in table 1. These deposit types have associated grade and tonnage models, and enough geologic information available for Puerto Rico and known mineral occurrences such that the resource assessment team could, with confidence, estimate numbers of undiscovered deposits.

MARK3 FLOW CHART

The flow of data within Mark3 is shown in figure 1 (Root and others, 1992). The simulator runs through 4,999 iterations (k), using a random number generator to sample distributions of numbers of deposits, suites of metals in the deposits, deposit tonnages, and deposit grades, for each deposit type in each permissive tract. Within Puerto Rico, estimates of numbers of undiscovered deposits were made for the aggregate of permissive tracts, and not for each tract. As seen in the Mark3 flow chart, after identification of the permissive tract and the mineral deposit type, a random selection is made from the distribution of the numbers of deposits (N). If applicable, values from a suite of metals for that deposit type are randomly selected, in conjunction with random samples from the grade and the tonnage distributions. Metal contents are computed for this iteration as the product of number of deposits, metal suite, and grade and tonnage. This computed metal product is stored in an accumulator and this cycle continues until the random number of deposits sampled (N) is satisfied. When this occurs, another deposit type within the same tract is selected and a calculation of the metal content is made. When all deposit types within a particular tract have been sampled, another tract is selected until all mineral deposit types in all tracts have been exhausted. The above described sequence of events accounts for one iteration (k) of the Mark3 simulator and will continue for 4,999 repetitions. The products of the 4,999 iterations for metals, numbers of deposits, and grades are sorted by value and ordered from the lowest to highest value, and their distributions examined.

MARK3 OUTPUT

The expected means in metric tonnes for metals contained within undiscovered deposits in Puerto Rico are shown in table 2. Each deposit type is accompanied by the mean number of deposits, total tonnage for that deposit type (mean deposit tonnage equals total tonnage divided by number of deposits), and metal content of metallic suites.

It is apparent from table 2 that porphyry copper-gold deposits are expected to account for a significant proportion of the copper, molybdenum, gold, and silver in the undiscovered deposits of Puerto Rico; iron is in the iron skarn deposits; zinc and lead are in polymetallic vein deposits; and manganese is in volcanogenic manganese deposits.

While the arithmetic means of the metals in undiscovered deposits provides a valid indication of what is to be expected, additional descriptive statistical information provides a more complete viewpoint of expectations.

Frequency distributions of grades and tonnages of mineral deposits are commonly asymmetrical, a higher proportion of lower graded and smaller tonnage deposits occurs than do the more desirable higher graded and larger tonnage deposits. Because of this asymmetry, the differences in the values for the arithmetic average (mean) and midpoint (median) for grades and tonnages can be quite large.

Table 3 contains the arithmetic mean and the 90th, 50th, and 10th percentile values of the frequency distributions for metal in the undiscovered mineral deposits of Puerto Rico. The 50th-percentile (median) values represent the midpoint of the distribution. This indicates that one would expect that in half the cases the undiscovered deposits would contain tonnages and metals greater than the median value, and in half of the cases they would contain less. For the 90th percentile, one would expect that in 90 percent of the cases the undiscovered deposits would contain tonnages and metals greater than the 90th percentile, and 10 percent of the time have a lesser value.

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TOPICAL STUDIES

Gold Deposits of Puerto Rico

Distribution of Platinum-Group Elements in Nickel-Bearing Laterites of Puerto Rico

Offshore Sediments and Sand and Gravel Resources on the Insular Shelf of Puerto Rico

Silt Heavy-Mineral Distributions in the Rio Cibuco System and Adjacent Rivers of North-Central Puerto Rico

Side-Looking Airborne Radar Mosaic of Puerto Rico

Lignite and Peat in Northwestern Puerto Rico

Gold Deposits of Puerto Rico

by

G.E. McKelvey

Gold in Puerto Rico is known to occur in at least five different mineral deposit types: gold placers, polymetallic veins, gold-copper skarns, porphyry copper-gold deposits, and acid-sulfate precious-metal deposits. Potential for undiscovered gold-bearing deposits exist in Puerto Rico in off-shore placer deposits, gold-copper skarns surrounding Tertiary intrusions and, polymetallic veins throughout the Commonwealth. There is also potential for large bulk concentrations within intensively acid sulfate altered areas. While there is no direct evidence for their existence, it is possible that Puerto Rico contains both sediment-hosted and laterite gold deposits. Modern prospecting for gold in Puerto Rico has not been exhaustive.

Placer gold deposits (USGS model #39A, Cox and Singer, 1986) were perhaps the first gold deposits worked in Puerto Rico. These were best developed along many of the major rivers draining north from the central mountains (Cordova, 1920). While not individually large, the aggregate of these deposits is thought to have contained as much as 1 million ounces (25,000 kg) of gold. These deposits, first worked by the Spanish in the 1500's (Cardona, 1974), are best developed along the Rio Fajardo, Rio Mameyes, Rio Humacao, Rio Maville, Rio Cibuco, Rio Daguao, Rio Grande de Loiza, Rio Sibuco, Rio Anasco, and Rio Grande de Manati drainage systems. Gold in small placer deposits is also known in the vicinity of several of the porphyry copper-gold deposits in the Utuado District and in small drainage basins surrounding the intrusion hosted gold occurrences at Barranquitas. Prospecting for on-shore gold placer deposits appears to have been extensive and perhaps nearly exhaustive. However, potential may exist in the narrow, shallow off-shore shelf along the north shore of the island, especially down stream from the previously productive placer deposits. It is also possible that several of the underground rivers developed in the extensive karst environment along the north slope of the island could host small placer deposits.

Gold occurs along with copper, zinc, lead, arsenic, and silver in veins and fissures developed in several host rock settings throughout the Commonwealth. The best developed are the small veins and metamorphic veins in the serpentinite terrane in the Bermeja Complex at the Minillas deposits (Mattson, 1960). Quartz veins, developed in many places within east-west shear zones, vary in width from 10 cm to 1.5 meters, and have strike lengths of as much as 1,000 meters. Past production is small: 180 tons of 0.74 oz/ton. Mineralization is not continuous throughout these veins, and appears best developed along intersecting structures and within the widest portions of the veins. Several polymetallic vein deposits are known within the outer halo zones of major intrusive related deposits. While not extensive, these deposits contain gold concentrations of as much as 50 g/tonne gold (USGS model #22, Cox and Singer, 1986).

Gold bearing skarn deposits, especially surrounding the Rio Blanco stock in the Sierra de Luquillo, were discovered and first worked by the Spanish in the early 1600's (Cardona, 1984). While the production appears to have been limited to several small adits, the zone of alteration is an extensive 2- to 4-kilometer-wide zone surrounding the entire Rio Blanco stock. Placer gold deposits persist for nearly the entire distance of 10 km to the Atlantic Ocean. Garnet, epidote, chlorite, pyrite, and chalcopyrite are the predominant minerals within the best known occurrences.

Gold occurs within the porphyry copper deposits in the Utuado area of west-central Puerto Rico (Cox, 1985). While resource estimations of the gold tenor within these deposits are not available, limited analyses of gold from these copper deposits indicate the grade of gold to be as high as 0.015 oz/ton (0.5 g/tonne)(Cox, 1985). These occurrences are described by USGS model #20d (Cox, 1991). Gold would be a significant by-product should these deposits ever be mined.

Gold also occurs in large advanced argillic alteration systems, occasionally associated with Eocene intrusions. Gold has been determined to exist in the intensely altered quartz-diorite intrusion at Barranquitas (Flint, 1965) and in silica- and alunite-rich breccias and structural zones in the Cerro Avispa area (Cardona, 1982 and Cox and Briggs, 1973). While not previously described as a separate mineral deposit type, these systems are consistent with the acid-sulfate precious-metal deposit type of Kesler and others (1990). Alternatively, the data are consistent with these deposits being a high level end-member of the porphyry gold model described by Cox (1991).

Large areas of advanced argillic alteration are developed along northwest-trending structures in Puerto Rico. These zones are hosted by Eocene andesitic volcanics and volcaniclastic formations. Extensive zones of argillic, alunitic, and silica/scinter alteration are hosts to several gold occurrences. Gold is also hosted by breccia pipes, linear zones of stockwork quartz veins, and areas of intense fracturing. Gold persists in concentrations of one to ten times higher than silver. Arsenic is present, and copper is anomalous in most areas of gold mineralization. Silicification, where present, is in open spaces and vuggy in appearance, although massive silica is present at a few localities. Rare quartz-porphyry dikes are the only direct evidence of the possibility of underlying intrusions.

05/06/99

DISTRIBUTION OF PLATINUM-GROUP ELEMENTS IN NICKEL-BEARING LATERITES IN PUERTO RICO

By

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and Allen L. Meier

INTRODUCTION

Nickel-bearing laterites and their underlying serpentinites in southwestern Puerto Rico have been the subject of several studies. The purpose of this reconnaissance study is to investigate the potential for platinum-group elements (PGE) and gold in the laterites.

GEOLOGY AND PGE POTENTIAL

The nickel-bearing laterites are on the southwestern end of the island East and South of Mayagüez (figure 1). The ultramafic rocks that underlie the laterites were emplaced over a period of time that began probably in the late Cretaceous (Mattson, 1960) and ended in the Eocene (Krushensky, oral commun., 1991). Mattson (1960) argued that the ultramafic rocks were exposed briefly during the Cretaceous and then were buried by a series of sedimentary formations until being exposed sometime during the Eocene, at which time the present-day laterite began to form. However, Krushensky (1978) presented evidence that deposition in western Puerto Rico was continuous from the Cretaceous to the middle Eocene. In either event, it seems clear that the great majority, if not all, of the laterite formed between the middle Eocene and the present.

Of the several studies of the laterites, the most extensive was by Heidenreich and Reynolds (1959), in which they examined 279 drill holes totaling nearly 3,300 m and assayed them for nickel, cobalt, iron, and chromium. Table 1 summarizes the resources of these metals, based upon a 0.6 percent Ni cutoff. Cram (1972) drilled some more in the largest of the deposits, the Guanajibo, and estimated 37 million tons of laterite at 1.2 percent Ni. Cram did not estimate the other metals. The two estimates are remarkably close in terms of the amount of nickel in the Guanajibo area. Heidenreich and Reynolds' (1959) figures yield about 410,000 tons of nickel while Cram's figures yield about 440,000 tons of nickel (to the nearest 10,000 tons in each case).

Here we present the results of a reconnaissance sampling of the laterite for PGE in several areas. Elevated PGE values occur in laterites in Australia (see, for instance, Derrick, 1991). We collected samples at various locations where a complete section or nearly complete section of laterite (from serpentinite to the iron cap) was present. The samples were analyzed for PGE by ICP mass spectrometry. The results are shown in table 2 and graphically in figure 1. The PGE concentrations in the laterites are higher than the serpentinite directly below by a factor of 4.3 to 11.7, averaging 7.4. The highest total concentration of PGE is in the Maricao East deposit (about 340 parts per billion, or ppb). In almost every profile the content of PGE increases just above the laterite-serpentinite contact and remains high throughout the laterite profile. Only in the upper part of the Las Mesas 1 locality does the PGE content drop back to near the levels of the serpentinite. Preliminary geochemical analysis of other elements indicates a good correlation between PGE and cobalt. However, further detailed study will be necessary in order to elucidate the relation between the changes in PGE and the other chemical changes that have occurred in the laterite. All the samples were analyzed for gold and all were found to contain less than the detection limit of 0.01 ppm.

Although the data presented here are not detailed, they do show significant increases in PGE concentration in Puerto Rican laterites over that of bedrock. These increases suggest similarities to the laterite developed over some Alaskan-type complexes in New South Wales, Australia (Elliott and Martin, 1991). Detailed exploration and drilling revealed that PGE concentrations in one of them, the Tout complex, has typical grades of platinum of 20-50 ppb in dunite and 800 ppb in the overlying laterite, and some assays are as high as 16 ppm (Derrick, 1991). If that kind of enhancement is encountered in western Puerto Rico as a result of subsequent, more detailed study, PGE values of hundreds of ppb to perhaps 1 ppm may be encountered. On the basis of these observations, the Puerto Rican laterites may be considered a speculative resource for platinum- group elements.

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Offshore Sediments and Sand and Gravel Resources on the Insular Shelf of Puerto Rico

by

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Summary

Data from more than 2,500 samples were compiled from published and unpublished sources to create a map, which groups the insular shelf sediments of Puerto Rico into three categories: high calcium carbonate, low calcium carbonate (terrigenous), and mixed (carbonate and terrigenous). The map shows that terrigenous sediment deposits are concentrated near the mouths of major rivers, particularly on the north shelf. In areas where the shelf is sufficiently wide to extend beyond the direct influence of sediment input from rivers, the middle and outer shelf is dominated by biogenic carbonate sands. The southwest shelf, the south-central shelf, and the Virgin Islands Platform east of Puerto Rico are such areas. Mixed sediments generally lie between areas of dominantly terrigenous and dominantly carbonate sediment.

Three potential sites for mining of sand and gravel from the insular shelf are considered: Escollo de Arenas (off the western end of Vieques), Isabela (northwest shelf), and Cabo Rojo West (southwest corner of Puerto Rico). At these locations large accumulations of sand, fed by longshore currents, have been identified. Of the three sites, the Escollo de Arenas appears to be the most promising for offshore mining.

Surficial Sediment Map

Introduction

This map showing types of surficial sediment (map 1) is highly generalized and should be considered as a starting point, a base map for more focused studies. The U.S. Geological Survey (USGS) is currently mapping the geology of the insular shelf of Puerto Rico in more detail (scale 1:40,000). Most of the maps in the series have been published (Rodriguez and others, 1977; Beach and Trumbull, 1981; Grove, 1983; Pilkey and others, 1987; Trias, 1991; Rodriguez and others, 1992; Morelock and others, 1994 see fig. 1) or are in press (Rodriguez and others, in press; Schlee and others, in press; Scanlon and Trias, in press; Scanlon and others, in press; Schlee and others, in press; Trias and Scanlon, in press; Trias and others, in press; see fig. 1). Four additional maps, covering the shelf east of Puerto Rico and surrounding Culebra and Vieques, are in preparation. The published maps and the data collected for the maps in preparation (Scanlon, unpublished data) have been used in the present study.

Methods

To produce this map of surficial sediments on the insular shelf of Puerto Rico, the many sediment types were grouped into three very general categories: high calcium carbonate, low calcium carbonate (terrigenous), and mixed (carbonate and terrigenous). This was done to establish a common denominator for the differing types of data compiled from numerous sources.

Data from more than 2500 samples, from over 35 separate studies, were compiled to create this map. The type of data available varies from study to study. Calcium carbonate analyses and complete grain size data are available for some sets of samples; only field descriptions are available for other sets. Unpublished theses are a major source of data (Beach, 1975; Bush, 1977 and 1991; Grove, 1977; Fernandez, 1978; Grossman, 1978; Fuerst,1979; Rodriguez, 1979; Stout, 1979; Anderson, 1981; Lincoln, 1981; Prehmus, 1981; Brackett, 1985; Benes, 1988; Lightner, 1988; see fig. 1). Previously published maps were used as guides in areas where sample localities are sparse. Although the quantity of data varies, high-quality data are available for localities throughout the map area. Schneidermann and others (1976) is the only previous attempt to map the surficial sediments of the entire shelf of Puerto Rico, but since it is based on rather sparse data, we used their map only where no other data exist.

Where carbonate analyses are available, we used 25 percent and 75 percent CaCO3 as the lower and upper limits, respectively, of the "mixed" sediment type. These limits were chosen because most of the previously published studies of Puerto Rico shelf sediments used these numbers. A sample containing more than 75 percent CaCO3 is classed as carbonate; a sample containing less than 25 percent CaCO3 is classed as terrigenous. Where only descriptions are available, we classified the samples on the basis of color, texture, and major constituents mentioned. We also took into account the local environment and descriptions and analyses from any similar samples from nearby. Where published maps showing types of sediments are available, but not including data for individual samples, we used the description for each mapped unit to categorize all the samples contained therein.

Discussion

As one might expect, the map shows that terrigenous sediment deposits are associated with the mouths of major rivers. This is particularly evident on the north side of the island where rainfall and, consequently, runoff are greatest. Rio Grande de Loiza, which drains Sierra de Luquillo, where annual rainfall approaches 200 in. (Calvesbert, 1970), has a large deposit of terrigenous sediments near its mouth. Rio de la Plata and Rio Grande de Manati also exhibit localized terrigenous sediment deposits. On the western part of the north shelf, the terrigenous deposits merge in a continuous band. Pockets of terrigenous sediment are also present on the south shelf, both at the mouths of rivers (for example, Rio Guayanilla and Rio Tallaboa) and in the protected areas behind reefs (for example, near Jobos; see map 1). The shelf east and southeast of Puerto Rico is dominated by carbonate sediment. Small patches of terrigenous or mixed sediment are found along the coast near the mouths of rivers. The rivers in southeastern Puerto Rico have a small drainage area in comparison with those that empty onto the north shelf and would not be expected to create large terrigenous deposits (Wilson and Iseri, 1969). An elongate sand shoal of mixed terrigenous and carbonate sediment extends northwest from the western end of Isla de Vieques.

Areas where the shelf is wide, and therefore extends beyond the direct influence of rivers, are dominated by biogenic sands having a high carbonate content. This can be seen particularly on the southwest shelf, on the Virgin Islands Platform east of Puerto Rico, and the south-central shelf. Not surprisingly, mixed sediment deposits are generally found between areas of predominantly terrigenous and predominantly carbonate sediment, such as off the west coast of Puerto Rico and near Isla Caja de Muertos on the south shelf.

Offshore Sand and Gravel

Introduction

Sand and gravel are important commodities in Puerto Rico because of their use as aggregate for concrete, in road construction, as fill, and for beach replenishment. Decades of industrial growth in Puerto Rico have increased the demand for sand and gravel. During the 1950's and 1960's this demand was often met by mining beaches and dunes. In the late 1960's, the importance of the beaches and dunes, both as sources of tourist revenue and as natural protection from high seas, was recognized and Federal and Commonwealth legislation was enacted to prohibit or greatly restrict their destruction. But, like many island nations, Puerto Rico has discovered that the sand and gravel available on the island will not supply all its future needs. Since the cost of transporting this bulky commodity is high, it is expensive to import. Nearby sources that can be mined while avoiding unacceptable environmental impact are needed. A potential solution may be found under water, on the insular shelf.

Offshore sand and gravel are mined elsewhere. For example, the United Kingdom, the Netherlands, Denmark, and Japan have well-established marine-mining industries, which satisfy nearly 20 percent of their sand and gravel needs (Williams, 1986). Factors affecting the feasibility of mining of sand and gravel on the insular shelf of Puerto Rico are of three types: technological, economic, and environmental.

The technology exists to carry out large-scale mining in water as deep as 30 m (Williams, 1986). Other factors affecting technological feasibility are speed of the current and frequency of high seas. The ideal site should be protected from the prevailing winds and should not have strong currents.

Economic considerations include transportation distances and thecharacteristics of the deposit. Williams (1986) gives 50 km as a rule of thumb for maximum haul distance, but this number should be based on local costs for transporting the sand and gravel by barge. Transportation distances from port to the site of where the sand and gravel will be used should also be considered. The characteristics of a deposit that make it attractive include a large volume and a low percentage of fine sediment. It is also important that the deposit be thick and that the material underlying it not be mud or other fine sediment. Thalassia sea grass beds tend to trap fine sediment and can render an otherwise economic deposit too ‘dirty’.

Environmental considerations are both biological and geological in nature. Direct impact on the biota of the deposit needs to be evaluated, as well as indirect impact, such as the effects of suspended sediment on nearby reefs. Changes in the shape of the sea floor can alter local wave and current action (Cruikshank and Hess, 1975), which can cause an increase in erosion of nearby beaches. It would be sadly ironic if the mining of offshore sand for beach replenishment actually caused additional beach erosion. A more complete discussion of biological and geological impacts that would result from offshore dredging in Puerto Rico can be found in Cintron and others (1984).

Definitions and standards

The terms "sand" and "gravel" are grain-size classes of rock particles and do not imply a particular composition. Several scales for describing grain size are in current usage (Folk, 1974). In this report, sand grains range from .0625 mm to 2 mm in diameter; gravel includes the size classes "granule" and "pebble" and is between 2 mm and 64 mm in diameter. In the real world, deposits may contain a mixture of grain sizes and are described by compound names such as "muddy sand" (a deposit that is predominantly sand, but has a finer grained component).

There is little difference between sand and gravel mined on land and that taken from a submarine source. Impurities such as salt or organic material can easily be washed from the marine sand and gravel if necessary.

Industry requirements for grain size, grain shape, sorting, and composition vary widely and depend partly on the intended usage. Although published standards exist, they are not universally followed (Williams, 1986). In general, terrigenous (that is, non-carbonate) deposits are preferred for construction purposes, whereas carbonates are used as a source of lime (Cruickshank and Hess, 1975). Replenishing beach sand with sand that matches the existing sand is important for both aesthetic and practical reasons. Sand that is too fine may be winnowed away quickly; that which is too coarse may be more stable, but may produce a steeper shore profile (Williams, 1986). Material that is much too coarse may not return to the beach if it is shifted offshore during a storm.

Discussion of potential for sand and gravel

Grove and Trumbull (1978) identified three offshore sand deposits that, on the basis of a preliminary study, showed potential for offshore mining. The three sites are Escollo de Arenas (off the western end of Vieques), offshore of Isabela (northwest shelf) and Bahia Sucia (east of Cabo Rojo). In a later study, Cintron and others (1984), after evaluating 23 sites on the insular shelf of Puerto Rico for their potential as sources of sand and gravel, also identified Escollo de Arenas and Isabela as sites that deserved further study. They eliminated the Bahia Sucia site (on the grounds of biological sensitivity and potentially severe coastal erosion if mined) and added Cabo Rojo West (on the shelf southwest of Cabo Rojo) as a favorable site. The three most promising areas (Isabela, Cabo Rojo West, and Escollo de Arenas) are discussed below.

Isabela

The Isabela area is on the north insular shelf of Puerto Rico, at the westernmost end of the island, where the shelf widens from less than 4 km to about 6.5 km (fig. 2). The water depth in the deposit area is between 20 m and 45 m. The sediment is predominantly carbonate, and terrigenous river-derived sediments are confined to a narrow strip parallel to the coast (map 1). Fine-grained material is present in these river sediments and in deep-water deposits beyond the shelf edge (>80 m), but the carbonate sediments on the middle shelf are relatively free of fines (Cintron and others, 1984; Trias, 1990).

The first known study to evaluate the Isabela area as a potential source of sand and gravel was conducted in 1973 by Borinquen Minerals, Inc., a local mining company. They estimated a sand volume of between 20 and 25x106 m3 (Cintron and others, 1984) and requested a permit to dredge. No seismic-reflection profiles were collected (Trias, 1990). Two subsequent studies (Grove and Trumbull, 1978; Grove, 1983) discussed the composition and texture of the surficial sediments. Grove (1983) showed line drawings of two shallow-penetration seismic-reflection profiles across the shelf in the Isabela area, but they are of little value in estimating the volume of sand.

A study by the USGS (Trias, 1990) estimated that the volume of sand and gravel at the 30-km2 Isabela site is 8.7x106 m3, less than half of the volume previously suspected by Borinquen Minerals, Inc. (Cintron and others, 1984). Trias (1990) based his estimate on more than 100 line-km of well-navigated, high-resolution seismic-reflection profiles in a grid having approximately 500-m spacing between lines. He concludes that the Isabela offshore sand deposit is economically unattractive for three reasons. First, the volume is relatively low, and the deposit is thin and patchy (fig. 3). Second, most of the sand is in deep water (30-45 m), and would be expensive to recover. Third, the area is unprotected from the prevailing northeast winds and is prone to rough seas.

Cabo Rojo West

Cabo Rojo is a promontory of land on the southwest corner of the island of Puerto Rico. The Cabo Rojo West sand deposit is 1-6 km west and southwest of Cabo Rojo in water depths of 10-20 m (fig. 2). Except for a pocket of mixed terrigenous-carbonate sediments adjacent to the west side of Cabo Rojo, the sediments of this area are predominantly carbonate (map 1).

Previous work in the area consists of a Master's thesis (Fernandez, 1978) and a USGS report by Shideler (1980), both of which dealt with composition and texture of the surficial sediments. A later USGS report (Trumbull and Trias, 1982) incorporated a well-navigated grid of seismic profiles having line spacing of approximately 500 m. They estimated the volume of sand in the deposit to be 80x106 m3 over a 33-km2 area (fig. 4). They also reported favorable results of compressive strength tests applied to concrete made with the Cabo Rojo West sand. Cintron and others (1984), however, reported that as much as 90 percent of the volume estimated by Trumbull and Trias (1982) may be unsuitable for mining because of excessive fines in the substrate of seagrass beds and algal plains growing where the sand is thickest. They estimate that only a 3-km2 area containing 8x106 m3 of sand is suitable for mining.

Escollo de Arenas

The Escollo de Arenas is an elongate shoal that extends 6 km into Pasaje de Vieques from the northwest corner of Isla de Vieques (fig. 2). The 100- to 1000-m-wide shoal is covered by only 2-8 m of water and is clearly visible from the air (fig. 5). The deposit rises as much as 9 m above the surrounding seafloor (fig. 6) and has a maximum thickness of 17 m, but most of the sediment is in a layer 6-14 m thick (fig. 7). The Escollo de Arenas is composed of mixed terrigenous and carbonate sand and gravel (map 1) underlain by a consolidated Pleistocene surface (Rodriguez, 1979; Rodriguez and Trias, 1989). Cemented beachrock slabs are known to be present (Rodriguez and Trias, 1989), but their extent is unknown.

Grove and Trumbull (1978) discussed the textural and compositional characteristics of the Escollo de Arenas. They had no seismic profiles, so they did not estimate a volume. The hydrography and biology of the Escollo were discussed by Cintron and others (1984). They recommended further study to define the volume and extent of cemented lenses in the deposit. Rodriguez and Trias (1989) estimated a volume of 90x106 m3 of unconsolidated sediment, based on 80 line-km of well-navigated, high-resolution seismic-reflection profiles spaced about 100 m apart. This large volume, together with the shallow water depth of the deposit and the fact that the sand "generally meets the requirements as construction aggregate" (Ocean Dynamics Corporation, 1972) caused great interest in the Escollo de Arenas as a source of sand and gravel.

In 1989 Hurricane Hugo struck Puerto Rico. Comparison of aerial photographs of the Escollo de Arenas taken before and after the hurricane suggested that large amounts of sand were lost from the Escollo (Rodriguez and Webb, 1990). However, subsequent detailed seismic profiling and sampling studies by the USGS to assess the effects of Hurricane Hugo (Delorey and others, 1993) indicated that although the grain-size distributions and bedforms on the Escollo were altered, less than 4 percent of the volume of sand estimated by Rodriguez and Trias (1989) was permanently lost to adjacent lower energy environments. It was hoped that the new high-resolution seismic-reflection profiles collected for the post-Hugo study would allow mapping of the cemented beachrock slabs, but they could not be discerned in the profiles. The volume of extractable sand may be limited by the beachrock, but its extent remains unknown.

Conclusions

Compared to the land areas of Puerto Rico, the insular shelf is a poorly known geologic frontier. The generalized surficial sediment map of the insular shelf presented here is the first attempt to compile the data generated by the numerous small studies carried out over the last 15 years. Recent detailed mapping of parts of the shelf has revealed deposits of sand and gravel that may be able to satisfy some of the island's future requirements for these commodities. As detailed mapping continues and our knowledge of the shelf sediments and processes grows, our ability to use the shelf resources wisely will also increase.

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Silt heavy-mineral distributions in the Rio Cibuco system and adjacent rivers of north-central Puerto Rico

by

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ABSTRACT

Mineralogical studies of the silt-sized fraction of sediment samples from the Rio de la Plata, Rio Grande de Manati, and rivers of the Rio Cibuco system in north-central Puerto Rico have examined the effects of lateritic weathering and explored the silt for possible economic heavy minerals. This fraction, which is slightly enriched in heavy minerals relative to the sand fraction, is predominantly detrital, but contains a strong authigenic component. The detrital silt heavy-mineral fraction is dominated by an amphibole-garnet-pyroxene-epidote assemblage. The authigenic silt heavy-mineral fraction, which is largely an artifact of the lateritic weathering, is dominated by iron oxides and altered grains. This laterization has dramatically altered the relative percentages of the minerals originally present in the source rocks.

Lateral variability within the Rio Cibuco system is considerable and related to the changing composition of the underlying source rocks along the course of the river and its tributaries. Important differences between the silt heavy-mineral assemblages present in the Rio de la Plata, Rio Grande de Manati, and rivers of the Rio Cibuco system and between the heavy-mineral assemblages in the silt- and sand-sized fractions are also apparent.

We detected no minerals containing significant amounts of Cu, Ni, Sn, or Zn in any of the river-sediment samples. However, elevated concentrations of titanium-bearing minerals and small amounts of cerargyrite, chromite, gold, and manganese oxides occur.

INTRODUCTION

This paper describes the results of a reconnaissance study on the silt-sized heavy and light-mineral fractions of the Rio Cibuco system and the adjacent rivers of north-central Puerto Rico. Earlier studies of heavy-mineral distributions in Puerto Rico (Guillou and Glass, 1957; Grossman, 1978; Lincoln, 1981; Pilkey and Lincoln, 1984; Bush et al., 1988) were limited to the sand fraction. These studies concentrated on the sand fraction for several reasons that include: (1) the surface tension of organic heavy liquids used in the separatory process made it difficult to achieve complete submergence of the finer-grained particles; (2) petrographic analyses were difficult to perform on the finer grain sizes due to the physical limits on the resolution of optical microscopes; (3) X-ray powder diffraction (XRD) is too crude to detect many of the mineral species that occur in trace amounts; and (4) most commercial placer deposits exploit the sand fraction. These problems have dissuaded researchers from studying the scientifically- and, possibly, commercially-important silt-sized fraction. However, the recent introduction of the heavy liquid sodium polytungstate separation method (Callahan, 1987; Gregory and Johnston, 1987) and the availability of automated image analyzers (AIA) for scanning electron microscopes (SEM) equipped with energy-dispersive X-ray spectrometers (EDS) now facilitates the study of silt-sized heavy minerals (Commeau et al., 1992).

The purpose of this report is to describe the diagnostic characteristics of the silt heavy- and light-mineral fractions. These descriptions are used to determine whether this assemblage is controlled by source, weathering, or diagenetic processes, to compare the silt fraction mineralogy with that of the sand fraction, to evaluate the potential for placer and concentrated lode deposits within the Rio Cibuco system, and to discuss what the silt fraction tells us about the sedimentary processes operating in the rivers of north-central Puerto Rico.

REGIONAL GEOLOGY

Puerto Rico, which is the smallest and easternmost island of the Greater Antilles, can be readily divided into an Early Cretaceous-Eocene volcanic-plutonic terrane, a carbonate terrane primarily of Oligocene and Miocene age, and Holocene coastal lowlands (Weaver, 1964; Fig. 1). The volcanic-plutonic terrane forms an east-west mountain range (the Central Cordillera) that is composed mainly of volcanic tuffs, volcanic breccias, and andesitic and basaltic lavas mainly of the Los Negros, Avispa, Pozas, and Perchas Formations (Berryhill, 1965; Nelson, 1967; Cox and Briggs, 1973). Occurring with these volcanics are marine, reworked pyroclastic rocks of the Magueyes, Cibuco, and Palmarejo Formations and a few light gray-reddish limestones and limestone breccias of the Corozal Limestone. Associated with these volcanic strata are intrusive igneous rocks. The bulk of these intrusives are granodiorites and quartz diorites, but diorites, gabbros, and quartz monzonites are locally common in dikes and sills. Secondary mineralization associated with vein deposits of hydrothermal origin is also common.

The carbonate terrane rests on the flanks of the volcanic-plutonic terrane and is composed mainly of limestones with smaller amounts of marl, dolomite, and calcareous quartz sandstones of the Cibao Formation, Lares Limestone, and Mucarabones Sand (Nelson, 1967; Monroe, 1973). Along the northern coast, this province dips to the north and displays a spectacular karst topography (Monroe, 1968; Monroe, 1976).

The island's rainfall is controlled by moisture-laden cloud systems that are driven by northeast trade winds and encounter the higher elevations of the Central Cordillera (Ehlmann, 1968; Bush et al., 1988). Inasmuch as the resultant precipitation falls mainly on the northern side of the mountains, most of the major rivers on the island have their headwaters in the Central Cordillera and drain to the north. One of these rivers, the Rio Cibuco, has a 175 km^2 drainage basin and a maximum discharge of about 27,400 cfs (776 m^3/s; Lopez and Colon-Dieppa, 1973; Fig. 1).

The upstream portions of the Rio Cibuco, Rio de la Plata, and Rio Grande de Manati, like many of the northward-flowing rivers (Weaver, 1958), are actively cutting into the Central Cordillera. Rapids and waterfalls are common in these upstream areas, suggesting highly oxygenated conditions. Meandering downstream sections of these rivers have a lower gradient and appear to have lower flow velocities. Terrigenous sediment eroded from the island is transported by these rivers to the northern insular shelf.

FIELD AND LABORATORY METHODS

The river samples were collected during 1990-1991 by driving along the banks of the Rio de la Plata, Rio Grand de Manati, and rivers of the Rio Cibuco system and sampling at conveniently accessible points (Figs. 1, 2). As in a previous study of the sand fraction of the Rio de la Plata (Bush et al., 1988), particular emphasis was placed on taking samples at points where accumulations of placer mineral were likely to occur; for example at the upstream ends of point bars and at channel bars located just downstream from rapids. The samples are texturally representative of the fluvial bedload at these sites; no field processing, such as the removal of gravel by sieving or concentration of the heavy fraction with standard gold pans, was attempted.

The silt-sized sediments (particles of 62-μm decreasing to those hydraulically greater than or equivalent to quartz spheres of 4-μm) were isolated from the sand and gravel fractions bywet-sieving and from the clay fraction by decantation prior to the heavy-liquid separations. A random subsample of the remaining silt fraction was suspended in a small amount of distilled water, added to a solution of sodium polytungstate, and disaggregated by sonification. The suspension was then rapidly evaporated at 60^{o}C in a convection oven to the proper specific gravity (S.G. 2.85) and centrifuged to separate the light and heavy minerals. The bottoms of the centrifuge tubes were then frozen in liquid nitrogen to trap the heavy minerals. The unfrozen supernatant containing the light mineral fraction was then washed from the tube. The light- and heavy-mineral fractions were independently suction-mounted onto pre-weighed 0.45 μm Millipore filters. These filters were rinsed, dried, and weighed to determine the relative weight percents of the heavy- and light-mineral fractions.

Splits of both the heavy and light silt fractions were analyzed by XRD; additional splits of the heavy-mineral fraction were analyzed by SEM/AIA/EDS. The splits for XRD analysis were ground, mounted on glass slides, and X-rayed as randomly oriented aggregates. Semiquantitative estimates of the minerals present were made by comparing the diffraction peak areas and intensities of each sample with the areas and intensities recorded from a collection of external standards (Goehner, 1982).

The splits for the SEM/AIA/EDS analysis were dispersed on carbon mounts (Fig. 3A). In the SEM, the computer-driven electron beam automatically scanned the field of particles, the AIA system measured their sizes, shapes, and grayness (an indirect measure of atomic weight), and the EDS system acquired an X-ray spectrum from each particle. SEM/AIA/EDS analyses of the heavy-mineral grains continued until at least 300 grains were analyzed for each sample.

Most heavy-mineral species or groups can be readily identified during the SEM/AIA/EDS analyses by their distinctive composition and morphology. Polymorphs and minerals with overlapping compositions were combined into "macrogroups" and, if possible, differentiated by XRD analysis. For example, XRD analyses of the heavy-mineral fractions were specifically checked for the presence of individual minerals or groups in the amphiboles+pyroxenes+tourmaline+olivine macrogroup that could not be differentiated by the SEM/AIA/EDS system or spodumene, kyanite, andalusite, and sillimanite that would appear chemically to be part of the beryl+topaz macrogroup. If no diffraction maxima characteristic of a given mineral were observed in any of the XRD patterns, then this mineral was assumed to be absent.

As with other heavy-mineral separatory techniques, the separation of phyllosilicates is difficult because the specific gravities of the layer silicates may straddle that of the heavy liquid (S.G. 2.85) and not all of the grains are removed in the heavy-mineral residue. Therefore, SEM/AIA/EDS and XRD analyses were used to determine the concentrations of the layer silicates present in the heavy and light mineral fractions. These concentrations have been subtracted and reported separately (Poppe et al., 1991b). See Poppe et al. (1991a, 1992) and Commeau et al. (1992) for a more complete discussion of the techniques employed during this study.

The sand fraction (2.0-0.062 mm) from some of the river sediment samples was analyzed for comparison with the silt fraction. The sand heavy- and light-mineral fractions were separated with tetrabromoethane (S.G. 2.96) and a Franz magnetic separator using standard procedures. The minerals were identified with both binocular and petrographic microscopes. Selected grains were examined with a SEM to check the optical identifications.

RESULTS

The concentrations of silt- and sand-sized heavy minerals in the river samples are given in Table 1. These concentrations average 14.6% and 11.9% for the silt and sand fractions, respectively. Although no downstream trends in the total concentration of the heavy-mineral fraction are apparent, the concentrations vary greatly from river to river. For example, concentrations of sand and silt heavy minerals are usually lower in the Rio Indio and Rio Morovis samples. Conversely the concentrations for both the silt- and sand-fraction heavy minerals are consistently greater in the Rio Mavilla sediments.

The individual silt-fraction heavy-mineral species and groups identified in the river sediment samples and their population percents are listed in Table 2. The titanium-bearing minerals, which are common accessory minerals in igneous, hydrothermal, and plutonic rocks, are present in every sample from the study area. Ilmenite (ilmenite and ilmenomagnetite) usually dominates the titanium-bearing minerals, but smaller amounts of the TiO_2 group, which is composed of rutile, anatase, brookite, and leucoxene, and sphene are almost always present. Many of the grains in the TiO_2 group are small (<8 µm), bladed, sometimes twinned, euhedral crystals of rutile; most of the ilmenite grains have corroded surfaces covered with lattices of diagenetic rutile prisms (Fig. 3B,C). Ilmenite is more common in the Rio Grande de Manati than in any of the Rio Cibuco system tributaries (Fig. 4A).

Because the EDS system can not detect oxygen or carbon, the iron oxides and iron carbonates are combined into the hematite+goethite+magnetite+maghemite+siderite group. XRD analyses show that hematite dominates this group in most of the samples from the Rio Cibuco system. Goethite, which is present in minor amounts in every sample, is the most abundant mineral from this group in the sample from the Rio Las Carreras. Small amounts of aluminum present within the iron oxide and iron carbonate group suggest that some of the goethite may be Al-bearing (Mendelovici et al., 1979). Magnetite (Fig. 3D) is also present in every sample and is the most abundant iron oxide in the Rio de la Plata, Rio Morovis, and Rio Grand de Manati sediments. However, broadened shoulders on the higher two-theta-angle side of the magnetite XRD peaks suggests that at least some maghemite may also be present. Siderite occurs only in small amounts (<2%) and only in the downstream samples collected from over the Tertiary carbonate terrane. Mineral grains of the manganese oxide+manganosiderite+ferromanganese group occur in trace amounts in almost half of the river sediment samples. All of the Mn-bearing grains contain at least some iron.

Pyrite, which occurs in the bedrock as vein fillings and along faults (Berryhill, 1965), was the only silt-fraction sulfide mineral detected in any of the samples. This mineral is most common in the samples from the carbonate terrane, where it often occurs in its authigenic framboidal form (Fig. 3E). Pyrite grains from the more oxygenated mountain streams over the igneous terrane are occasionally euhedral (Fig. 3F), but usually rounded, partly altered detrital fragments that exhibit greater Fe/S ratios than normal pyrite suggesting that some conversion to iron oxide has occurred. Although small barium deposits have been described just west of the Rio Grande de Manati (Cox and Briggs, 1973), only one sample from the Rio Cibuco contained traces of barite.

Zircon, corundum, and beryl+topaz, which are common igneous accessory minerals, occur in the silt fraction of most samples from the study area (Fig.5A). Although not positively identified, occasional small peaks in the XRD patterns at 5.54 angstroms suggest that traces of anadalusite, prehaps formed by contact metamorphism, may occur in the beryl+topaz group of some samples. Minor amounts of apatite+vivianite group minerals occur in the silt sediments of the Rio Cibuco, Rio Morovis, and Rio Grande de Manati, but no monazite was detected in any of the river sediment samples.

The silt detrital heavy-mineral suite is dominated by an amphibole-garnet-pyroxene epidote assemblage (Fig. 5B,C). Together, these minerals range in concentration between 45.4% and 76.6% of the samples. The abundances of the minerals in this assemblage, and some of the other silt heavy-mineral species and groups, vary spatially in the study area. The amphiboles and garnets are usually more abundant in the Rio Cibuco system; the pyroxenes andepidote are usually more common in the Rio de la Plata and Rio Grande de Manati (Fig. 4B). Chemical composition of the mineral grains suggests that the main garnet group mineral present is probably almandine.

The Rio Cibuco and Rio Mavilla are the only two rivers with enough sample locations to examine along-stream trends in the silt fraction. Although the data contain substantial variability, some along-stream trends are readily apparent. For example, garnet increases in abundance upstream in the Rio Cibuco (Fig. 4C). Conversely, the highest epidote and amphibole abundances occur downstream and decrease upstream to the south.

Most of the detrital mineral grains have corroded surface textures(Fig. 5B). This corrosion has progressed on many of the mineral grains to the degree where they could not be identified because of their extensive alteration. These altered grains, which range in concentration from 0.88% to 9.12% of the silt heavy fraction, are somewhat rounded and resemble microconcretions that are usually composed of cemented mixtures of Fe, Al, Si, and Ti oxides.

Minerals of obvious commercial importance were specifically targeted during the SEM/AIA/EDS analyses. Chromite, an oxide of iron and chromium, occurs in trace amounts in most of the river sediment samples from the study area (Fig. 5D). Chromite exceeds 1% of the silt heavy-mineral fraction in one sample from the Rio Mavilla and in the sample from Rio Dos Bocas. Most of the samples in this study contained at least a trace of gold. However, flakes of relatively pure gold were found in only two samples. Both samples were from the weathered igneous terrane, one from the Rio Cibuco and one from the Rio Mavilla. These gold particles are 0.6-7.0 µm in diameter. The remaining gold occurred as minute (<0.3 µm) particles intimately associated with much greater amounts of iron oxide and, as such, were sorted into the hematite+goethite+magnetite+maghemite+siderite group during the SEM/AIA/EDS analysis. Silver occurs in the form of cerargyrite and ranges in population percent (relative to numbers of particles rather than weight) up to 2.0% of the heavy-mineral fraction (Fig. 5E). The cerargyrite grains, which are present in 19 of the 25 samples from both the igneous and carbonate terranes, are small, averaging only 0.34 µm in diameter. The high specific gravity of gold and silver makes these finer-grained particles hydraulically equivalent to silt. Because of the small particle size in which they occur, the weight percent of the gold and silver actually present is only about 10% of the value reported as population percent. No mineral grains containing significant concentrations (>1%) of Cu, Ni, Sn, or Zn were detected in any of the samples.

The silt light-mineral fraction in the Rio Cibuco system is dominated by quartz. Most of this quartz undoubtedly originated from the erosion of granodiorites and quartz diorites (Nelson, 1967), but some probably came from the alteration products of weathered glass shards in the tuffs (Berryhill, 1961) and hydrothermally emplaced linings in open fractures (Pease, 1960). Plagioclase, which is always more common than K-feldspar, occurs in amounts greater than, or relatively equal to quartz in the Rio de la Plata and Rio Grand de Manati. The feldspar grains are extensively corroded (Fig. 5F) and, based on XRD analyses, partly replaced by smectite and halloysite (Poppe et al., 1991b). The results of this study are presented on a calcium carbonate-free (calcite+aragonite) basis. Although XRD analyses of the silt light mineral fraction showed that most samples from the

Rio Cibuco system, Rio de la Plata, and Rio Grande de Manati contained very little or no calcium carbonate, the samples from the Rio Indio contained about 3-7% calcite, perhaps suggesting some active down-cutting of the stream bed of that river into the underlying Tertiary limestones.

DISCUSSION

Prolonged rainfall and intermittent dry seasons under the tropical conditions present in north-central Puerto Rico are conducive to lateritic weathering of the mafic source terrane underlying the highland areas near the island divide. Because of these lateritic conditions, the exposed bedrock in the study area and elsewhere along the Central Cordillera (Weaver, 1958) is weathered to a yellowish brown. The silt-fraction minerals present in the Rio Cibuco system and adjacent rivers, like those in the clay (Ehlmann, 1968; Poppe et al., 1991b) and sand fractions, clearly reflect this intense lateritic weathering and several examples are readily apparent. First, the abundance of bladed authigenic rutile crystals and presence of chemically leached ilmenite grains covered with trellis structures of rutile suggest that at least some of the individual rutile grains were probably formed diagenetically during the chemical leaching of Fe from the ilmenite and released transport-related abrasion (Valentine and Commeau, 1990; Poppe et al., 1991a). Second, laterization concentrates Si, Fe, Al, and Ti (Allen, 1948). Altered grains composed almost entirely of the oxides of these elements are common in the silt heavy-mineral fraction. Third, free quartz is only present in small or trace amounts in the source rocks except in the granodiorites of the Morovis and Ciales stocks and the quartz diorites and monzonites where quartz may make up as much as 20-25% of the source rocks (Weaver, 1958; Lidiak, 1965; Fig. 1), and in a few scattered hydrothermally altered zones. The dominance of quartz in the detrital, silt light-mineral fraction and the corroded, altered condition of the remaining feldspars suggests that most of the feldspars are destroyed during the weathering process.

Because of the short, steep nature of the rivers, the along-stream trends observed in the Rio Cibuco (Fig. 4C) are probably not related to preferential sorting. Inasmuch as the Rio Cibuco and its tributaries are rapidly eroding the rocks from at least ten formations, numerous intrusives, and undivided units (Berryhill, 1965; Nelson, 1967), the along-stream trends and the variability within these trends are probably related to dilution due to the increasing distance from an individual source rock and the diversity of the contributing rock types. For example, the silt heavy-mineral fractions from samples 4, 6, and 22 in the Rio Cibuco and sample 20 in the Rio Mavilla have low amphibole/pyroxene ratios due to the underlying clinopyroxene-rich basaltic tuffs of the Los Negros Formation (Nelson, 1967). Sediment samples from just downstream in these rivers contain much higher concentrations of amphiboles due to input from a large, hornblende-rich, quartz diorite intrusive (Nelson, 1967; Fig. 1). Contact metamorphism of the basaltic tuffs during emplacement of the intrusive may also be responsible for the elevated garnet concentrations in these four upstream samples.

Comparisons of the silt-fraction mineralogy with the sand-fraction mineralogies from previously conducted studies and from some preliminary results on the samples collected during this study (Table 3; Fig. 6) suggest that the compositions of these fractions differ markedly. For example, work near the mouth of the Rio de la Plata (Pilkey et al., 1987; Bush et al., 1988) and in beach sands along the northern coast (Guillou and Glass, 1957) found that magnetite makes up 30-40% of the carbonate-free, sand-sized heavy-mineral fraction, but the entire iron oxide+iron carbonate group comprises less than 10% of the Rio de la Plata silt heavy-mineral fraction. Similarly, magnetite comprises 77.4% of the sand heavy-mineral fraction in sample 26 from the Rio Morovis (Table 3), but the silt iron-oxide+iron-carbonate group averages only about 9.3% in this river. Garnet, which averages 24% of the silt heavy-mineral fraction in the river sediment samples, is present only as trace to small amounts (1-15%) in the sand heavy-mineral fraction of the river and beach sediments. Bush et al. (1988) reported that rutile and leucoxene do not constitute any significant percentage of the sand heavy-mineral fraction and analyses of the sand heavy mineral fraction of the river sediments samples from this study revealed similar values. However, the TiO_2 group averages 2.0% of the silt heavy-mineral fraction in the rivers. Ilmenite and altered grains are usually more common in the sand fraction; tourmaline and olivine are more common in the silt fraction.

Minor deposits of gold, silver, copper, manganese, and monazite have been previously reported in the study area (Berryhill, 1965; Nelson, 1967; Meyerhoff, 1933; Cox and Briggs, 1973; Pilkey and Lincoln, 1984; Bush et al., 1988). Most of these deposits are associated with veins and, in the case of some of the gold and all of the monazite, placers.

Most of the gold detected during the SEM/AIA/EDS analyses occurred as very small crystals encrusted with iron oxides. This close association of gold with iron oxides in lateritic environments, which has been previously discussed by Mann (1984), Bhaskara Rao (1987), and Nair et al. (1987), occurs when the gold is dissolved from the parent rocks and is reprecipitated in the weathering crusts. Because of the small, unconcentrated nature of the river sediment samples, the limited quantities of gold detected during this study does not preclude the possibility that deposits of economic value exist. Sample size averaged about 642 g. More complete, accurate numbers could have been generated for gold if the heavy fractions were magnetically concentrated (gold should be found in the least magnetic fraction) and if more grains were analyzed during SEM/AIA/EDS analysis.

The cerargyrite (AgCl or horn silver), which is found in small amounts throughout the study area, was probably formed by the oxidation of argentite (Ag_2S). The universal presence of chlorine in hydrothermal waters, especially in the marine-reworked volcanic sandstones present in the study area, and the insolubility of AgCl make the occurrence of cerargyrite common in the oxidized zones above silver-bearing ore deposits (Lindgren, 1933). However, silver solubility increases under conditions of low Ph, high Eh, and increasing chloride concentration, despite the limited solubility of AgCl, because silver also forms the soluble chloride complexes of $AgCl_2^-$ and $AgCl_3^{-2}$ (Sillen and Martell, 1964; Mann, 1984). Inasmuch as earlier work has shown that the conditions in the highlands are acidic (Norton, 1974) and because the abundance of hematite is evidence for a strongly oxidizing environment, at least the first two conditions are clearly present in the weathered igneous terranes of Puerto Rico. Therefore, much of the silver originally present as secondary mineralization in the eroding hydrothermal vein deposits within the igneous terrane (Hildebrand, 1961) may be mobilized and removed from the source rocks in the dissolved state and not represented in the fluvial sediments. If this is the case, then unweathered veins with commercially significant concentrations of silver may exist at relatively shallow depths in the study area.

Small deposits of copper, which are associated with secondary sulfide mineralization in veins lining fractures, have been reported at thirteen locations in the area drained by the rivers in this study (Cox and Briggs, 1973). Interestingly, no Cu-bearing mineral grains (Cu >1%) were detected in the silt heavy-mineral fraction. Explanations for this absence may include: (1) copper precipitates under surface conditions (higher Eh and pH) as a very minor constituent in the hydrous iron oxides in such small quantities that it is not separately identified, (2) the copper is dissolved during weathering and erosion and not transported in the particulate state, (3) the copper is confined to a different size class (i.e. colloidal or sand), or (4) the sample sites were too far from the sources. However, no copper minerals have been detected in the sand fraction. Because the silver is usually associated with copper (Cox and Briggs, 1973) and because silver was also detected in many of the river sediment samples, one of the first two explanations is most likely correct.

Monazite has been reported in concentrations of as much as 9% of the sand heavy-mineral fraction in samples from the Rio de LaPlata, Rio Cibuco, and northern insular shelf of Puerto Rico (Pilkey and Lincoln, 1984; Bush et al., 1988). However, the absence of monazite in both the sand- and silt-sized river sediment samples from this study and chemical analyses of the sand fraction (D. Bush, Duke University, oral communication, 1991) makes these earlier results highly suspect.

Possible commercial concentrations of the minerals found in the river sediments during this study may occur upstream in eroding veins and shear zones or downstream in placer deposits on the insular shelf. Earlier work has shown that the sand heavy-mineral fraction on northern Puerto Rico's narrow, high-energy shelf is in equilibrium and exhibits strong seaward sorting (Schneidermann et al., 1976; Pilkey and Lincoln, 1984). This sorting is based on the seaward decrease in the energy of wave-driven bottom currents and the specific gravities and characteristic sizes of the heavy-mineral grains. Inasmuch as individual silt-sized heavy-mineral species are also concentrated in narrow zones within shelf environments because of their hydraulic equivalence (Poppe et al., 1991a), a likelihood exists for the occurrence of silt-fraction placers at the mouths of rivers and in ancient shorelines off rivers with upstream fluvial placer and concentrated lode deposits.

SUMMARY

We offer the following conclusions about silt-sized mineral distributions in the rivers of north-central Puerto Rico.

(1) Heavy-mineral concentrations are high in the river sediments and average 14.6% and 11.9 % in the silt and sand fractions, respectively. Comparisons of individual heavy-mineral species and group abundances between the silt and sand fractions reveal marked differences.

(2) The unaltered, detrital silt heavy-mineral fraction in the Rio Cibuco system is dominated by an amphibole-garnet-pyroxene-epidote assemblage. Pyroxenes are more common than amphiboles in the Rio de la Plata and Rio Grande de Manati sediments; ilmenite is most common in the Rio Manati. Along-stream changes in the detrital, silt heavy-mineral fraction are probably related to the underlying, rapidly-eroding source rocks, rather than to sorting.

(3) Lateritic weathering has dramatically altered the silt mineralogy and produced a significant authigenic component. This authigenic component is dominated by iron oxides and altered grains; grains of bladed rutile and leached ilmenite are common. Altered, corroded feldspar grains are a major part of every light-mineral fraction.

(4) Small amounts of silver, chromium, and gold and elevated concentrations of the titanium-bearing minerals occur in the river sediments. However, the potential for fluvial and, presumably, offshore placer mineral resources of other elements is probably limited.

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Side-looking Airborne Radar Mosaic of Puerto Rico

Kathryn M. Scanlon

Introduction

This high-resolution, cartographically accurate side-looking airborne radar (SLAR) image mosaic of Puerto Rico (Fig. 1) was completed in 1987 and is the first of its kind of a Caribbean island. A SLAR image mosaic differs from an aerial photographic mosaic in several important ways. Unlike visible and near-infrared wavelengths, radar energy (at the correct wavelength) can penetrate most clouds, making it an especially useful tool in Puerto Rico, where a persistent cloud cover generally obscures parts of the island. With SLAR, the terrain is illuminated at an oblique angle to enhance subtle geologic structures such as folds and faults. Light and dark areas on the image are caused by high and low radar reflectivity, respectively. For additional information about radar fundamentals and imaging radar systems, see chapters 9 and 10 in the second edition of the 'Manual of Remote Sensing' (Moore, 1983 and Moore and others, 1983).

Technical information

The SLAR digital image data of Puerto Rico were acquired in March 1987 by INTERA Technologies, Inc. (USGS contract 14-08-0001-23065) using the X-band (3.1-cm wavelength) STAR-1 synthetic aperture radar (SAR) system. The SLAR data were acquired in flight lines oriented N. 20 W. at 8,230 m above mean sea level and having a N. 70 E. look direction and average depression angle of 14 degrees (far range). Sections from eleven 46-kilometer-wide image strips were mosaicked and photogrammetrically controlled to the USGS 1:25,000-scale Universal Transverse Mercator (UTM) topographic maps of Puerto Rico. Using the Mini Image Processing System (MIPS) at the USGS laboratory in Woods Hole, Mass., the mosaic was digitized and reprojected at the polyconic projection (central meridian = 67 degrees W., latitude of true scale = 18 degrees N.), used throughout this mineral resource assessment of Puerto Rico. A linear spectral stretch and an edge enhancement filter were also used.

Major features

The most striking lineaments visible in the SLAR mosaic are long northwest-trending ones that cross the southern two-thirds of the island. They represent the surface expression of the Great Southern Puerto Rico Fault Zone (Scanlon and Southworth, 1989). The Utuado Batholith in the west-central part of the island is almost devoid of lineaments, whereas the San Lorenzo Batholith in southeastern Puerto Rico shows lineaments trending north-south and east-west. This lineament pattern is distinctly different from that of the surrounding terrain and may represent fracturing caused by cooling of the intrusive rocks.

The long east-west scarp separating the Tertiary carbonate rocks of northern Puerto Rico from the mountainous central core of volcanic rocks and intrusive granodiorites of Cretaceous and early Tertiary age (Briggs, 1964) is clearly visible in the mosaic. The generally east-west lineaments north of the scarp represent bedding planes and contacts in the limestone. The sinkholes and mogotes of the rugged karst topography in the limestones (Monroe, 1976) are also evident in the SLAR mosaic.

Availability of SLAR data

For precise analysis of the SLAR data, the flight-line strips should be used because these have not been cosmetically altered to produce an attractive mosaic. Some resolution is lost in the process of changing projections, as was done for this publication. The SLAR image mosaic of the main island of Puerto Rico (UTM projection) and unmosaicked strips covering Puerto Rico and all of its satellite islands are available from the USGS EROS Data Center, Sioux Falls, SD 57198.

Lignite and Peat in Northwestern Puerto Rico

By

Jean N. Weaver

U.S. Geological Survey

Table of Contents

Previous studies

Deposits of lignite have long been known to be present in Puerto Rico, but definitive information about the quantity and quality of the resource has been lacking. The earliest reports of lignite being present in Puerto Rico date back to the Spanish regime, when lignite was extracted from a site near Moca to act as a fuel for a Spanish boat returning to Spain (Bureau of Mines, 1941). Subsequent investigations in the late 1800's (Nitze, 1899; Hill, 1899) reported that lignite containing iron pyrites was present in western Puerto Rico. Some of these locations are near the towns of Utuado, Moca, Lares, and San Sebastian (fig. 1).

The largest reported seam was 6 in. thick and the average seam varied between 1 and 2 in. These lignites were high in ash and sulfur contents. Mitchell-Thorre (1954) noted that "... so much pyrite is present that the coal crumbles to powder upon exposure to the atmosphere. Further, the lignites have a high sulfur content and a very low carbon content, so that often the lignite cannot be kept burning. However, in other localities, the lignite contains much less pyrite, more carbon and in places the seams reach a width of 18 in."

In 1980, a project was initiated to assess the oil and gas source rock potential of the North Coast Tertiary basin of the island (Ueng and Larue, 1988) (fig. 2). Drill holes along the north coast and samples from the San Sebastian Formation were collected for analysis. Through Rock Eval pyrolysis, the samples were examined to determine the amount of organic carbon. One interesting aspect of the results was that thin lignite beds appeared much farther east than previously reported (KEWANEE 4CPR well, fig. 2 and fig. 3).

Peat and other organic-rich sedimentary deposits have been previously mentioned in reports and maps. Roberts (1942) delineated peat, muck, and other organic-rich soil units and showed them on maps. Recent mapping of the geologic quadrangles of northwestern Puerto Rico resulted in discriminating organic-rich and peaty sediments as swamp deposits (Monroe, 1963, 1967,1969; Briggs, 1965, 1968). Morris and others (1990) recently stated that noncommercial lignite and peat deposits are present in Puerto Rico.

In 1960, Kewanee Interamerican Oil Company drilled a deep test well (No. 4CPR) that penetrated the post-Eocene strata in northern Puerto Rico. Coal beds were found in the San Sebastian Formation at approximately 4,640 ft, commonly interbedded with calcareous claystones (Briggs, 1961).

In 1980, North American Exploration, Inc, a private drilling company from Charlottesville, Va., initiated an extensive drilling project. Forty-four holes were drilled within the San Sebastian Formation targeting lignite deposits. Results indicated approximately 10 locations where lignite or coaly fragments appeared in the cuttings. A sample collected by North American Exploration, Inc., from an outcrop near Lares showed the following characteristics:

As received:

moisture	33.04 percent
ash	11.72 percent
volatile matter	25.93 percent
fixed carbon	29.31 percent
sulfur	0.63 percent
Btu/lb	5,817

Dry:

Btu/lb	8,687

These data were obtained from, and published with, the consent of Dr. Ramon Alonso Harris, Division de Geología, Departamento de Recursos Naturales, San Juan, Puerto Rico.

Present study

Field investigations guided by available information were conducted in northwestern Puerto Rico along the outcrop belt of the San Sebastian Formation (fig. 4). Coal, coaly claystone, and coaly sandstone were found primarily in roadcut exposures along Puerto Rico route 111. Route 111 generally coincides with the outcrop belt of the San Sebastian in the Utuado, Bayaney, San Sebastian, Central La Plata, and Moca 1:20,000-scale quadrangles. Exposures of coaly material were found at nine different locations along the San Sebastian outcrop belt, but most of the exposures were too weathered to allow detailed, confident interpretation of lithology and thickness or meaningful sample collection. One sample for coal analysis was collected in the Moca quadrangle, and eighteen samples were collected at exposures in an area near the town of Lares, in the San Sebastian and Bayaney quadrangles.

During collection and summation of available information about coaly materials it was found that other organic-rich sediments were also present. Variously termed muck, peat, peat-like, organic-rich, or simply swamp deposits, sedimentary deposits of peaty character had been observed and mapped by both geologists and soil scientists. As an incidental part of the present study, three swamp deposits were visited and samples were collected for analysis.

Geologic setting

The coal-bearing San Sebastian Formation and its partial lateral-equivalent, the Lares Limestone, are within the North Coast Tertiary basin of northwestern Puerto Rico. The San Sebastian and the Lares are of Oligocene age and are overlain by Tertiary and Quaternary sedimentary units, both unconformably overlie folded and faulted rocks of Cretaceous, Paleocene, and Eocene age.

The North Coast Tertiary basin is bounded on the south by the central mountainous spine of the island, which is largely composed of volcanic rocks of Eocene age and older. Sedimentary rocks of equivalent age to the San Sebastian and Lares were deposited south of the central spine but have not been reported to contain coaly materials.

Coal deposits

All of the coal deposits reported on Puerto Rico fall within the San Sebastian Formation. A total of nine locations where coaly and carbonaceous materials could be observed were visited during the field-checking database acquisition part of this study. Most of the locations had been previously reported, but some exposures have been destroyed by construction and agriculture activities and new exposures created by the same type of earth-moving activities. Recent construction of buildings and highways in the area including the town of Lares, for example, created the best, and freshest, exposures of the coal-bearing segments of the San Sebastian.

San Sebastian Formation

The San Sebastian Formation crops out as a narrow band from west of the town of Moca eastward to just south of San Juan (fig. 4). From Moca to the Rio Grande de Arecibo, the San Sebastian Formation is present in an apparently uniform thickness of approximately 738 ft. Subsurface thicknesses from drill holes indicate that the formation increases in thickness to as much as 1,090 ft farther north. Near the Rio Grande de Arecibo, it is locally missing where the Lares Limestone and Cibao Formation have scoured it out. In places between the towns of San Sebastian and Moca, the overlying Lares Limestone intertongues with clastic rocks indistinguishable from the San Sebastian Formation.

Hubbard (1923) described the San Sebastian Formation: "... although it is predominantly shale, it consists in large part of dark bluish clay carrying seams of lignite and pyrite and marcasite, conglomerate and pebble beds, red calcareous sand or lime sand, green marl, and impure limestone." Monroe (1980) elaborated on this description by adding that "... locally the San Sebastian Formation consists of conglomerate, composed of particles ranging from pebbles to boulders, and contains beds of lignite or carbonaceous shale."

Peat and organic-rich sediments

Peat has previously been reported as present on Puerto Rico. During recent geologic quadrangle mapping, many deposits of organic-rich sediments were identified in areas adjacent to the present-day north coast of Puerto Rico. Several of these organic-rich deposits were visited and sampled during this study.

Modern coastal sediments

Deposits of organic-rich sediments mapped as swamp deposits are shown on geologic maps along the coast of northwestern Puerto Rico. The swamp deposits have been variously described as "... nearly black carbonaceous muck, muck of which rests on a layer of black stringy peat..." (Monroe, 1962); and "... sandy, organic muck and peat associated with mangrove swamps..." (Monroe, 1967). Briggs (1965 and 1968) recognized two types of swamp deposits: "Clay, sandy clay, and silty clay--commonly with high organic content--" and "... peat and peaty muck..." and discriminated the two types in mapped units.

Three different soil units discriminated by Roberts (1942) were sampled as an incidental part of the present study. All three sample localities are in areas mapped as swamp deposits by Monroe (1963, 1967, 1969). All three samples were collected in mangrove swamps, two of that are landward of barrier sand dunes. The other sample locality is in a mangrove swamp on a river flood plain.

Coal

Coal is a solid fossil fuel formed from plant-derived organic remains along with nonorganic minerals. The organic components of coal constitute the combustible part. In order to consider this material coal and not rock, the organic components should constitute more than 50 percent dry weight and 70 percent by volume of the rock.

Grossling (1981) classed solid fossil fuels by the amount of fixed carbon present, ranging from peat (29 percent), lignite, subituminous coal, bituminous coal, to anthracite (95 percent). This increase of the fixed carbon, which happens during coalification, is one basis for characterizing rank.

Coalification implies the increasing of the fixed carbon content, generally increasing the calorific value and is associated with a decrease in the volatile matter and the hydrogen and oxygen content. The calorific value increase of a coal is of particular interest and importance when one views coal as a source of fuel. Although the source vegetable matter across the seam may vary, the coalification process leads to essentially coal of one rank throughout the seam.

Field work

Field studies were conducted during February 1991. Coaly materials were found at nine different locations along the outcrop belt of the San Sebastian Formation between the towns of Lares and Moca (table 1, fig. 2).

Samples were collected at one locality near Moca and four locations in the town of Lares. A total of nineteen samples were collected and submitted for standard coal analyses, and for major, minor, and trace element analyses (table 2 and table 3). Samples were not collected at the other four localities because the coaly materials were too thin and (or) too badly weathered and oxidized.

Figure 4 shows the areal relations of the localities where samples were collected to the outcrop belt of the San Sebastian Formation. In most places in the outcrop belt, the softer, more easily weathered parts of the San Sebastian are weathered, concealed by vegetation, and covered by slumped younger roc in most areas the lateral extent, lithologic character, geometric characteristics, and correlation of coal-bearing segments are unclear or undetermined.

Figure 5 shows the sequence of rocks of the San Sebastian Formation exposed in the Lares area. As the diagram shows, individual thin beds of coal are not laterally continuous. However, sequences of coaly rocks herein designated as zones 1, 2, and 3 are correlated between the four localities. The maximum zone thickness shown is 4.5 ft, and the thickest coal bed within any zone is 1.3 ft. The exposures shown in figure 5 owe their condition to recent construction activities and are the freshest found during this study. Figure 6 presents a more detailed view of the coal zones found in the Lares area and indicates graphically the sequence represented by different samples that were collected for analysis.

Analytical results

The standard coal analyses and other related determinations were performed by Geochemical Testing, Inc., of Somerset, Penn., under contract to the USGS. The results for northwestern Puerto Rico are presented in table 2. The standard coal analyses include proximate and ultimate analyses, heat of combustion, forms of sulfur, free-swelling index, ash-fusion temperature and Hardgrove grindability index determinations. Proximate analysis data for coal (moisture, ash, volatile matter, fixed carbon) are used as indicators of coal quality, to classify coal, to determine the market value of the coal, and as a guide to furnace design (Schweinfurth and others, 1990). The ultimate analysis determines the hydrogen, carbon, nitrogen, oxygen, and sulfur contents of the coal. The major, minor, and trace-element analyses were performed by USGS analytical laboratories in Reston, Va. (table 3). Major elements are defined as those present in concentrations exceeding 0.5 percent (5,000 ppm), minor elements in concentrations from 0.02 to 0.5 percent, and trace elements as less than 0.02 percent (200 ppm). Table 4 summarizes the proximate and ultimate analyses statistically for 19 coal samples. The results of proximate and ultimate analyses indicate ranges of physical and chemical characteristics that are useful in making broad estimates of the behavior of coal in mining, preparation, and utilization (American Society for Testing and Materials, 1986, 1988, 1992).

Classification of coals by rank, that is according to their degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite, is necessary for gross predictions of potential for utilization and for informed planning for extraction, transport, storage, preparation, and use. In low-rank coals, such as those in Puerto Rico, classification by rank is based on the moist, mineral-matter-free heat value stated in British thermal units (Btu) per pound. The apparent rank of the Puerto Rico coals is lignite B.

Classification of coals by grade is based upon the amount of recognized noncombustible constituents present in the coal. A high moisture content compromises the cost benefits of using such coals as a fuel because part of the heat is used to evaporate the moisture. The Puerto Rican coal samples range from 1.1 to 30.3 percent in moisture, the content averaging about 29 percent. The ash content of Puerto Rican coal samples ranges from 1.2 to 48.8 percent and averages about 43 percent. Coals containing more than 15 percent ash are categorized as having a high ash content (Wood and others, 1983). High-ash coals require considerations such as particular boiler designs and ash-disposal plans. The sulfur content of the Puerto Rican coal samples ranges from 0.87 to 5.7 percent and averages about 4.2 percent. Such coals are categorized as high sulfur content and require special handling and technology to prevent atmospheric pollution during combustion by release of sulfur oxides.

The arsenic analyses were performed on a whole-coal basis by neutron activation analysis. Average arsenic value (500 ppm) and selenium (3.9 ppm) contents of the Puerto Rican coals exceed the average amount of these elements (13 and 0.6 ppm, respectively) in the average shale of the world (Turekian and Wedepohl, 1961). In comparison, lignitic coals of Texas and Louisiana contain as little as 4 ppm of arsenic and 5 ppm selenium (Oman and Meissner, 1987). Many of the elements present in major and minor concentrations are largely found in the inorganic residue (mineral matter or ash) produced during combustion of the coaly material. These elements are by custom reported as oxides (table 5). The oxide composition of coal ash may be used in conjunction with tests such as ash-fusibility determinations to assist in predicting the slagging and fouling behaviour of coals during combustion. They are important environmentally also; for example, the amount of CaO in a coal determines the amount of limestone required in a fluidized bed combustion system to reduce sulfur emissions.

In common practice, the ash remaining after controlled combustion of coal samples is analyzed by standard chemical methods for as many as 47 elements (Turekian and Wedepohl, 1961). The elements Si, Al, Ca, Mg, Na, Fe, Ti, P, and S are reported on the oxide basis in percent. The remainder of the determined elements are reported in parts per million.

The reported oxide composition of the ash could be used in conjunction with such tests as ash-fusibility determinations and with a wide variety of largely empirical formulas to assist in explaining and predicting the behavior of coals during combustion and conversion. Regarding the composition of whole coal, as many as 25 minor trace elements are determined in the whole coal and, as previously stated, are reported on a whole-coal basis. Some are determined in this manner because of the particular analytical technique in use. Vast amounts of research have been done on the elemental assemblage of coals, especially on the forms in which the elements are present and the relationship of the resulting information to problems during utilization and (or) the possibilities of recovery of valuable byproducts (Gluskoter and others, 1981).

Resource estimates

Knowledge of a Nation's coal resources is important in planning for the exportation and importation of fuel. A detailed resource classification accomplishes the following factors: (1) identifies deposits of coal based on location, (2) distance from points of information, (3) thickness of coal and overburden, (4) rank and quality, and finally, (5) estimates of quantity (Wood and others, 1983).

The estimates of coal resources presented here were made in accordance with procedures presented by Wood and others (1983), in USGS Circular 891 "Coal Resource Classification System of the U.S. Geological Survey." Criteria used to calculate the resources of the Lares coal area are as shown in table 6.

Figure 4 shows the location of Lares 1, 2, 3, and 4 measured sections (fig. 5, fig. 6, fig. 7) along with the drill holes from the North American Exploration, Inc., drill program of 1980. Table 7 shows the areas that were delineated and the classification of those areas according to bed thickness, estimation reliability, and overburden thickness used in the calculations. Measured and indicated estimates appear in table 8, and inferred estimates are in table 9. Total resource estimates are summarized in table 10.

Depositional interpretation

The San Sebastian Formation is conformably overlain by the Lares Limestone at most places and is laterally equivalent in part to the Lares in some areas. The coal zones in the Lares coal area are closely associated with beds containing marine fossils (fig. 5 and fig. 6). Marine fossils are found in most of the sandstone units associated with the coal beds in the Lares area. In some cases, borings made by marine organisms are visible within the sandstone units. These associated sandstone bodies, which are very fine grained and friable, closely resemble sand deposits of a modern beach or offshore bar. In contrast, most of the part of the San Sebastian Formation below the coal zones in the Lares area is nonmarine. The thick red-bed sequence at the base of Lares #1 exposure represents an alluvial plain that filled some of the lowlands eroded on the Cretaceous through Eocene basement rock (Frost and others, 1983). These outcrops are good examples of the transition from nonmarine to marine environments (fig. 8).

The presence of marine fossils associated with coal zones, coupled with burrowed sandstone units, infers that the lignites were deposited in low-lying, brackish-paralic environments on the broad coastal shelf of the island. The low-lying areas developed into swamps, commonly brackish in nature due to periodic rise of sea level. Palynology of the coals indicates the presence of Rhysophor-type (mangrove) pollen, and fungal spores (Habib, 1971).

The mangrove swamps probably never existed undisturbed for a sufficient period of time to result in bodies of peat thick enough to create thick coal beds. The thin, cyclic, poorly developed coals of the San Sebastian in the Lares area reflect the transient nature of the paralic environments in which they were deposited. Coals having high ash and sulfur contents are common in the depositional environment just described. For example, many of the coals in the lower portion of the Dakota Sandstone in southwestern Colorado, northwestern New Mexico, and northeastern Arizona are high-ash, high-sulfur coals. The high ash is usually due to the interfingering of organic-rich and organic-poor layers. Coals having high sulfur contents have commonly been subjected to marine influences (Landis, oral commun., 1992).

Peat

Peat is an inorganic material that develops as a result of the incomplete decomposition of wetland vegetation under conditions of excess moisture and oxygen deficiency. Organic matter accumulates when the rate of production exceeds that of degradation. Peat is defined as having 25 percent or less of ash and more than 75 percent of organic matter on a dry basis (fig. 9; Andrejko and others, 1983). Peat has long been used in the horticulture and agriculture sectors. The accumulation of organic matter is sometimes large, implying economic reserves that can be utilized for energy and agriculture (Chateauneuf and others, 1991).

Field work

Eight samples of peaty, organic-rich sediment were collected at three mangrove sites along the north coast of the island (fig. 4). All three sites are in present-day mangrove swamps. The Isabela and Punta Maracayo locations are both back-barrier beach deposits; the Quebradillas location could be considered an open (?) coastal estuary. The geologic maps that include the sample sites (Monroe, 1963, 1967, 1969) show the mapped swamp deposits to be as much as 5 m thick. Because collection of peaty materials was prior to initiation of fieldwork, samples were collected in a primitive fashion, using a 15-in. piece of 2-in. PVC tubing. Consequently, all samples represent only the uppermost part of the swamp deposits at each site.

Sample descriptions:

Isabela #1.

Sampled 3 in. from water edge; 12-in. core; sandy and dark brown; strong H_2S (?) odor.

Isabela #2.

Sampled 4 ft from Isabela #1; water 3 in. deep at sample locality; sandy, dark brown; strong H_2S odor.

Isabela #3.

Sampled 100 m west of Isabela #2; 4 ft into the swamp; 6 in. core. Water is brownish-red but clear. Sample was sandy and dark brown.

Isabela #4.

Sampled 15 ft from Isabela #2; 10 ft farther into swamp from Isabela #2. Water is 6 in. deep, and area is clear of roots. Sample was sandy and contains soft wood fragments; more organic material was present than in previous three samples.

Quebradillas #1.

Sampled 3 ft from shoreline. 6-in. core in 3 in. of brackish water. Sample was very sandy.

Quebradillas #2.

Sampled 2 ft from shore near mangroves. 3-in. in 1 ft of water. Sample was sandy, snails and shells were present along with twigs, rootlets, and woody material. Sample was darker in color than in previous Quebradillas #1 sample.

Punta Maracayo #1.

Sampled in red mangrove swamp; 4-in. sandy core, organic-rich. Strong H_2S odor.

Punta Maracayo #2.

Sampled in red mangrove swamp; 8-in. sandy, dark-brown, clayey, organic-rich (twigs, stems).

Sample analyses

From each sample bag, enough material was taken to obtain >20 g of wet sample. The wet samples were dried in evaporation dishes for 24 hours at 105? C. Moisture was calculated as weight in percent (that is, weight lost during drying/weight of wet sample).

The dry samples were converted to ash in a muffle furnace by raising the temperature to 550? C over 3 hours and maintaining at 550? C for 16 hours. Ash yield was then calculated as weight percent of sample after ashing/weight of dry sample before ashing.

Results of moisture and ash determinations are shown in figure 10 and table 11. The samples all had significant quantities of mineral matter, apparent to the touch when the sample was rubbed between the fingers. The moisture content ranged from 25 to 54 percent (fig. 10). The ash percentage ranged from 85 to 96 percent. After ashing, the samples appeared to be fairly coarse reddish sediments and several contained shells and shell fragments (Neuzil, S., written commun., 1991).

As expected, because of the type of available sampling equipment, none of the samples represented more than the surficial layers of the swamp deposits. None of the samples qualified as peat because of the large percentage of inorganic material, and no other characteristics, such as heat value, were determined. Both the observed depositional settings of the samples and available literature indicate that peat could be present under some, or many, of the present-day swampy areas in Puerto Rico. The purpose of the analyses presented here is to introduce the procedures used (in simplistic terms) and to emphasize that peat should still be considered as a potential resource for energy and other purposes. Further investigations and sampling programs would be needed to properly assess the peat resource potential of Puerto Rico.

The deposits accumulating now in and around mangrove swamps along the north coast of Puerto Rico are in many ways present-day analogs to the coaly sequences in the San Sebastian Formation. The size and shape of the coals and carbonaceous shale beds, the lithology and minor characteristics of the associated sandstone and finer clastic beds, and the type of plant debris accumulated to form organic-rich sediments are similar.

Conclusions

Coals and closely related rocks such as coaly shale, coaly sandstone, and carbonaceous shale and sandstone are present in the San Sebastian Formation of Oligocene age in many places in northwestern Puerto Rico.

The San Sebastian is the basal unit of a generally transgressive rock sequence of middle and late Tertiary age that occupies the North Coast Tertiary structural basin. The rocks included in the San Sebastian were deposited in near-shore fluvial, paralic, and shallow-water marine environments. The different environments impinged upon and replaced each other in short-term transitions typical of those observable under present-day coastal conditions. The coaly deposits in the San Sebastian reflect their depositional history in their external size and shape and their internal physical and chemical characteristics.

Coaly sequences were examined at nine different locations and sampled at five locations. However, only four of the locations could be used to derive a representative understanding of the resource. All four locations are recent exposures of the coaly part of the San Sebastian in an area that includes the town of Lares. Information gathered in the present study was supplemented by data from five previously drilled exploration wells. Resource estimates for coal beds more than 0.3 m thick, almost all overlaid by less than 150 m of overburden, total about 1.5 million tons. All of the resources fall in the subeconomic class because they are too thin to be economically mined at present. The coal is of lignite B rank and is classed as high-ash and high-sulfur grade. The potential for peat deposits in Puerto Rico cannot be evaluated with presently available information.

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Figures:

Figure 1: Side-looking airborne radar (SLAR) mosaic of Puerto Rico. Scale: 1:200,000; Projection: Polyconic.

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