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Puerto Rico Mineral Resource Assessment

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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. The Keystone Mine (site 85) was developed as an open pit, which, in combination with the Island 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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