Descriptive and Grade-Tonnage Models of Volcanogenic Manganese Deposits in Oceanic Environments—a Modification

By DAN L. MOSIER and NORMAN J PAGE

A characterization of four types of
submarine volcanogenic manganese deposits,
based on descriptive and grade-tonnage
models for such deposits in the
Franciscan Complex of California,
Cuba, the Olympic Peninsula, and Cyprus

U.S. GEOLOGICAL SURVEY BULLETIN 1811

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Mosier, Dan L.
Descriptive and grade-tonnage models of volcanogenic manganese deposits in oceanic environments—a modification.

(U.S. Geological Survey Bulletin 1811)
Bibliography: p.
Supt. of Docs. no.: I 19.3:1811
1. Manganese ores. I. Page, Norman J, 1939– . II. Title.
III. Series: United States. Geological Survey. Bulletin 1811.
QE75.B9 no. 1811 557.3s 87–600462
[TN490.M3] [553.4'629'09162]

CONTENTS

Abstract 1
Introduction 1
  Acknowledgments 2
Methodology 2
Manganese models 3
  Franciscan type 4
  Cuban type 5
  Olympic Peninsula type 10
  Cyprus type 12
Comparison of models by properties 12
  Mineralogy 12
  Host rock 16
  Shape, dimensions, and volume 16
  Tonnage 16
  Grade 16
  Contained metal 16
  Mineral-deposit density 16
Application of the models and constraints on genetic models 16
References cited 18

FIGURES

1. Plots of median inplace and shipping manganese grades, and of inplace versus shipping manganese grade, for Franciscan-, Cuban-, and Olympic Peninsula-type deposits 3
2. Schematic illustration of original tectonic settings of four types of submarine volcanogenic manganese deposits 4
3. Generalized model of a Franciscan-type deposit 4
4. Diagram comparing median length, width, and thickness for volcanogenic manganese deposits by region and type 6
5. Plot of cumulative frequency of tonnages for Franciscan-type deposits 7
6. Plot of cumulative frequency of Mn grades for Franciscan-type deposits 8
7. Diagram showing median volumes and the 95-percent-confidence intervals for four types of volcanogenic manganese deposits 8
8. Generalized model of a Cuban-type deposit 10
9. Plot of cumulative frequency of tonnages for Cuban-type deposits 11
10. Plot of cumulative frequency of Mn grades for Cuban-type deposits 11
11. Generalized model of an Olympic Peninsula-type deposit 12
12. Plot of cumulative frequency of tonnages for Olympic Peninsula-type deposits 13
13. Plot of cumulative frequency of Mn grades for Olympic Peninsula-type deposits 13
14. Generalized model of a Cyprus-type deposit 14
15-19. Plot of:
  15. Cumulative frequency of tonnages for Cyprus-type deposits 14
  16. Cumulative frequency of Mn grades for Cyprus-type deposits 15
  17. Cumulative frequency of Fe grades for Cyprus-type deposits 15
  18. Cumulative frequency of tonnages and median tonnages for four types of volcanogenic manganese deposits 17
  19. Cumulative frequency of Mn grades and median Mn grades for four types of volcanogenic manganese deposits 17

20. Diagram showing mean Fe grades and 95-percent-confidence intervals for four types of volcanogenic manganese deposits **18**
21. Diagram showing median contained manganese metal and 95-percent-confidence intervals for four types of volcanogenic manganese deposits **18**

TABLES

1. Abundances of manganese minerals, in order of median rank **5**
2. Frequencies and percentages of host-rock types in the four types of volcanogenic manganese deposits **6**
3. Median values for dimensional extent and volume of ore bodies by region and deposit type **7**
4. Mineral-deposit densities of volcanogenic manganese deposits by rock unit and region **9**
5. Information level and geologic, geochemical, and geophysical characteristics of volcanogenic manganese deposits **19**

APPENDIXES

A. Franciscan-type volcanogenic manganese deposits **25**
B. Cuban-type volcanogenic manganese deposits **26**
C. Olympic Peninsula-type volcanogenic manganese deposits **27**
D. Cyprus-type volcanogenic manganese deposits **28**

Descriptive and Grade-Tonnage Models of Volcanogenic Manganese Deposits in Oceanic Environments—a Modification

By Dan L. Mosier *and* Norman J Page

Abstract

Four types of volcanogenic manganese deposits, distinguished on the basis of geologic, geochemical, and geophysical characteristics, appear to result from a combination of volcanic and hydrothermal processes related to hot-spring activity in oceanic environments. We compare these four deposit types, here called Franciscan, Cuban, Olympic Peninsula, and Cyprus, with respect to host rocks, associated rocks, minerals, deposit shape, dimensions, volume, tonnage, grade, and mineral-deposit density (number of deposits per unit area).

Franciscan-type deposits occur in obducted oceanic ridge and backarc marginal-basin environments, are associated with chert, shale, and graywacke around the margins of mafic volcanic centers, and have a median tonnage of 450 t and median grades of 36 weight percent Mn and less than 5.1 weight percent Fe. Cuban-type deposits occur in island-arc environments, are associated with tuff and limestone around domal structures or intrusions inferred to be volcanic centers, and have a median tonnage of 6,400 t and median grades of 39 weight percent Mn and less than 4.4 weight percent Fe. Olympic Peninsula-type deposits occur in obducted oceanic midplate settings, are associated with argillaceous limestone, argillite, and graywacke around mafic volcanic centers (seamounts or islands), and have a median tonnage of 340 t and median grades of 35 weight percent Mn and less than 6.5 weight percent Fe. Cyprus-type deposits occur in the same tectonic environments as Franciscan type but are associated with basalt, marl, chalk, silt, and chert off the ridge-axis position and have a median tonnage of 41,000 t and median grades of 33 weight percent Fe and 8 weight percent Mn. All these deposits are thin ellipsoids, concordant to the host rocks, but Cyprus- and Cuban-type deposits are larger than Franciscan- and Olympic Peninsula-type deposits. Except for Cyprus-type deposits, which are manganiferous iron (umber) deposits composed of hydrated iron and manganese oxides, all volcanogenic manganese deposits contain manganese oxides, silicates, and carbonates.

Mineral-deposit densities, along with grade and tonnage information, are useful for estimating the number, size, and grades of these deposits in resource assessments.

INTRODUCTION

This investigation modifies the descriptive (Koski, 1986) and grade-tonnage (Mosier, 1986) models for volcanogenic manganese deposits formed on the sea floor. The original descriptive model represents deposits varying in geologic characteristics, and the original grade-tonnage model yields a median tonnage (47,000 t) and median grade (42 weight weight weight percent Mn) that may not be indicative of those for deposits with similar geologic attributes in particular tectonic environments, such as a midoceanic ridge. In this report, we differentiate volcanogenic manganese deposits on the basis of geologic characteristics and lithotectonic environments, and from these observations, we develop new models that may represent more accurately the different types of deposits and that may be applicable to resource assessment and exploration. We propose four types of submarine volcanogenic manganese deposits and compare them with respect to tonnage, grade, size, shape, volume, mineralogy, host rocks, associated rocks, and mineral-deposit density (number of deposits per unit area). For each deposit type, on the basis of the criteria in the descriptive model, we present grade and tonnage models, as well as mineral-deposit densities, for quantitative, probabilistic resource estimations.

Volcanogenic manganese deposits consist of stratabound lenses of manganese oxides, silicates, and carbonates in volcanic-sedimentary sequences. Manganese ore bodies may have either a proximal or a distal relation to volcanic rocks. Beneath the lenses, the rocks may be altered to clay, chlorite, and zeolite, and veined by quartz, calcite, barite, hematite, and manganese minerals. The genetic implication is that these deposits are formed by hydrothermal solutions emanating from ocean-floor vents as a result of volcanic processes. Taliaferro and Hudson (1943) suggested that the manganese deposits found in chert and basalt of the Franciscan Complex, Calif., were derived from submarine hydrothermal activity, similar to the processes occurring at oceanic spreading centers. Recently, these deposits have been compared to the hydrothermal mounds actively forming at oceanic ridges (Snyder, 1978; Namson and others, 1981; Crerar and others, 1982). A similar origin has been proposed for the manganese deposits associated with limestone and tuff formed in an island-arc environment in the Oriente Province, Cuba (Park, 1942; Simon and Straczek, 1958; Mitchell and Bell, 1973); for the deposits associated with basaltic seamounts in the Olympic Peninsula, Wash. (Park, 1942; Cady, 1975); and for the manganiferous iron deposits in pillow basalt, derived from an oceanic ridge, in Cyprus (Gass, 1968; Elderfield and others, 1972). Because of detailed geologic studies in these four areas, we have chosen these deposits to represent four models of volcanogenic manganese deposits formed in oceanic environments.

Acknowledgments

We thank Donald A. Singer and James D. Bliss, both of the U.S. Geological Survey, for discussions on some of the analytical techniques used in this report; Gary B. Sidder, Ted G. Theodore, and George A. Havach, all of the U.S. Geological Survey, for their helpful suggestions; and Andreas Panayiotou of the Geological Survey Department, Cyprus, for valuable information on the manganese deposits of Cyprus.

METHODOLOGY

Submarine volcanogenic manganese deposits were assigned to one of four types, here called Franciscan, Cuban, Olympic Peninsula, and Cyprus (hereafter for brevity referred to in this report as "Franciscan deposits," "Cuban deposits," "Olympic Peninsula deposits," and "Cyprus deposits"), named from the type locality that best represents each model. Franciscan deposits occur in chert associated with basalt derived from midoceanic ridges. Cuban deposits occur in pyroclastic rocks derived from island-arc volcanism. Olympic Peninsula deposits occur in limestone and basalt that are present as seamounts in midplate settings. Cyprus deposits are umbers associated with basalt, clay, marl, and chert on the flanks of midoceanic ridges.

The method of collecting and grouping the data used in this report follows that outlined by Cox and Singer (1986). First, the descriptive (and genetic) models for submarine volcanogenic manganese deposits were made by describing the attributes of deposits occurring in distinct lithotectonic environments. Second, the grade-tonnage models were made for each of the deposit types, and those characteristics were compared. Third, other quantitative properties, such as size, shape, mineralogy, host rock, and mineral-deposit density, were analyzed for differences.

Data extracted from the literature were tabulated under the following headings: name, length, width, thickness, volume, tonnage, grade, minerals, geologic environment, and comments. A total of 913 deposits were classified into the four deposit types. Care was taken to include deposits from regions where the lithologic and tectonic environments are well established; these data are currently being compiled.

The term "deposit" refers to a single lens or bed of manganese ore as it presently occurs. For example, a bed or lens separated completely by a fault was counted as two deposits. However, where tiny pods or nodules are closely strung out along a bed, or thin bands of ore and rock alternate, these materials were considered collectively as a single deposit. The number of pits, open cuts, or underground workings generally indicates the number of deposits present. Deposits considered to be float or in a landslide were excluded from the final analysis.

Dimensional properties of deposits were either taken directly from previous reports or measured from maps. "Length" refers to the maximum dimension of the ore body, "width" to the intermediate dimension, and "thickness" to the minimum dimension. We used maximum values for lengths and widths, and average values for thicknesses; however, for some deposits, we utilized maximum values for thicknesses when average values could not be determined. Deposit volumes represent ellipsoids (in cubic meters). Tonnage is the total premining weight (in metric tons) of the deposit, including either inplace reserves or production plus inplace reserves after production. Owing to the availability of the data, only production or shipping ore is reported for some deposits; such data tend to cause an underestimate of the mean tonnage. Grades for manganese and iron include the average inplace grade of the deposit, the shipping grade (generally more than 37 weight percent Mn), or the analytical grade of grab or chip samples. Shipping and analytical grades are used only in the absence of average deposit grades; such data tend to cause an overestimate of the average grade of the deposit (fig. 1).

For each mine reported, the number of deposits was determined. For some deposits, individual ore bodies were reported, giving the dimensions, tonnage, and average manganese grade (by production and reserves); for others, these parameters had to be estimated from less detailed descriptions. Where estimates were not possible, those variables were left blank in the tabulation. Also, for each deposit, host rock and mineralogy were determined from the literature. No assumptions concerning host rock or mineralogy were made; if these parameters were not reported, they were left blank in the tabulation.

The tonnage, grade, volume, length, width, and thickness data for the four deposit types were tested for differences (at the 5-percent-confidence level), using the analysis-of-variance F-ratio test. Comparative diagrams were made for the logarithms of volume, length, width, and thickness, and for the arithmetic values of iron grade, showing the median values and the 95-percent-confidence intervals for each deposit type. Inverse cumulative-frequency plots for tonnage, manganese grade, and iron grade were constructed, using the method of Singer (1975, 1984). The horizontal axis shows these variables, while the vertical axis shows the cumulative proportion of deposits. A logarithmic scale is used for tonnages, and an arithmetic scale for grades. Each dot represents one deposit, cumulated inversely in ascending order. Smooth curves are plotted through the points, and intercepts of the 10th, 50th, and 90th percentiles are drawn. These smooth curves represent percentiles of a log-normal distribution (except for grades) that have the same mean and standard deviation as the observed data. For ease of comparison among deposit types, the cumulative-frequency plots for each variable for all types are shown on a single diagram.

Host rocks for each deposit type were tested for frequency of occurrence. A single rock type hosting a deposit was counted as one. If more than one rock type hosts a deposit, each type was counted as a fraction of the total number of rock types hosting the deposit. The counts of each rock type then were summed to give the frequency of the host-rock occurrence in each deposit type. A special test was made for Franciscan-type deposits in California to see whether proximity to greenstone is significant. The deposits were assigned to two groups, on the basis of whether or not greenstone crops out within 1,600 m of the deposit.

Mineralogy was tested for the frequency of occurrence of mineral assemblages in deposits and for the relative abundance of individual minerals. In the first test, mineral assemblages were counted and categorized into the following groups: oxides (hydroxides), carbonate-oxides, silicate-oxides, carbonate-silicate-oxides, and Fe-Mn material. The counts for each group were then converted into percentages. In the second test, individual minerals were ordered according to their relative abundance in each deposit, using the method of Bliss (in press). This test was done only for those regions where the order of abundance of the minerals is reasonably well known. For each mineral, individual ranks were summed, and a median rank was calculated.

Mineral-deposit density is defined as the number of deposits per unit area. Using the method of Bliss and others (1986), deposit densities were determined for those regions where exploration has been extensive, where the locations of deposits are known, and where detailed geologic maps of an appropriate scale are available. A closely spaced net of gridlines was placed over the geologic map, and only the rock unit containing deposits was point-counted to determine the area (in square kilometers). The total number of deposits was divided by this area to give the mineral-deposit density (in number of deposits per square kilometer). Calculated for a deposit type, this value can be used to estimate the number of undiscovered deposits expected within a given unexplored area, assuming that the unexplored area is permissive for such deposits and geologically similar to that described for the deposit type.

MANGANESE MODELS

The characteristics of each of the four types of volcanogenic manganese deposits are discussed below. Generally, these four types occur in different depositional environments (fig. 2), and each type shows particular characteristics, whether in petrography, mineralogy, size, or shape. Both Franciscan and Cyprus deposits are believed to have formed on the ocean floor at the rock-seawater interface by solutions emanating from fractures at or near a midoceanic ridge or in a rifted basin. Olympic Peninsula deposits formed similarly on or around seamounts in an ocean basin. Cuban deposits are associated with felsic to intermediate island-arc volcanic rocks and are thought to have formed from sea-floor hot springs in a shallow marine environment.

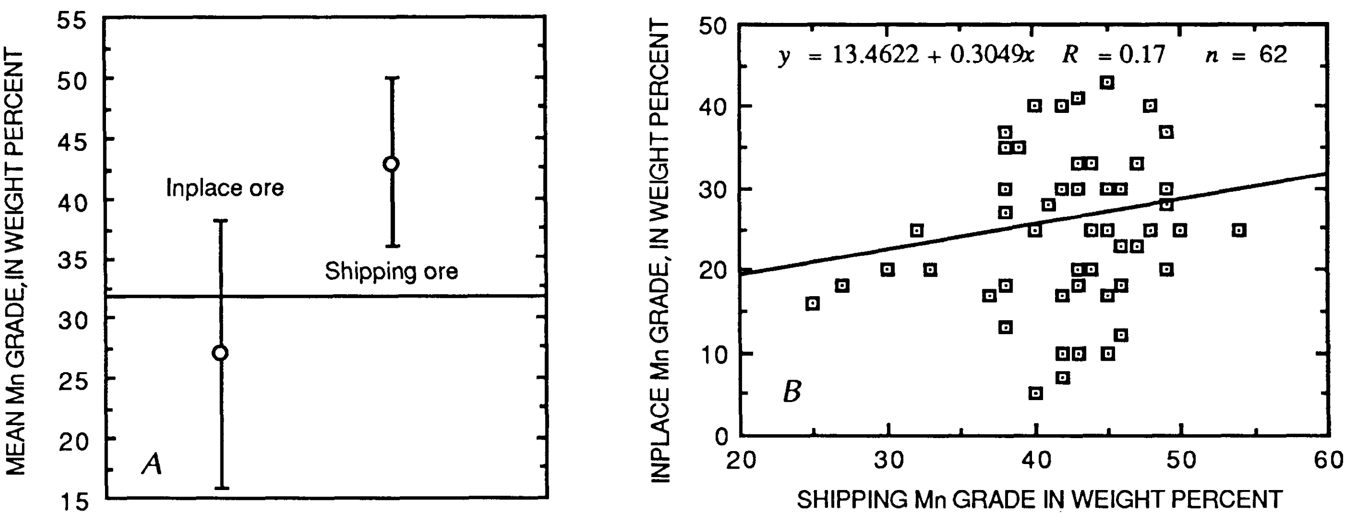

Figure 1. Ranges of manganese grade for inplace and shipping ore (*A*), and inplace versus shipping manganese grade for Franciscan-, Cuban-, and Olympic Peninsula-type deposits (*B*). Horizontal line in figure 1*A* is overall mean for both types of ore; circles are the means for both types of ore; error bars, 1σ. Sloping line in figure 1*B* is curve of best fit to data points, described by equation. *n*, number of data points; *R*, correlation coefficient.

Franciscan Type

The manganese deposits occurring in the Franciscan Complex of the Coast Ranges, Calif., best represents the Franciscan type. These deposits are commonly hosted in massive or thin-bedded chert with or without shale partings, and range in age from Paleozoic to Tertiary. The ore deposits are generally thin, elliptical bodies, concordant with bedding, and composed of massive and disseminated psilomelane, pyrolusite, rhodochrosite, hausmannite (Mn_3O_4), braunite ($3Mn_2O_3 \cdot MnSiO_3$), neotocite ($MnSiO_3 \cdot H_2O$), and other minor manganese oxides and silicates. Colloform and botryoidal shapes are common. Near the surface, the primary carbonates and silicates are commonly altered either partially or completely to oxides. In some deposits, manganese carbonates and silicates, as well as quartz, calcite, aragonite, and barite, occur in fractures and breccias beneath the main ore body. Some deposits have been metamorphosed to greenschist facies (Trask and others, 1943). Franciscan deposits are found in California, Oregon, Nevada, Japan, New Zealand, Australia, the Philippines, Costa Rica, Malaysia, New Caledonia, Yugoslavia, Afghanistan, Pakistan, and elsewhere in Europe and Asia. Appendix A contains a descriptive model for Franciscan deposits in the form of Cox and Singer (1986). Associated with the chert are mafic volcanic rocks (greenstone), tuff, serpentine, and graywacke. A generalized model based on the data of Crerar and others (1982) is shown in figure 3.

Mineralogy.—In the Franciscan Complex of the California Coast Ranges, the predominant manganese minerals are psilomelane, rhodochrosite, pyrolusite, neotocite, hausmannite, braunite, and bementite [$Mn_8Si_6O_{15}(OH)_{10}$] (table 1). Assemblages of only manganese oxides occur in 70 percent of these deposits, followed by carbonate-silicate-oxide assemblages (14 percent), carbonate-oxide assemblages (10 percent), and silicate-oxide assemblages (4 percent). A typical manganese oxide assemblage is psilomelane, pyrolusite, wad, and other

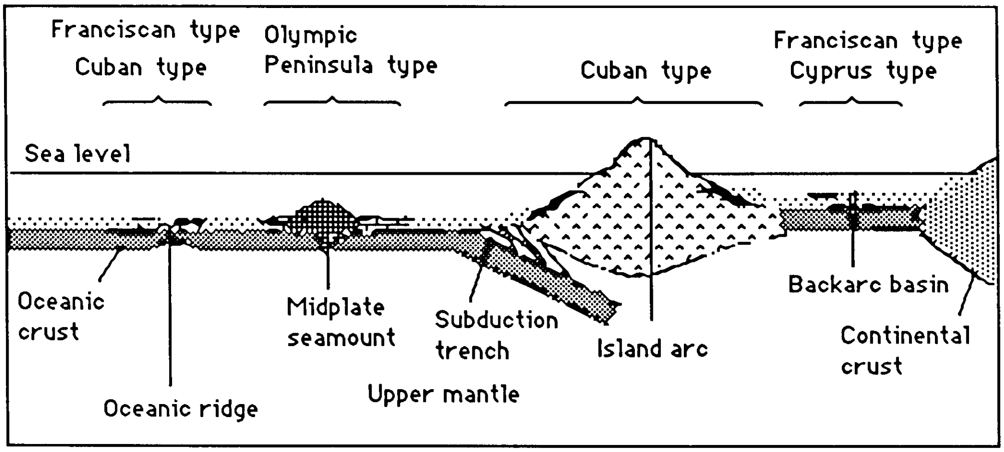

Figure 2. Original tectonic settings of four types of submarine volcanogenic manganese deposits.

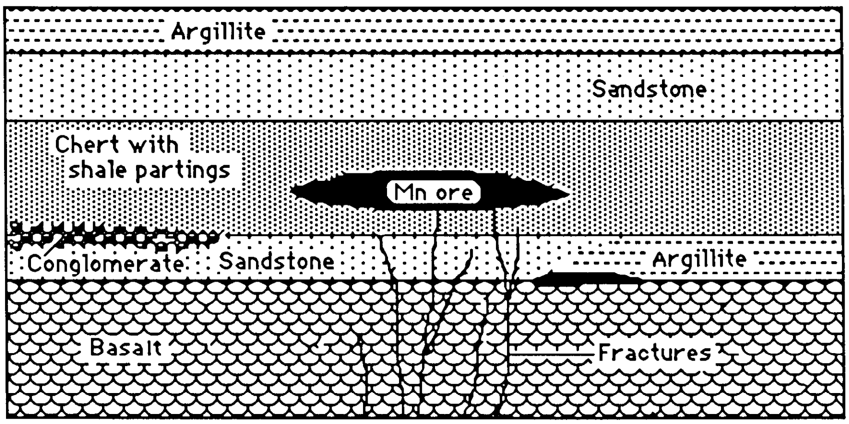

Figure 3. Generalized model of a Franciscan-type deposit, based on the data of Crerar and others (1982).

Table 1. Abundances of manganese minerals, in order of median rank

[Cyprus-type deposits are not shown because of the paucity of manganese minerals]

Median rank	Franciscan type		Cuban type				Olympic Peninsula type
	California	Oregon	Cuba	Mexico	Turkey	California	Washington
1	Psilomelane, Mn-Fe oxide	Pyrolusite, manganite, wad	Psilomelane	Braunite	Pyrolusite, psilomelane, rhodochrosite	Psilomelane, Mn chert	Bementite, hausmannite
2	Rhodochrosite, pyrolusite, Mn chert, neotocite, hausmannnite, braunite	Rhodonite	Pyrolusite, bementite, neotocite, braunite, rancieite	Pyrolusite, cryptomelane, bementite	Hausmannite, braunite, cryptomelane	Rhodonite, pyrolusite, Mn calcite, bementite	Neotocite
3	Bementite, rhodonite	Psilomelane	Manganite, inesite	Neotocite, pyrolusite, manganite	Manganite, rhodonite	Neotocite, rhodochrosite	Inesite, Mn-Fe oxide, Mn calcite
4	Wad	- - - - -	Wad	- - - - -	Rhamsdelite	Braunite	Rhodochrosite, rhodonite, pyrolusite
5	Inesite	- - - - -	- - - - -	- - - - -	Celadonite	- - - - -	Wad, spessartine, braunite
6	- - - - -	- - - - -	- - - - -	- - - - -	Pumpellyite	- - - - -	- - - - -

minor minerals; all primary minerals have been completely oxidized. A typical carbonate-silicate-oxide assemblage is rhodochrosite, neotocite or bementite, and manganese oxides. A carbonate-oxide assemblage contains rhodochrosite and manganese oxides, and a silicate-oxide assemblage consists of bementite or neotocite and manganese oxides. In Franciscan deposits in Japan, the assemblages are similar to those in California, except that braunite is the primary silicate mineral. In similar deposits in Oregon, manganite is an abundant oxide mineral. Traces of chalcocite, cuprite, malachite, native copper, pyrite, and cinnabar occur in some deposits. Quartz, chalcedony, hematite, calcite, siderite, and barite are the main gangue minerals.

Host rock.— The predominant host rock of the Franciscan deposits is chert, commonly red, white, or green, in 83 percent of the deposits; thin-bedded chert predominates over massive (thick bedded) chert, some of which contains radiolarians. Other host rocks include greenstone, jasper, sandstone, shale, slate, serpentine, limestone, and schist (table 2). In the Coast Ranges of California, only 46 percent of 461 deposits occur within 1,600 m of an outcrop of greenstone.

Shape and size.—Ore bodies of Franciscan deposits range in shape from thin and narrow to wide and ellipsoidal (fig. 4). Lengths range from 1.2 to 1,200 m, widths from 0.6 to 450 m, and thicknesses from 0.01 to 14 m. For 111 deposits, the median length is 33 m, the median width 12 m, and the median thickness 1.5 m (table 3). Deposits in California, Oregon, and the Philippines are thin and linear, whereas those in the Philippines are significantly longer and thicker. Deposits in Japan, which have the largest median length and width, form thin ellipsoidal masses.

Tonnage, grade, and volume.—For 181 Franciscan deposits, the median tonnage is 450 t, and the median manganese grade 36 weight percent Mn (figs. 5, 6). The mean iron grade for 23 deposits is 5.1 weight percent Fe. The median volume for 210 deposits is 75 m^3 (fig. 7; table 3).

Mineral-deposit density.—Deposit densities were calculated only for Franciscan deposits in the Franciscan Complex, Calif., and the Kitakami Mountains, Japan. In California, 1.9×10^{-2} deposit per square kilometer (table 4) occurs in rocks mapped as the Franciscan Complex on the 1:750,000-scale geologic map of Jennings and others (1977). In the Kitakami Mountains, Japan, areas were delineated on the basis of the manganese-bearing Carboniferous to Cretaceous units, as mapped on a 1:1,000,000-scale geologic map (Geological Survey of Japan, 1978). Permian and younger rocks have generally similar deposit densities, ranging from 1.9×10^{-2} to 6.7×10^{-2} deposit per square kilometer, whereas Carboniferous rocks have a deposit density an order of magnitude smaller (3.8×10^{-3}) (table 4).

Cuban Type

The manganese deposits occurring in the Cobre Formation, Oriente Province, Cuba, best represent the Cuban type. These deposits occur along certain beds in a pyroclastic sequence or along pyroclastic beds in limestone. The pyroclastic rocks range in composition from dacite to basalt. The

Table 2. Frequencies and percentages of host-rock types in the four types of volcanogenic manganese deposits.

[The value on the left side of each column is the number of times a rock type was hosting a deposit, and the value in parentheses on the right is the percentage of the rock type calculated to 100 percent. Data are derived from type areas discussed in the text]

Host rock	Franciscan type	Cuban type	Olympic Peninsula type	Cyprus type
Rhyolite to andesite tuff	2.00 (0.37)	65.14 (50.52)	1.00 (1.02)	---
Agglomerate	---	4.33 (3.36)	---	---
Rhyolite to andesite flow	---	4.41 (3.42)	---	---
Jasper	16.34 (3.06)	27.49 (21.32)	3.50 (3.57)	.50 (0.55)
Limestone	.33 (0.06)	11.91 (9.24)	44.00 (44.90)	1.00 (1.10)
Mudstone, shale, clay, or argillite	36.34 (6.81)	8.83 (6.85)	3.00 (3.06)	3.50 (3.85)
Marl		2.82 (2.19)	---	9.30 (10.23)
Chert or radiolarite	441.50 (82.68)	4.00 (3.10)	---	5.00 (5.50)
Basalt or greenstone	24.00 (4.49)	---	46.50 (47.45)	62.80 (69.09)
Chalk	---	---	---	7.80 (8.58)
Serpentine	1.00 (0.19)	---	---	.50 (0.55)
Gabbro	---	---	---	.50 (0.55)
Slate	2.00 (0.37)	---	---	---
Hornfel	.50 (0.09)	---	---	---
Glaucophane or mica schist	2.00 (0.37)	---	---	---
Sandstone	8.00 (1.50)	---	---	---
Total number of deposits	534.01 (99.99)	128.93 (100.00)	98.00 (100.00)	90.90 (100.00)

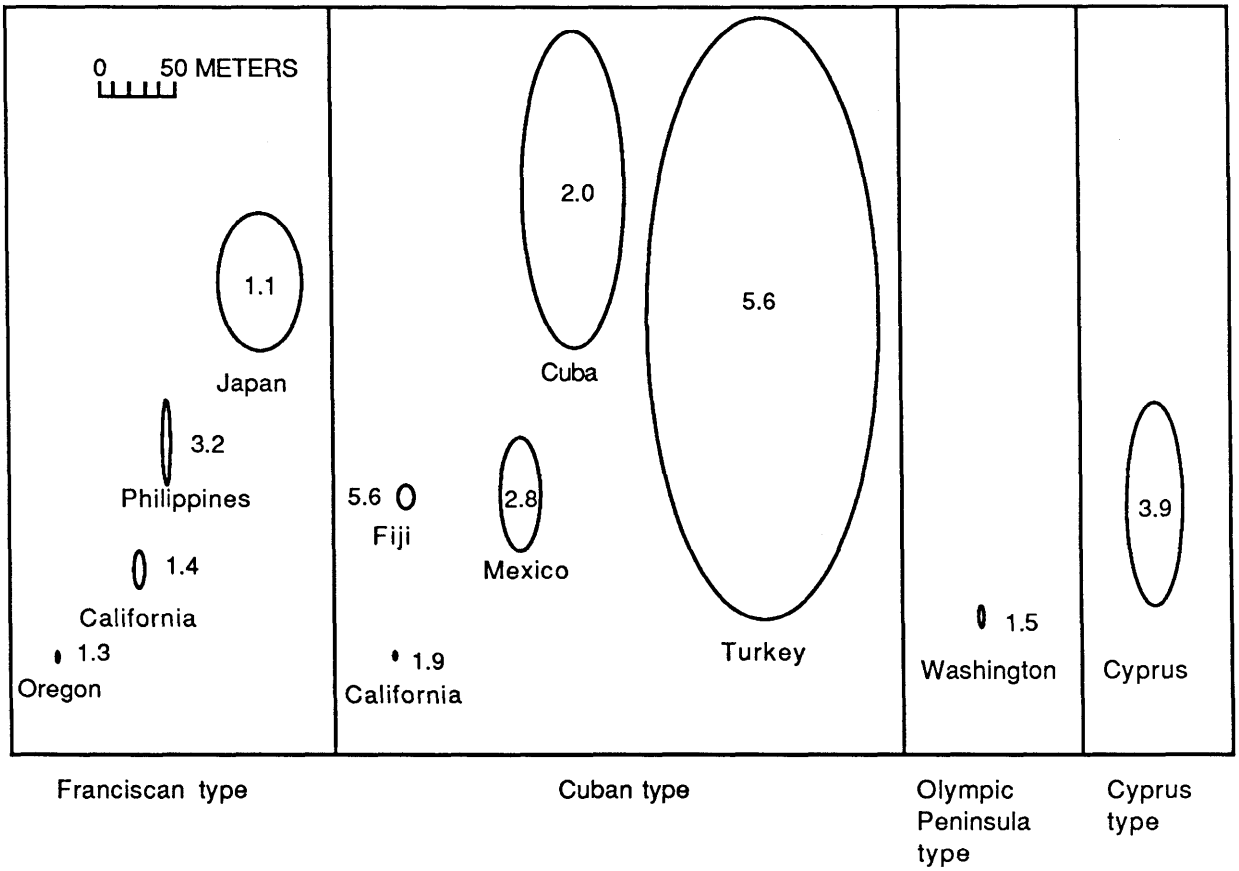

Figure 4. Comparison of median length, width, and thickness for volcanogenic manganese deposits by region and type. Length is vertical dimension, width is horizontal dimension, and thickness is number in center of or next to ellipse. Dimensions of deposits are listed in table 3.

Table 3. Median values for dimensional extent and volume of ore bodies by region and deposit type.

[n(lwt), number of deposits by length, width, and thickness; n(v), number of deposits by volume. Discrepancies between these two numbers are due to the availability of reported data. Cu, Cuban; Cy, Cyprus; Fr, Franciscan; O, Olympic Peninsula]

Region	Length (m)	Width (m)	Thickness (m)	n(lwt)	Volume (m^2)	n(v)
California (Fr)	26.4	8.7	1.4	69	78.7	164
Oregon (Fr)	7.2	3.3	1.3	6	4.6	7
Japan (Fr)	89.7	57.0	1.1	20	7.4	44
Philippines (Fr)	54.8	7.7	3.2	5	703.0	5
Turkey (Cu)	400.0	150.0	5.6	1	4,930.0	1
California (Cu)	5.9	2.4	1.9	3	53.5	5
Cuba (Cu	211.8	68.6	2.0	34	13,243.0	41
Mexico (Cu)	75.2	28.0	2.8	7	5,728.0	7
Fiji (Cu)	17.5	10.1	5.6	2	40.2	3
Washington (O)	13.5	4.7	1.5	41	1,239.0	41
Cyprus (Cy)	133.4	36.1	3.9	26	6,902.4	26
Type						
Franciscan	33.3	12.0	1.5	111	75.0	210
Cuban	99.0	38.3	2.1	60	6,039.5	75
Olympic Penin.	13.5	4.7	1.5	41	40.2	41
Cyprus	133.4	36.1	3.9	26	6,902.4	26

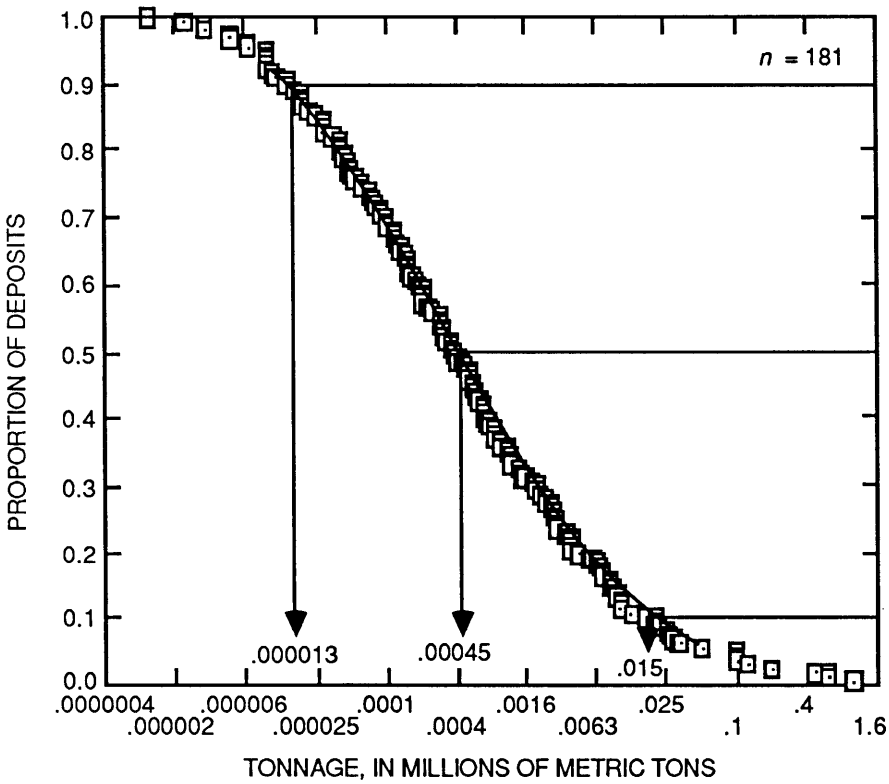

Figure 5. Cumulative frequency of tonnages for Franciscan-type deposits.

host rock ranges in age from Cambrian to Pliocene. The shape of the ore bodies is tabular and elliptical, and they are mostly stratabound and conformable to bedding, occurring as fine- to coarse-grained massive layers, nodules, disseminations, veinlets, and stringers containing predominantly psilomelane, pyrolusite, braunite, bementite, and neotocite. The adjacent pyroclastic rocks may be altered to montmorillonite, chlorite, and zeolite. Hematitization is common (Simons and Straczek, 1958). Appendix B contains a descriptive model for Cuban deposits in the form of Cox and Singer (1986). A generalized model based on the data of Simons and Straczek (1958) is shown in figure 8.

Cuban deposits are found in the Oriente Province, Cuba; Viti Levu, Fiji; the Shasta district and Sierra Nevada, Calif.; Mexico; Panama; Honduras; Turkey; Argentina; Iran; Nova Scotia; Great Britain; France; and Algeria. In the Oriente Province, Cuba, these deposits are closely associated with structural domes (Simons and Straczek, 1958).

Mineralogy.—The predominant mineral in the Cuban deposits are silicates and oxides; carbonates are absent. Psilomelane is the most abundant oxide mineral, followed by pyrolusite and manganite. Braunite, neotocite, and bementite are the most abundant silicate minerals (table 1). Less abundant are rancieite, orientite, wad, inesite, piedmontite, hausmannite, and rhodonite. Rhodochrosite is rare; it is reported from only two deposits in California and Turkey. Hematite, magnetite, pyrite, chalcopyrite, cuprite, malachite,

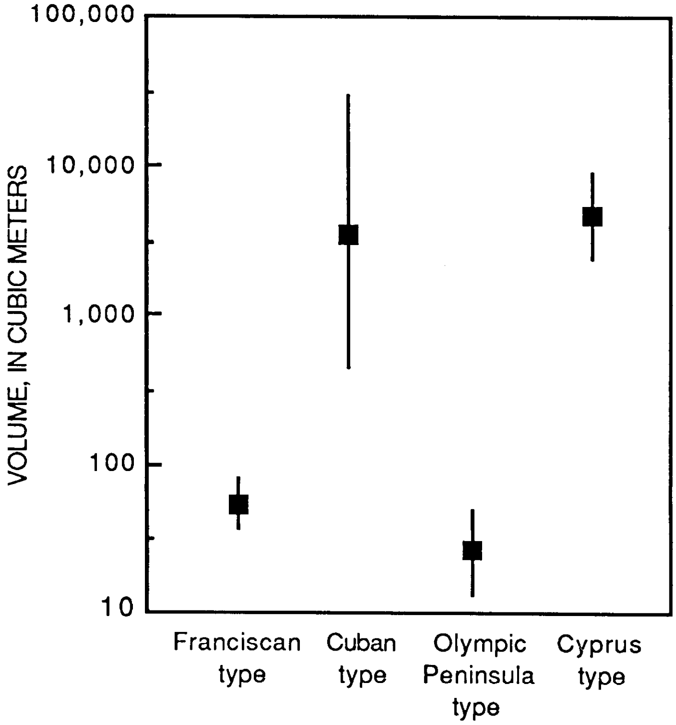

Figure 7. Median volumes and 95-percent-confidence intervals (vertical bars) for four types of submarine volcanogenic manganese deposits.

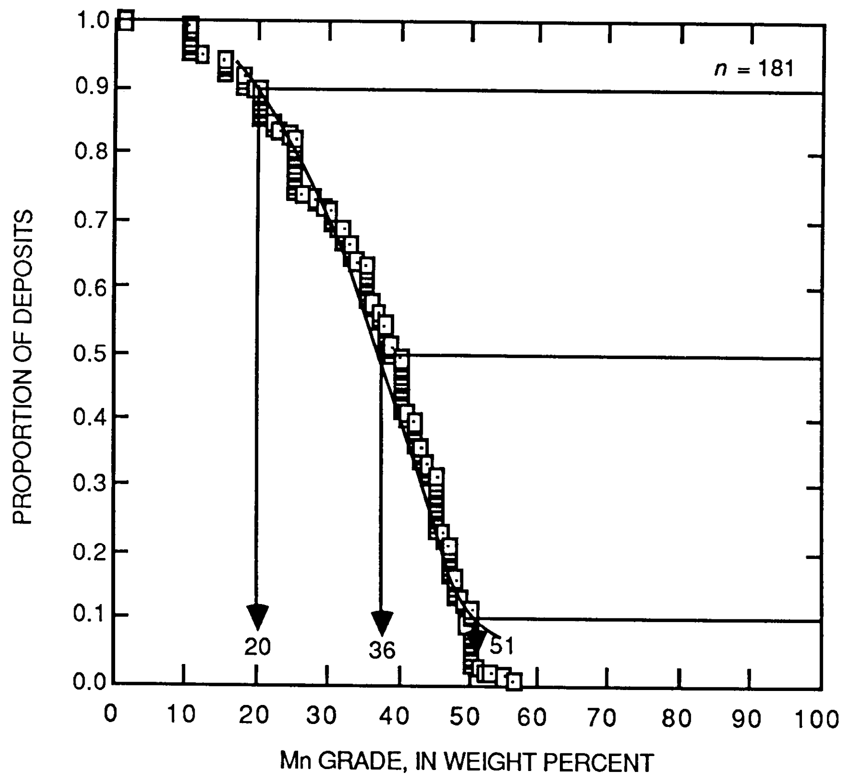

Figure 6. Cumulative frequency of manganese grades for Franciscan-type deposits.

Table 4. Mineral-deposit densities (number of deposits per square kilometer) of volcanogenic manganese deposits by rock unit and region.

Host Rock	Area (km²)	Number of deposits	Number of deposits per km²
Franciscan type			
Franciscan Complex, California	23,655	453	0.019
Kitakami Mountains, Japan			
Upper Jurassic to Lower Cretaceous sandstone, slate, chert	75	3	.040
Permian to lower Mesozoic sandstone, slate, chert, limestone, basalt	1,048	70	.067
Permian sandstone, slate, chert, limestone, conglomerate, basalt	2,241	42	.019
Lower Carboniferous sandstone, slate, limestone, basalt, andesite	530	2	.0038
Cuban type			
Cobre Formation, south-central Oriente, Cuba			
Charco Redondo limestone member	197	16	.081
Tuff, agglomerate, subordinate flows	927	93	.10
Limestone	9	1	.11
Jasper	2	9	4.50
Total (includes other members not containing deposits)	1,197	119	.10
Viti, Levu, Fiji			
Suva Marl—marl, sandstone, limestone (Pliocene and Miocene)	81	1	.012
Navosa—andesite pyroclastic rocks, mudstone, limestone, conglomerate (Pliocene and Miocene)	254	1	.0039
Nandi Group—conglomerate, marl, limestone, andesite (Pliocene and Miocene)	253	5	.020
Singatoka—sandstone, mudstone, volcanic rock (Miocene)	316	4	.013
Wainimbuka Trachyte—lithic tuff, lava, limestone (Miocene)	170	2	.012
Numbuonamboto Volcanic Conglomerate—conglomerate, volcanic rocks (Oligocene)	914	1	.0011
Mount Gordon Subgroup—volcanic rocks, mudstone, limestone (Eocene)	735	4	.0054
Total	2,723	18	.0066
Olympic Peninsula type			
Olympic Peninsula, Washington			
Pre-upper Eocene argillite and graywacke	686	9	.013
Lower and middle Eocene basalt flows and breccias, limestone	2,909	100	.034
Total	3,595	109	.030
Cyprus type			
Troodos Complex, Cyprus			
Upper Pillow Lavas	312	74	.24
Radiolarite and marl	13	8.5	.65
Clay	56	1.5	.027
Serpentine	64	1	.016
Gabbro	185	5	.0027
Chalk and marl	1,334	5.5	.0016
Total	1,964	91	.046

native copper, and chalcocite are present in some deposits. The main gangue minerals include quartz, chalcedony, jasper, calcite, barite, opal, siderite, ankerite, chlorite, halloysite, kaolinite, dolomite, feldspars, and biotite.

Host rock.—Rhyolitic, dacitic, and andesitic tuffs are host rocks for the ore in 51 percent of Cuban deposits (table 2). Tuff is a major host rock in all of the regions except Panama and the Foothill belt of California, where jasper or chert is the major host rock. In Mexico, Cuba, Honduras, and Turkey, tuff is a major host rock in at least 80 percent of deposits. In Fiji, about half the deposits have tuff as a host rock. Lenses of jasper in either tuff or limestone are a major host rock in 21 percent of Cuban deposits (table 2). In Panama, jasper is the host rock for 65 percent of deposits; and in the Foothill belt of

California, jasper and chert are the host rocks for 86 percent of deposits. Jasper is a minor host rock in Cuba and Fiji. Limestone, argillite, agglomerate, chert, marl, and volcanic flows are all minor host rocks (table 2).

Shape and size.—Ore bodies of Cuban deposits are generally thin ellipsoids (fig. 4). Lengths range from 1.5 to 2,900 m, widths from 0.4 to 470 m, and thicknesses from 0.1 to 15 m. For 60 deposits, the median length is 99 m, the median width 38 m, and the median thickness 2.1 m (table 3). Because of the small number of Cuban deposits in Turkey, Fiji, and California, the sizes shown in figure 4 may not be representative of deposits in those regions.

Tonnage, grade, and volume.—For 84 Cuban deposits, the median tonnage is 6,400 t, and the median manganese grade is 39 weight percent Mn (figs. 9, 10). The mean iron grade for 6 deposits is 4.4 weight percent Fe. The median volume for 75 deposits is 6,040 m^3 (fig. 7; table 3). Tonnage is correlated with Mn content ($r = 0.18$, $n = 84$) and Fe content ($r = 0.8$, $n = 6$) at the 5-percent-confidence level.

Mineral-deposit density.—Deposit densities were determined for Cuban deposits in the Oriente Province, Cuba, using a 1:50,000-scale geologic map (Lewis and Straczek, 1955), and in Viti Levu, Fiji, using a 1:250,000-scale geologic map (Rodda and Bank, 1966). In the east half of the Cobre Formation, which consists of 1,197 km^2 of Upper Cretaceous to middle Eocene limestone, tuff, and jasper, there is 1.0×10^{-1} deposit per square kilometer (table 4). In the pyroclastic member of the Cobre Formation, a similar deposit density is expected. Deposit densities for the Cobre Formation vary by as much as three orders of magnitude (table 4). In Viti Levu, Fiji, manganese-bearing rock units, which consist of 2,723 km^2 of Eocene to Pliocene andesite tuff and sedimentary rocks, yield 6.6×10^{-3} deposit per square kilometer (table 4). Deposit densities for individual rock units in Viti Levu are listed in table 4.

Olympic Peninsula Type

The type area for the Olympic Peninsula type of Mn deposits is the Olympic Peninsula, Wash. The deposits are hosted in argillaceous red limestone lenses that occur within a sequence of tholeiitic pillow basalt or at the contact between these two rock types. Some deposits occur within the basalt in the absence of limestone. Tuff, agglomerate, argillite, and graywacke are associated with the host rocks. These rocks, which are Eocene, are believed to have formed as seamounts in deep to shallow ocean basins; some of the basalt may have been deposited subaerially (Cady, 1975). Appendix C contains a descriptive model for Olympic Peninsula deposits in the form of Cox and Singer (1986). A generalized model based on the data of Park (1941, 1946) is shown in figure 11.

The ore bodies are commonly elongate tabular lenses, concordant to bedding. The ore is finely crystalline, massive or banded, with spongy or colloform structures, algal structures, or fecal pellets (that is, evidence of concretionary growth). Silicates, carbonates, and oxides of manganese are present; secondary manganese oxides form near the surface and along joints as oxidation products of bementite and other primary manganese minerals. Some veinlets of manganese silicates, quartz, hematite, calcite, and barite are present (Green, 1945; Magill, 1960; Cady, 1975).

Mineralogy.—The most abundant minerals in Olympic Peninsula deposits are bementite, hausmannite, and neotocite (table 1); less abundant minerals include pyrolusite, inesite, braunite, rhodochrosite, rhodonite, and manganocalcite. The silicate-oxide assemblage occurs in 77 percent of the cases, followed by the carbonate-silicate-oxide assemblage (17 percent). Small blebs or seams of cinnabar and disseminated specks of native copper and pyrite are locally present. Quartz, hematite, calcite, and rare barite are gangue minerals.

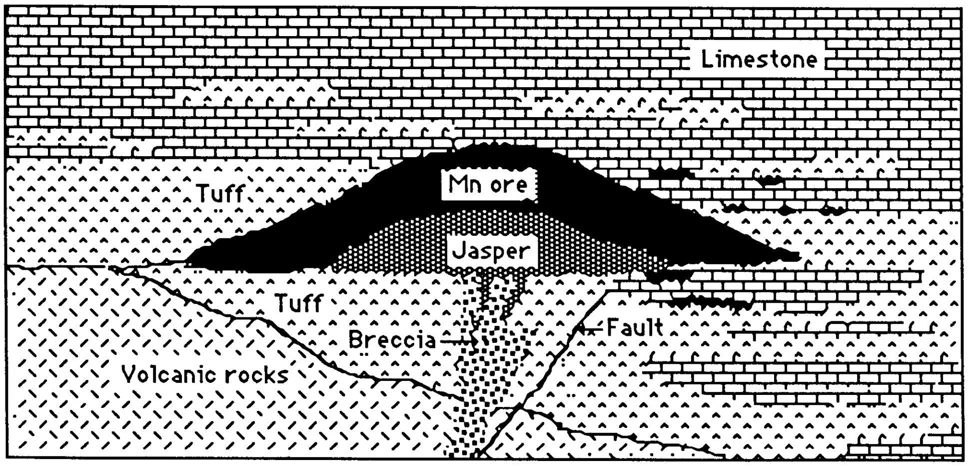

Figure 8. Generalized model of a Cuban-type deposit, based on the data of Simons and Straczek (1958).

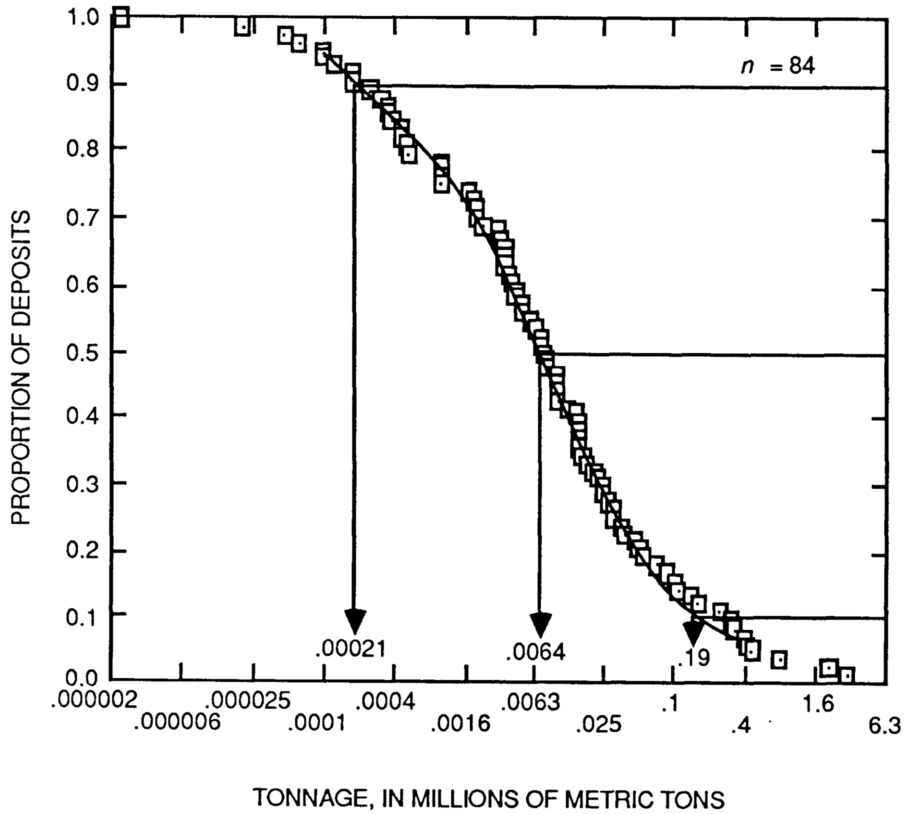

Figure 9. Cumulative frequency of tonnages for Cuban-type deposits.

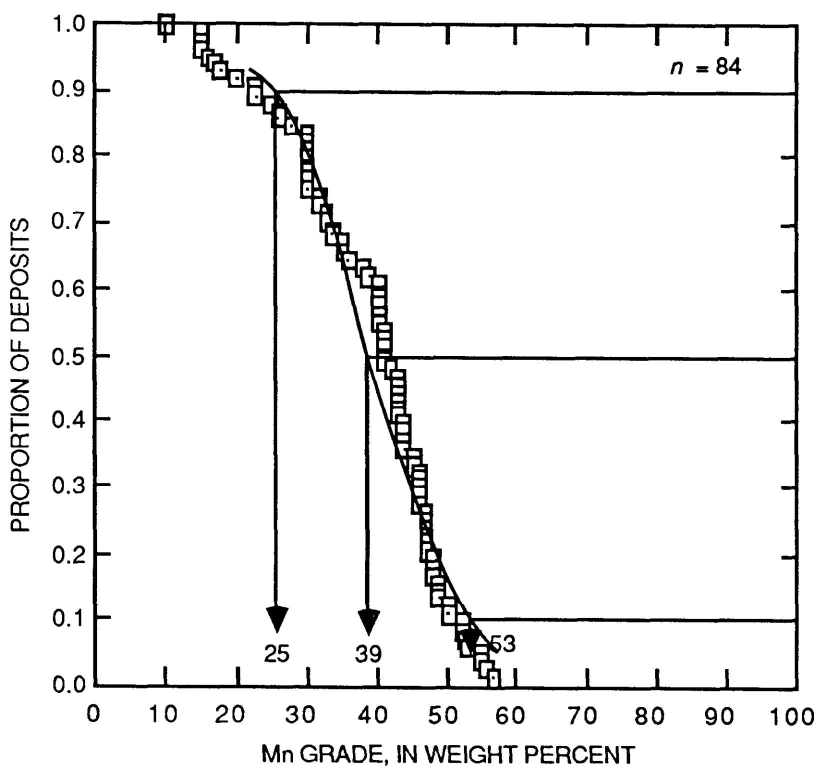

Figure 10. Cumulative frequency of manganese grades for Cuban-type deposits.

Host rock.—Of 98 Olympic Peninsula deposits, 47 percent are hosted in basalt, 45 percent in limestone, and the rest in tuff, jasper, and argillite (table 2). About a third of these deposits occur in the contact between limestone and basalt. In some of the limestone-hosted deposits, jasper lenses containing manganese were reported; however, jasper is not a major host rock.

Shape and size.—Ore bodies of Olympic Peninsula deposits are mostly thin, narrow ellipsoids. For 41 deposits, the median length is 14 m, the median width 4.7 m, and the median thickness 1.5 m (fig. 4; table 3). Lengths range from 0.9 to 366 m, widths from 0.3 to 152 m, and thicknesses from 0.2 to 8.5 m.

Tonnage, grade, and volume.—For 17 Olympic Peninsula deposits, the median tonnage is 340 t, and the median manganese grade 35 weight percent Mn (figs. 12, 13). The mean iron grade for 4 deposits is 6.5 weight percent Fe. The median volume for 41 deposits is 40 m^3 (fig. 7; table 3).

Mineral-deposit density.—The Olympic Peninsula, Wash., has 3.0×10^{-2} deposit per square kilometer (table 4) in an area limited by lower and middle Eocene basalt and limestone and pre-upper Eocene argillite and graywacke, as delineated on the 1:500,000-scale geologic map by Huntting and others (1961). Most deposits are in lower to middle Eocene rocks.

Cyprus Type

The manganese deposits occurring in the Troodos Complex, Cyprus, best represent the Cyprus type. These deposits generally are lenticular bodies of umber (manganiferous iron-rich sedimentary rock) overlying pillow-basalt flows, which are at the base of a sedimentary sequence. The umber is massive, structureless, and extremely fine grained, composed of goethite, maghemite, and an amorphous hydroxide of manganese. Iron oxides also occur in fractures and breccias beneath the umber. Umber deposits also occur in the Semail region, Oman. Appendix D contains a descriptive model for Cyprus deposits in the form of Cox and Singer (1986). A generalized model based on the data of Constantinou and Govett (1972) and Robertson (1975) is shown in figure 14.

Host rock.—Most of the umbers in the Troodos Complex are hosted in the Upper Cretaceous Upper Pillow Basalt (table 2). The umber is commonly overlain by various sedimentary rocks, such as clay, marl, chalk, radiolarian chert, jasper, and conglomerate.

Mineralogy.—No discrete manganese minerals have been identified in the umbers, except for an amorphous hydroxide. Goethite, maghemite, and rare pyrite and quartz, compose the bulk of the ore (Constantinou and Govett, 1972).

Shape and size.—Ore bodies of Cyprus deposits are thin, wide ellipsoids. Lengths range from 10 to 968 m, widths from 5 to 387 m, and thicknesses from 0.5 to 33 m. For 26 deposits, the median length is 133 m, the median width 36 m, and the median thickness 3.9 m, (fig. 4; table 3).

Tonnage, grade, and volume.—For 7 Cyprus deposits, the median tonnage is 41,000 t, and the median grades 8 weight percent Mn and 33 weight percent Fe (figs. 15-17). The median volume for 26 deposits is 6,900 m^3 (fig. 7; table 3).

Mineral-deposit density.—The Troodos Complex in Cyprus has 4.6×10^{-2} deposit per square kilometer, on the basis of a 1:250,000-scale geologic map (Cyprus Geological Survey Department, 1982). The most favorable host units are the radiolarite and marl unit (6.5×10^{-1} deposit per square kilometer) and the Upper Pillow Lavas (2.5×10^{-1} deposit per square kilometer).

COMPARISON OF MODELS BY PROPERTIES

Mineralogy

Minerals among the four deposit types were compared by relative abundance (table 1) and assemblage type. The most significant difference among the deposit types is the absence

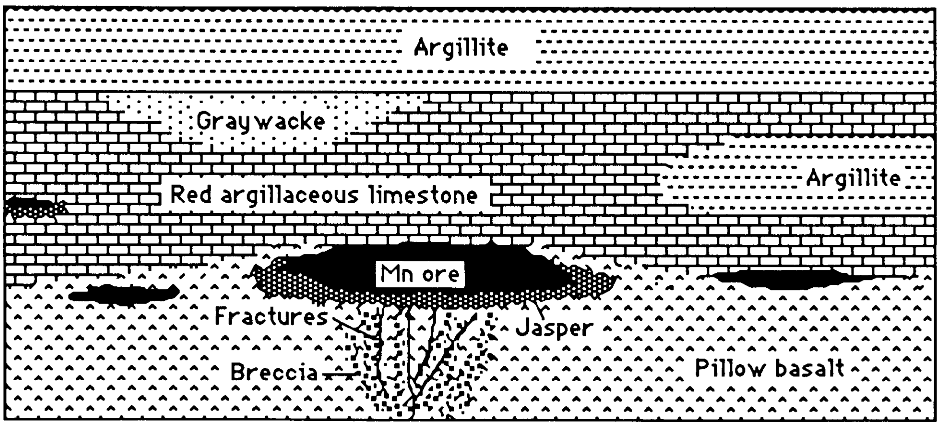

Figure 11. Generalized model of an Olympic Peninsula-type deposit, based on the data of Park (1941, 1946).

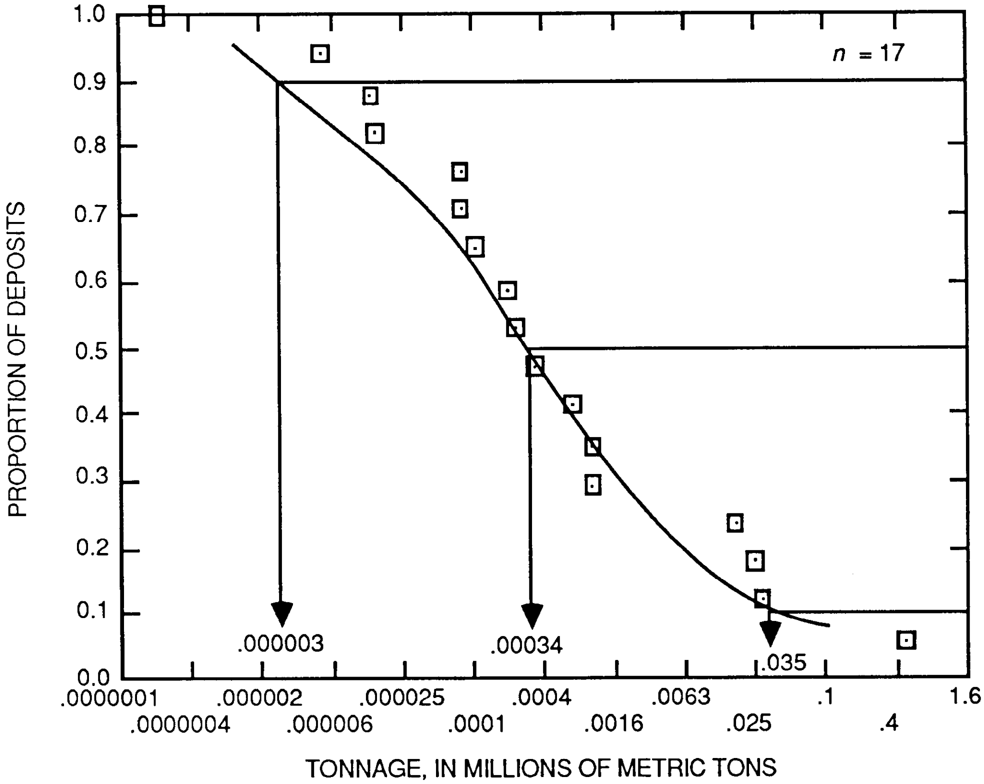

Figure 12. Cumulative frequency of tonnages for Olympic Peninsula-type deposits.

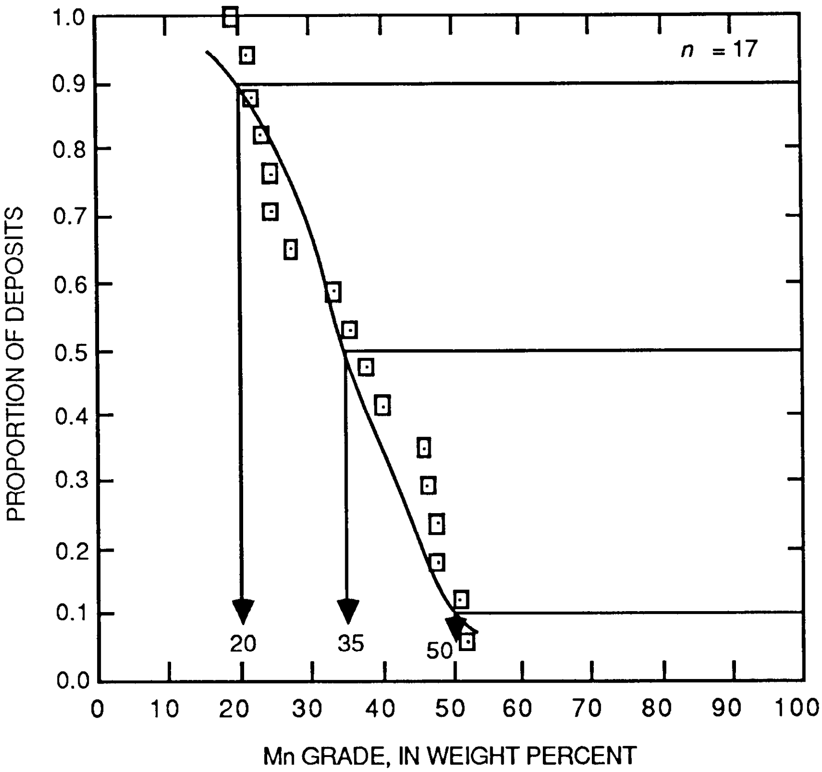

Figure 13. Cumulative frequency of manganese grades for Olympic Peninsula-type deposits.

of a manganese silicate or carbonate mineral in Cyprus deposits; an amorphous manganese hydroxide is the only major manganese mineral in the umbers of Cyprus deposits. All the deposit types contain manganese oxides or hydroxides, either as primary or secondary minerals. For example, hausmannite and manganite may be primary minerals in some deposits (Hewett, 1972), and psilomelane and pyrolusite are common secondary products of weathering.

Cuban deposits differ from both Franciscan and Olympic Peninsula deposits in the paucity or absence of manganese carbonate minerals, such as rhodochrosite or manganocalcite. Cuban deposits characteristically have manganese silicate-oxide assemblages, and braunite is the most common silicate mineral; however, the most common silicate mineral in Franciscan and Olympic Peninsula deposits is neotocite and bementite, respectively (table 1), except in Japan, where it appears to be braunite.

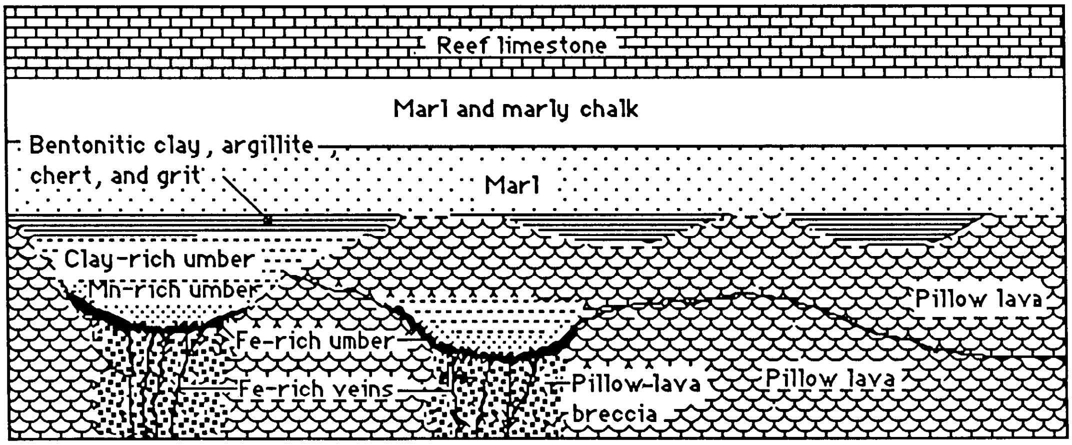

Figure 14. Generalized model of a Cyprus-type deposit, based on the data of Constantinou and Govett (1972) and Robertson (1975).

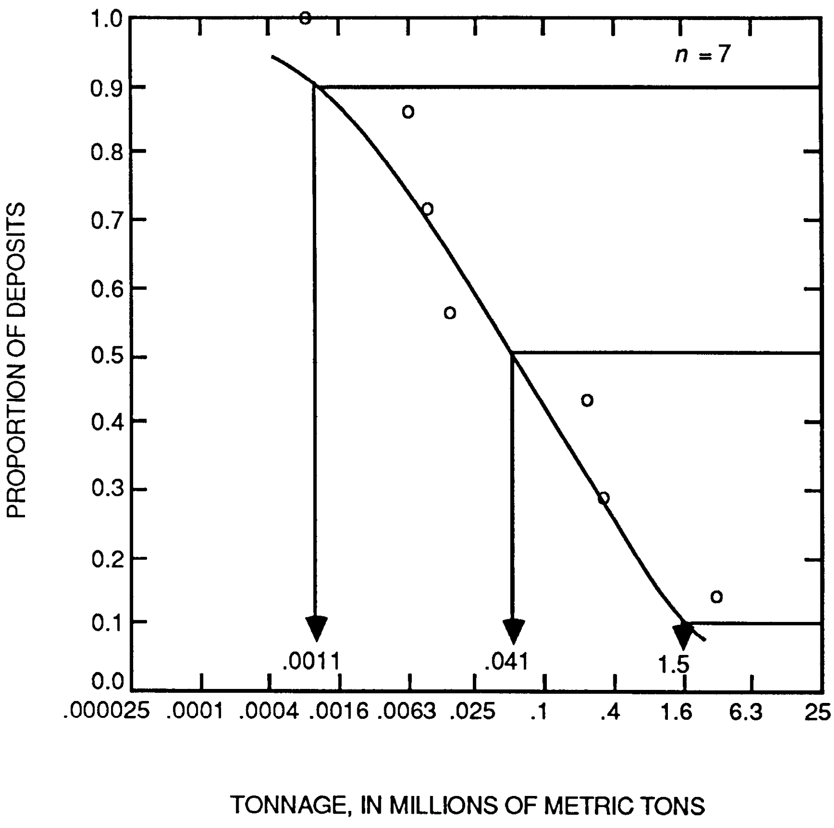

Figure 15. Cumulative frequency of tonnages for Cyprus-type deposits.

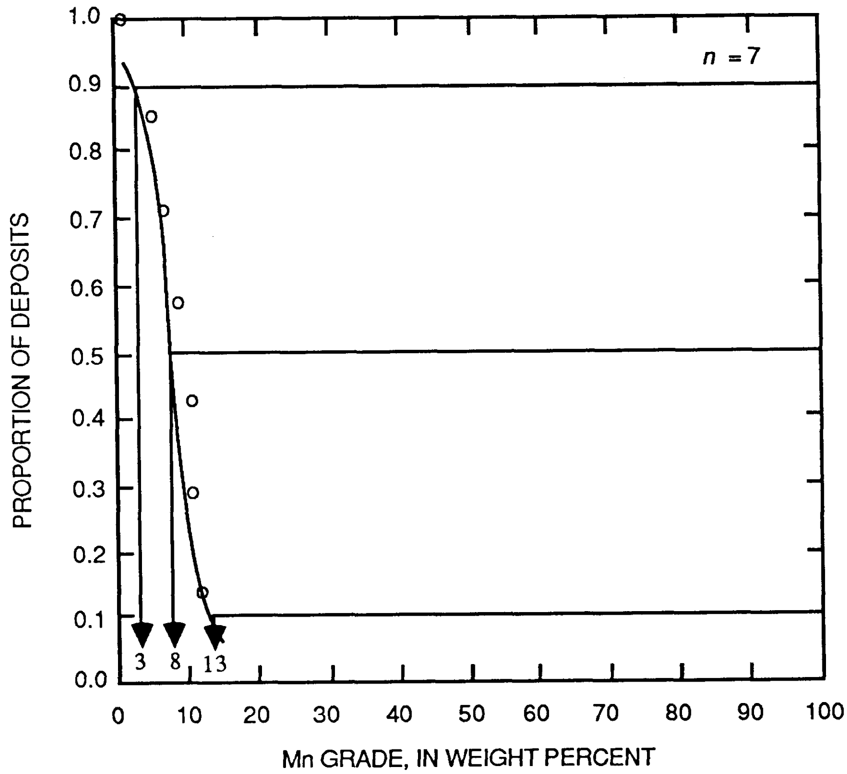

Figure 16. Cumulative frequency of manganese grades for Cyprus-type deposits.

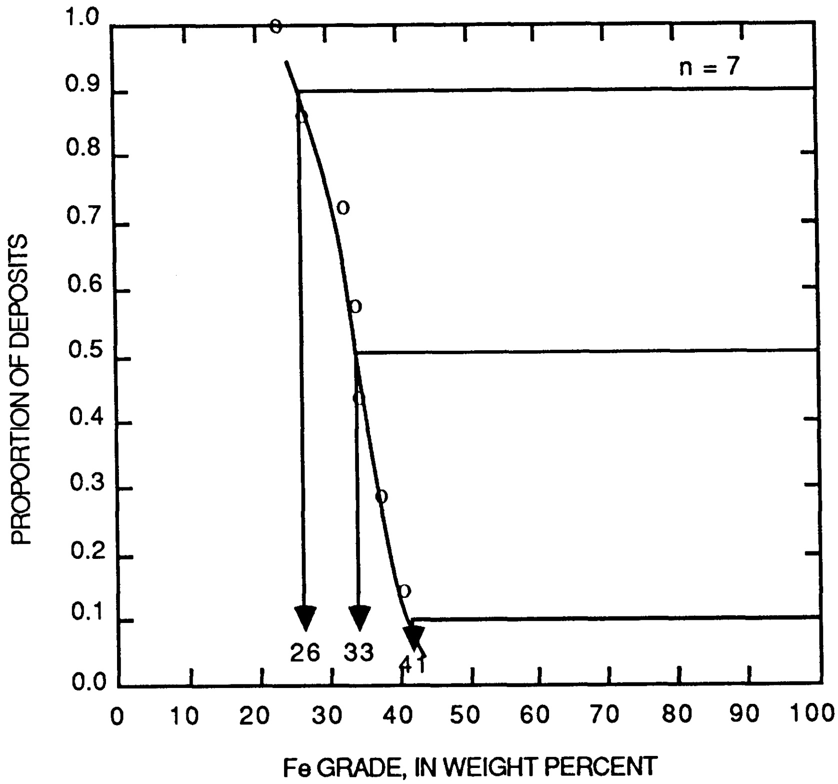

Figure 17. Cumulative frequency of iron grades for Cyprus-type deposits.

Franciscan deposits differ mineralogically from Olympic Peninsula deposits in several ways. Carbonate-bearing assemblages seem to be more common in Franciscan deposits but are minor in Olympic Peninsula deposits. In constrast, Olympic Peninsula deposits seem to be more silicate rich, and bementite and neotocite are abundant manganese silicates. Furthermore, hausmannite is an important economic ore mineral in Olympic Peninsula deposits, whereas psilomelane is important in Franciscan deposits.

Accessory pyrite and quartz occur in all the deposit types. Copper minerals, hematite, calcite, and barite are present in all except Cyprus deposits. Cinnabar is present in Franciscan and Olympic Peninsula deposits but is absent in Cuban and Cyprus deposits.

Host Rock

The host rocks among the four deposit types are distinct (table 2). The major host rock in Cuban deposits is dacitic to basaltic pyroclastic rocks and flows. Franciscan deposits are hosted mostly in white, red, or green massive to thin-bedded chert. Olympic Peninsula deposits are hosted in basalt or in the contact between basalt and limestone. Cyprus deposits are hosted in basalt flows and sedimentary rocks, such as clay, marl, chalk, or chert.

Shape, Dimensions, and Volume

Generally, ore bodies in the deposits are thin, narrow to wide ellipsoids; these shapes suggest a genetic association with linear structural features on the sea floor where the deposits were deposited. The range of shapes in the bedding plane is shown schematically by region and deposit type in figure 4. Lengths and widths among the deposit types differ significantly except among Cuban and Cyprus deposits, which are the largest in extent. Cyprus deposits are also significantly thicker than the other deposit types. Length-to-width ratios among the types are similar; for example, Franciscan, Cuban, and Olympic Peninsula deposits are about 3 times as long as they are wide, and Cyprus deposits about 4 times as long as they are wide. Length-to-thickness ratios range from 9 for Olympic Peninsula deposits to 47 for Cuban deposits. Width-to-thickness ratios range from 3 for Olympic Peninsula deposits to 18 for Cuban deposits. Interestingly, the length-to-thickness and the width-to-thickness ratios are similar for Franciscan and Cyprus deposits, two types formed in similar tectonic environments. The volumes for Cyprus and Cuban deposits are significantly larger than for Franciscan and Olympic Peninsula deposits (fig. 7; table 3).

Tonnage

The differences in tonnage among the deposit types are plotted in figure 18. Cyprus deposits have the largest median tonnage, and Olympic Peninsula deposits the smallest. The tonnages for Cyprus and Cuban deposits are significantly larger than for Franciscan and Olympic Peninsula deposits.

Grade

The differences in manganese grade among the groups are plotted in figure 19. Cuban deposits have the highest median grade, and Cyprus deposits the lowest. Manganese grades among the deposit types do not differ significantly, except for Cyprus deposits. The median iron grade for Cyprus deposits is at least 5 times that for the other types (fig. 20).

Contained Metal

The differences in contained manganese metal among the deposit types are plotted in figure 21. The median contained metal for Cuban deposits is significantly larger than for both Franciscan and Olympic Peninsula deposits. Although, Cyprus deposits do not differ significantly from the other types, because of their wide range in Mn content they are the largest in contained metal and tonnage of all submarine volcanogenic deposits.

Mineral-Deposit Density

Mineral-deposit densities for the four deposit types are listed in table 4. Deposit densities within each type vary by as much as two orders of magnitude, as in Fiji (0.0066) and Cuba (0.1), possibly because of the different levels of exploration in these two countries or the favorability levels of different types or ages of host rock. Deposit densities among the deposit types differ; for example, in the Kitakami Mountains, northeastern Honshu, Japan (Franciscan type), and in the Troodos Complex, Cyprus (Cyprus type), deposit densities differ by an order of magnitude. Because the differences in mineral-deposit densities within types can vary as much as those among types, comparison of deposit densities among types should be done with care.

APPLICATION OF THE MODELS AND CONSTRAINTS ON GENETIC MODELS

The application or usage of the volcanogenic manganese models for resource assessment is a three-step process (Singer, 1975, 1984) that involves: (1) delineating a tract or domain which contains rocks permissive for the occurrence of a particular deposit type, (2) estimating the number of undiscovered deposits, and (3) predicting the tonnage and grade characteristics of the undiscovered deposits by analogy to those of the same type known elsewhere. Combinations of characteristics from the descriptive models (appendixes A-D), particularly depositional environment, tectonic setting, and rock types, allow boundaries to be drawn around tracts or domains with geologic, geochemical, and geophysical constraints similar to the model. Each tract, defined in this way,

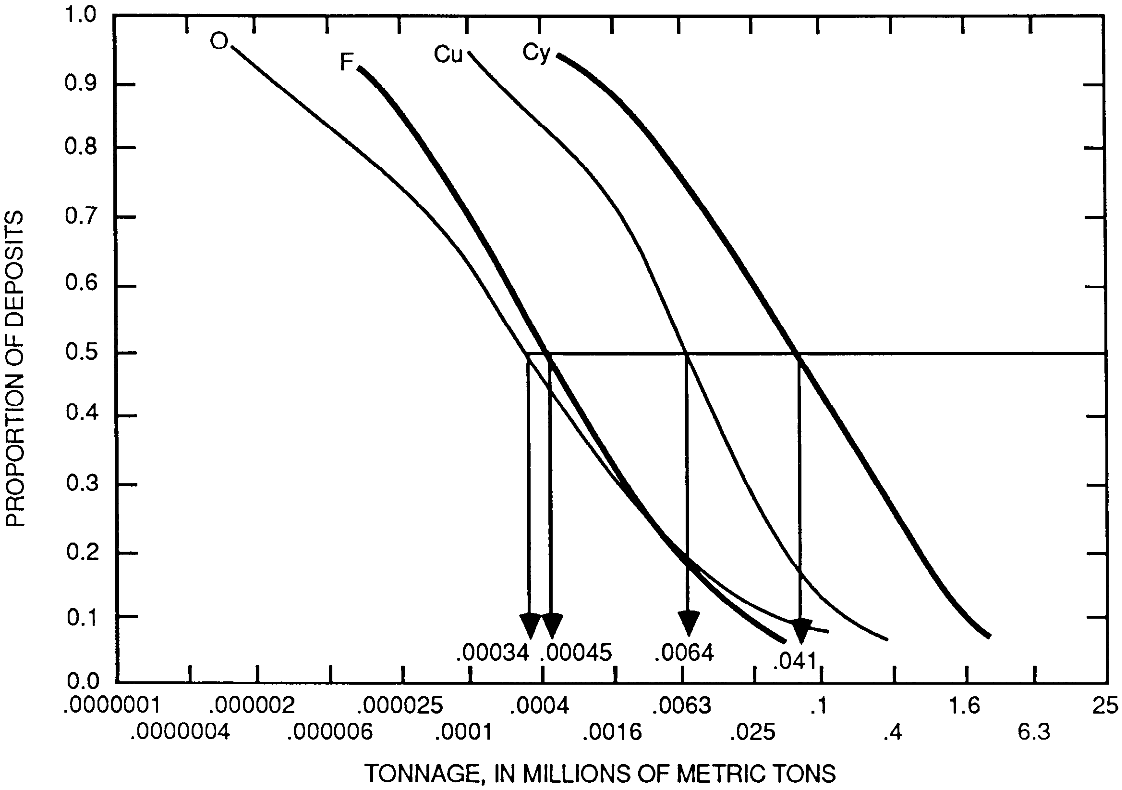

Figure 18. Cumulative frequencies of tonnages and median tonnages for four types of volcanogenic manganese deposits: Cu, Cuban; Cy, Cyprus; F, Franciscan; O, Olympic Peninsula.

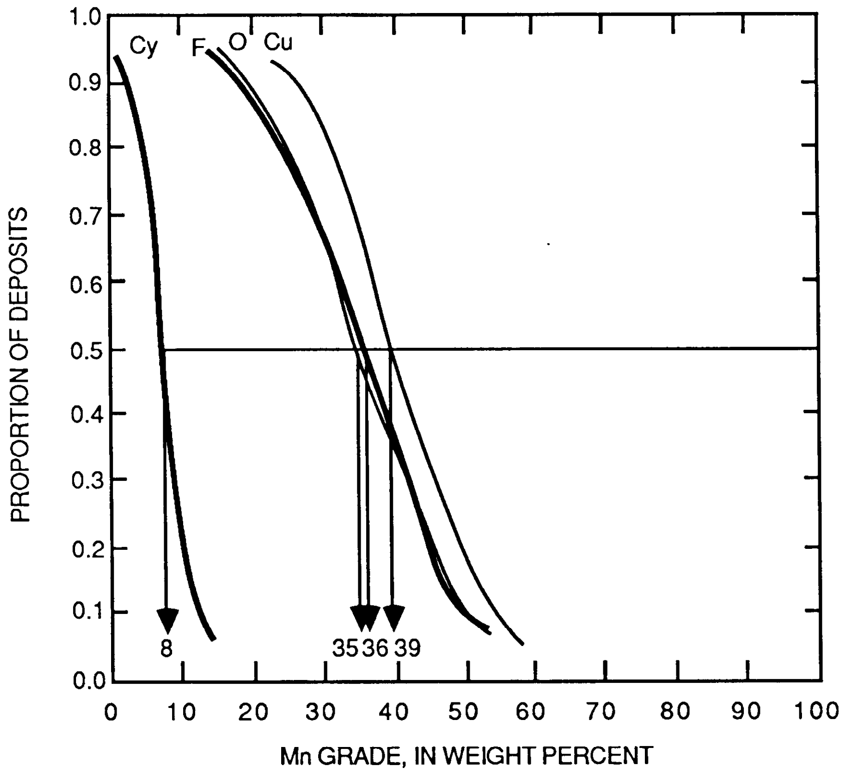

Figure 19. Cumulative frequencies of manganese grade and median manganese grades for four types of volcanogenic manganese deposits: Cu, Cuban; Cy, Cyprus; F, Franciscan; O, Olympic Peninsula.

contains an area with geology permissive for the occurrence of a particular deposit type. Different levels of geologic information are available for different areas, and so, some adjustments can be made to the boundaries of tracts as the level of geologic information increases. Geologically, geochemically, and geophysically derived characteristics for volcanogenic manganese deposits at different levels of information that can be used to constrain and refine boundaries of tracts are listed in table 5. This list is far from complete and could include rapid burial to preserve the deposits, deep or long-term weathering to enrich the deposits, and so on.

Once tracts have been identified, their areas, in combination with mineral-deposit density measured using the same criteria in table 4, can be used to estimate the number of deposits in the tracts. Such estimates should be adjusted with respect to the number of known deposits and their exploration history to estimate the number of undiscovered deposits in the tracts. By analogy, half of the total number of undiscovered deposits should have tonnages and grades below the median, and half above the median, of the appropriate tonnage and grade model. The size and volume distributions in this report, in combination with local geologic knowledge, should also help in the design of drilling programs to locate additional deposits.

Although the purpose of this report is not to derive genetic models for volcanogenic manganese deposits, the information compiled and analyzed herein imposes constraints on such models. In general, there appears to be a combination of volcanic and hydrothermal processes akin to hot-spring activity that produces different manganese deposits in at least four oceanic environments.

Similar processes have been postulated to be active in continental environments (Hewett, 1966, fig. 7). For example, the Three Kids deposit, Nev., is in a section of Pliocene tuff and sedimentary rocks that were deposited in a shallow lake or playa. Manganese is believed to have been carried into the basin by hot springs rising along marginal faults (Hunt and others, 1942). The lens of wad and minor manganite is about 915 m long, 458 m wide, and a maximum of 15 m thick; it contains 7.4 million t of ore grading 12.5 weight percent Mn and 1 weight percent Fe (Crittenden, 1964). Associated manganiferous veins or active hot springs may have a siliceous or calcareous apron rich in manganese. Some deposits are rich in base and precious metals (Ohe, Japan) or tungsten (Golconda, Nev.). Although this report focuses on the various types of submarine-hot-spring manganese deposits, the continental-hot-spring manganese deposits, which evidently belong to the same general class of volcanogenic manganese deposits, should be investigated similarly as more data become available.

REFERENCES CITED

Bliss, J.D., in press, Mineralogic and grade-tonnage information on low-sulfide Au-quartz veins: U.S. Geological Survey Open-File Report.

Bliss, J.D., Menzie, W.D., Orris, G.J., and Page, N.J, 1986, Mineral deposit density—a useful tool for mineral-resource assessment [abs.], *in* Sachs, J.S., ed., USGS research on mineral resources—1987 program and abstract: U.S. Geological Survey Circular 995, p. 6.

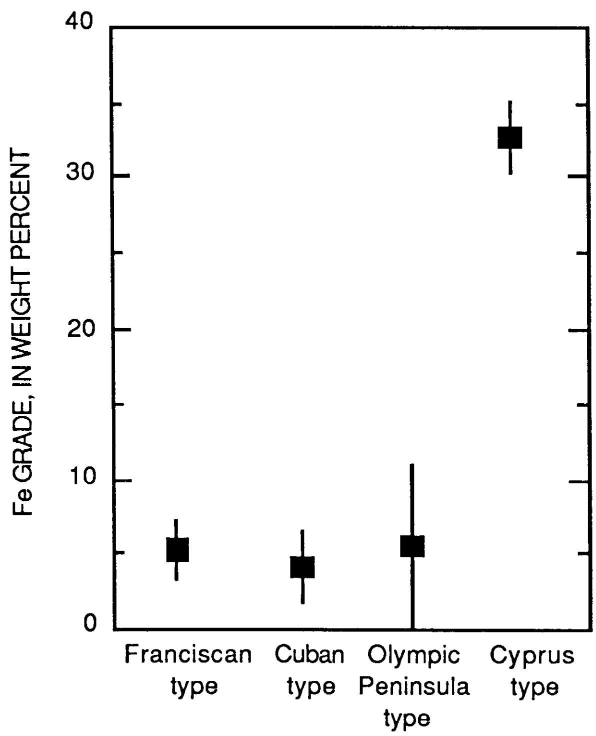

Figure 20. Median iron grades and 95-percent-confidence intervals for four types of volcanogenic manganese deposits.

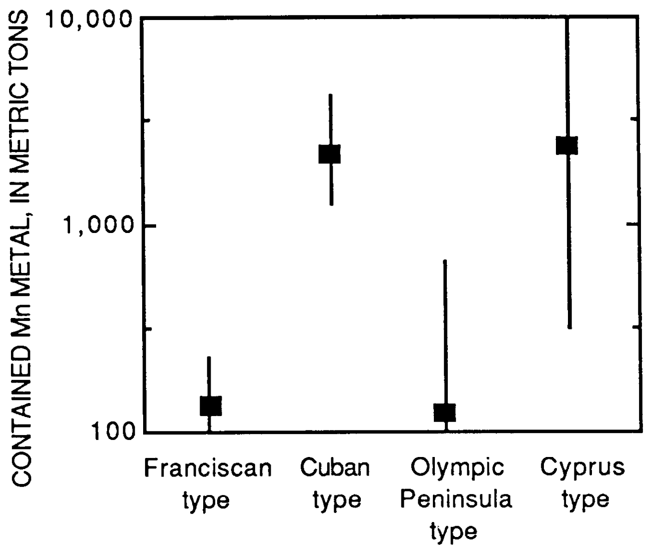

Figure 21. Median contained manganese metal and 95-percent-confidence intervals for four types of volcanogenic manganese deposits.

Table 5. Information level and geologic, geochemical, and geophysical characteristics of volcanogenic manganese desposits

Information level	Geologic, geochemical, and geophysical characteristics			
	Franciscan type	Cuban type	Olympic Peninsula type	Cyprus type
1	Environments obducted onto a continental margin (tectonic environment)			
	Midoceanic ridge or inner-arc basin	Island arc	Ocean basin (midplate setting)	Midoceanic ridge or inner arc basin
2	Volcanic-rock types present			
	Basaltic volcanic rocks related to ophiolites	Mafic to silicic volcanic and volcaniclastic rocks	Basaltic volcanic rocks related to seamounts	Basaltic volcanic rocks related to ophiolites
3	Associated rock types present			
	Interbedded tuffaceous limestone or limy tuff	Thick wedges of graywacke, sandstone, shale, and chert	Interbedded fine-grained argillaceous limestone, graywacke, and argillite	Interbedded marl, chalk, silt, and chert
4	Changes in depositional environment or evidence for cessation of volcanism			
	Rapid clastic sedimentation (turbidites) followed by slower rate of sedimentation (thin-bedded chert)	Volcanism followed by carbonate-rich sedimentation	Thick pillow basalt, tuff, and agglomerate followed by clastic thin-bedded sedimentary rocks	Thick pillow-basalt sequences with fault-controlled depressions, followed by sedimentation
5	Local tectonic position of deposition			
	Margins of volcanic centers	Presence of domal structures, or intrusions inferred to be volcanic centers	Absence of ultramafic and mafic rocks of ophiolitic origin, suggesting a midplate position	Minor amount of sulfide mineralization, suggesting off-ridge-axis position
6	Evidence of hydrothermal circulation systems			
	Mn carbonates and silicates, along with quartz and rare calcite, aragonite, and barite in fractures and breccias	Pervasive and fracture-controlled montmorrillonite, zeolite, nontronite, barite, calcite, and chlorite alteration	Veinlets of Mn silicates, quartz, specular hematite, calcite, barite, and zeolites in fractures and joints	Fe oxide in fractures and breccias
7	Geochemical anomalies			
	Mn, Fe, Cu, Hg, Ba	Mn, Fe, Cu, Ba	Mn, Fe, Cu, Hg, Ba	Mn, Fe, Ni, Cu, Zn, Co
8	Presence of manganese deposits, prospects, or occurrences			
	Mn oxide and Mn carbonate-oxide assemblages dominant	Mn oxide and silicate assemblages dominant	Mn silicate and oxide assemblages dominant	Absence of Mn silicate or carbonate assemblages

Cady, W.M., 1975, Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington: U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 573-582.

Constantinou, G., and Govett, G.J.S., 1972, Genesis of sulphide deposits, ochre and umber of Cyprus: London Institution of Mining and Metallurgy Transactions, v. 81, sec. B, no. 783, p. B34-B46.

Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Crerar, D.A., Namson, Jay, Su Chyi, Michael, Williams, Loretta, and Feigenson, M.D., 1982, Manganiferous cherts of the Franciscan Assemblage; I. General geology, ancient and modern analogues, and implications for hydrothermal convection at oceanic spreading centers: Economic Geology, v. 77, no. 3, p. 519-540.

Crittenden, M.D., Jr., 1964, Manganese, *in* U.S. Geological Survey and Nevada Bureau of Mines, Mineral and water resources of Nevada: Nevada Bureau of Mines Bulletin 65, p. 113-119.

Cyprus Geological Survey Department, 1982, Mineral resources map of Cyprus: scale 1:250,000.

Elderfield, H., Gass, I.G., Hammond, A., and Bear, L.M., 1972, The origin of ferromanganese sediments associated with the Troodos Massif of Cyprus: Sedimentology, v. 19, no. 1-2, p. 1-19.

Gass, I.G., 1968, Is the Troodos Massif of Cyprus a fragment of Mesozoic ocean floor?: Nature, v. 220, no. 5162, p. 39-42.

Geological Survey of Japan, 1978, Geological map of Japan: scale 1:1,000,000.

Georgiou, E., Christodoulou, E., and Panayiotou, A., 1981, Report on the investigations of the umber quarry licences of the Umber Corporation of Larnaca, Ltd.: Cyprus, Geological Survey Department report G/MR/001/81, 16 p.

Green, S.H., 1945, Manganese deposits of the Olympic Peninsula, Washington: Washington Division of Mines and Mining Report of Investigations 7, 45 p.

Hein, J.R., Koski, R.A., and Yeha, Hsueh-wen, 1987, Chert-hosted manganese deposits in sedimentary sequences of the Franciscan Complex, Diablo Range, California, *in* Hein, J.R., ed., Siliceous sedimentary rock hosted ores and petroleum: New York, Van Nostrand-Reinhold, p. 206-230.

Hewett, D.F., 1966, Stratified deposits of the oxides and carbonates of manganese: EconomicGeology, v. 61, no. 3, p. 431-461.

——1972, Manganite, hausmannite, braunite—features, modes of origin: Economic Geology, v. 67, no. 1, p. 83-102.

Hunt, C.B., McKelvey, V.E., and Wiese, J.H., 1942, The Three Kids manganese district, Clark County, Nevada: U.S. Geological Survey Bulletin 936-L, p. 297-319.

Huntting, M.T., Bennett, W.A.G., Livingston, V.E., and Moen, W.S., 1961, Geologic map of Washington: Washington Division of Mines and Geology, scale 1:500,000.

Jennings, C.W., Strand, R.G., and Rogers, T.H., compilers, 1977, Geologic map of California: California Division of Mines and Geology, California Geologic Data Map Series 2, scale 1:750,000.

Koski, R.A., 1986, Descriptive model of volcanogenic Mn, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 139.

Lewis, G.E., and Straczek, J.A., 1955, Geology of south-central Oriente, Cuba: U.S. Geological Survey Bulletin 975-D, p. 171-336.

Magill, E.A., 1960, Manganese deposits of the Olympic Peninsula, Washington: U.S. Bureau of Mines Report of Investigations 5530, 82 p.

Mitchell, A.H., and Bell, J.D., 1973, Island-arc evolution and related mineral deposits: Journal of Geology, v. 81, no. 4, p. 381-405.

Mosier, D.L., 1986, Grade and tonnage model of volcanogenic Mn, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 139-141.

Namson, Jay, Chyi, M.S., Crerar, D.A., Feigenson, M.D., and Williams, L., 1981, Evidence for a hydrothermal origin of manganiferous cherts from the Franciscan assemblage [abs.]: Geological Society of America Abstracts with Programs, v. 13, no. 2, p. 99.

Park, C.F., Jr., 1941, Manganese resources of the Olympic Peninsula, Washington: A preliminary report: U.S. Geological Survey Bulletin 931-R, p. 435-457.

——1942, Manganese deposits of Cuba: U.S. Geological Survey Bulletin 935-B, p. 75-97.

——1946, The spilite and manganese problems of the Olympic Peninsula, Washington: American Journal of Science, v. 244, no. 5, p. 305-323.

Robertson, A.H.F., 1975, Cyprus umbers: Basalt-sediment relationships on a Mesozoic ocean ridge: Geological Society of London Journal, v. 131, pt. 5, p. 511-531.

Rodda, P., and Band, R.B., 1966, Geology of Viti Levu: Geological Survey of Fiji Report G.S. 432, scale 1:250,000.

Simons, F.S., and Straczek, J.A., 1958, Geology of the manganese deposits of Cuba: U.S. Geological Survey Bulletin 1057, 289 p.

Singer, D.A., 1975, Mineral resource models and the Alaskan Mineral Resource Program, *in* Vogely, W.A., ed., Mineral materials modeling—a state-of-the-art review: Baltimore, John Hopkins University Press, p. 370-382.

Singer, D.A., 1984, Mineral resource assessments of large regions: Now and in the future, *in* Geological Survey of Japan, ed., U.S.-Japan joint seminar on resources in the 1990's: Tokyo, Japan, Earth Resources Satellite Data Analysis Center, v. 2, p. 32-40.

Skiba, W.J., 1964, Geological studies in southwest Viti Levu: Geological Survey of Fiji Memoir 1, 56 p.

Snyder, W.S., 1978, Manganese deposited by submarine hot springs in chert-greenstone complexes, western United States: Geology, v. 6, no. 12, p. 741-744.

Taliaferro, N.L., and Hudson, F.S., 1943, Genesis of the manganese deposits of the Coast Ranges of California, *in* Manganese in California: California Division of Mines Bulletin 125, p. 217-275.

Trask, P.D., Wilson, I.F., and Simons, F.S., 1943, Manganese in California—a summary report, *in* Manganese in California: California Division of Mines Bulletin 125, p. 51-215.

Watanabe, Takeo, Yui, Shunzo, and Kato, Akira, 1970, Metamorphosed bedded manganese deposits of the Noda-

Tamagawa mine, *in* Tatsumi, Tatsuo, ed., Volcanism and ore genesis: Tokyo, University of Tokyo Press, p. 143-152.
Yamada, Keiichi, Sudo, Sadahisa, Sata, Takeo, Fujii, Noriyuki, Sawa, Toshiaki, Hattori, Hitoshi, Satoh, Hiroyuki, and Aikawa, Tadayuki, 1980, Mines summary report, v. 1, North-east Japan: Geological Survey of Japan Report 260, p. 162.

APPENDIXES

APPENDIX A

DEPOSIT TYPE Franciscan-type volcanogenic manganese. **MODEL** 24 c-1

DESCRIPTION Lenses and stratiform bodies of manganese oxide, carbonate, and silicate in chert associated with sedimentary and mafic volcanic rocks. Genesis related to volcanogenic processes.

GENERAL REFERENCES Trask and others (1943), Koski (1986).

GEOLOGIC ENVIRONMENT

Rock Types Chert, shale, sandstone, graywacke, jasper, tuff, basalt, and serpentine. Thin- and thick-bedded red or white chert and jasper are the predominant host rocks. Tholeiitic and alkaline volcanic rocks.

Textures White, red, brown, and green chert in thin-bedded or massive lenses, commonly with shale partings. Some of the chert contains radiolarians.

Age Range Paleozoic to Jurassic.

Depositional Environment Sea-floor hot spring, deep water in a zone of oceanic upwelling at or near a continental margin.

Tectonic Setting(s) Oceanic ridges and rifted marginal basins (backarc setting) obducted onto a continental margin.

Associated Deposit Types Hot-spring mercury, silica-carbonate mercury, podiform chromite.

DEPOSIT DESCRIPTION

Mineralogy Abundant psilomelane, pyrolusite, rhodochrosite, hausmannite, braunite, and neotocite; minor bementite, wad, rhodonite, inesite, pyrochroite, tephroite, ganophyllite, dannemorite, pyroxmangite, stilpnomelane, spessartine, pyrophanite, nsutite, manganite, cryptomelane, jacobsite, manjiroie, Mn-phlogopite, todorokite, piedmontite, hollandite, manganocalcite, birnessite, alleghanyite, galaxite, and alabandite.

Texture/Structure Fine-grained massive crystalline aggregates, botryoidal, colloform in bedded and lensoid masses; veinlets and disseminations.

Alteration Primary carbonates and silicates altered to oxides; some silicates altered to carbonates.

Ore Controls Sufficient structure and porosity to permit sub-sea-floor hydrothermal circulation and sea-floor venting; redox boundary at sea-floor/seawater interface around hot springs; supergene enrichment to upgrade Mn content.

Weathering Strong development of secondary manganese oxides (psilomelane, pyrolusite, todorokite, birnessite, manganite) at the surface and along fractures.

Geochemical Signatures Mn, Fe, Cu, Hg, and Ba.

Examples Ladd mines, USCA (Hein and others, 1987); Noda-Tamagawa, JAPN (Watanabe and others, 1970; Yamada and others, 1980).

APPENDIX B

DEPOSIT TYPE Cuban-type volcanogenic manganese. **MODEL** 24 c-2

DESCRIPTION Tabular bodies of manganese oxide and silicate lying along certain beds of a pyroclastic sequence or along pyroclastic beds in limestone. Genesis is related to volcanogenic processes.

GENERAL REFERENCES Simons and Straczek (1958), Koski (1986).

GEOLOGIC ENVIROMENT

Rock Types Pyroclastic rocks, tuffaceous limestone, and volcaniclastic and volcanic rocks of basaltic to dacitic composition; calc-alkaline volcanic rocks.

Textures Fine- to coarse-grained massive or bedded limy and fossiliferous tuff; agglomerate contains rounded to angular fragments, as much as 15 m long, set in a tuff matrix; limestone is tuffaceous, massive to thin bedded.

Age Range Cambrian to Pliocene.

Depositional Environment Sea-floor hot spring, shallow marine in island-arc environments.

Tectonic Setting(s) Island-arc setting obducted onto a continental margin.

Associated Deposit Types Kuroko massive sulfide deposits.

DEPOSIT DESCRIPTION

Mineralogy Psilomelane, pyrolusite, braunite, bementite, neotocite are the most common; manganite, rancieite, wad, orientite, inesite, piedmontite are less abundant; hausmannite and rhodonite are rare.

Texture/Structure Fine- to coarse-grained massive layers, nodules, irregular masses, patches, disseminated fragments, pockets, veinlets, and stringers, mostly conformable to bedding and stratabound.

Alteration Andesitic and basaltic tuff, altered to montmorillonite clay minerals, chlorite, and zeolite; hematitization.

Ore Controls Sufficient structure and porosity to permit sub-sea-floor hydrothermal circulation and sea-floor venting; redox boundary at sea-floor/seawater interface around hot springs; supergene enrichment to upgrade Mn content.

Weathering Strong development of secondary manganese oxides at the surface and along fractures.

Geochemical Signatures Mn, Fe, Cu, and Ba.

Examples Quinto and Ponupo mines, CUBA (Simons and Straczek, 1958); Nambu mine, FIJI (Skiba, 1964).

APPENDIX C

DEPOSIT TYPE Olympic Peninsula-type volcanogenic manganese. **MODEL** 24 c-3

DESCRIPTION Tabular, conformable lenses of manganese oxides and silicates in or between argillaceous red limestone and pillow basalt. Genesis is related to volcanogenic processes.

GENERAL REFERENCES Green (1945), Magill (1960), Cady (1975), Koski (1986).

GEOLOGIC ENVIRONMENT

Rock Types Pillow basalt and red argillaceous limestone. Associated tuff, agglomerate, argillite, and graywacke. Alkaline or tholeiitic volcanic rocks.

Textures Basalt flows have massive and pillow structures; limestone is very fine grained, argillaceous, and siliceous; argillite is calcareous and ferruginous.

Age Ranges Eocene or older.

Depositional Environment Deep to shallow marine on or near basaltic seamount or islands; sea-floor hot spring.

Tectonic Setting(s) Ocean basin with seamounts and volcanic islands (midplate setting), obducted onto a continental margin.

DEPOSIT DESCRIPTION

Mineralogy Bementite, hausmannite, neotocite are common; inesite, manganite, rhodochrosite, rhodonite, pyrolusite, manganocalcite are less abundant; braunite, wad, tephroite, manganophyllite, piedmontite, jacobsite, spessartine are minor.

Texture/Structure Finely crystalline massive lenses and layers (banding), spongy or colloform layering of hausmannite, brecciation, nearly round microstructures to oolitic structures, algal structure or fecal pellets.

Alteration Silicification, greenschist-facies metamorphism.

Ore Controls Sufficient structure and porosity to permit sub-sea-floor hydrothermal circulation and sea-floor venting; redox boundary at sea-floor/seawater interface around hot springs; supergene enrichment to upgrade Mn content.

Weathering Secondary manganese oxides (pyrolusite and manganite) are formed as oxidation products of bementite or other manganese minerals; restricted to surface and along joints.

Geochemical Signatures Mn, Fe, Cu, Hg, and Ba.

Example Crescent mine, USWA (Magill, 1960).

APPENDIX D

DEPOSIT TYPE Cyprus-type volcanogenic manganese. **MODEL** 24 c-4

DESCRIPTION Lenticular bodies of umber (manganiferous Fe-rich sedimentary rock) overlying pillow-basalt flows at the base of a sedimentary sequence. Genesis is related to volcanogenic processes.

GENERAL REFERENCE Constantinou and Govett (1972).

GEOLOGIC ENVIRONMENT

Rock Types Umber, silt, grit, conglomerate, radiolarian chert, pillow basalt, red jasper, chalk, and marl; tholeiitic volcanic rocks.

Textures Basalt shows pillow structures and brecciation.

Age Ranges Late Cretaceous.

Depositional Environment Deep to shallow marine basin near continental margin.

Tectonic Setting(s) Interarc-basin and midoceanic-ridge settings obducted onto a continental margin.

Associated Deposit Types Cyprus massive sulfide deposits.

DEPOSIT DESCRIPTION

Mineralogy Amorphous manganese hydroxide, goethite, and maghemite. No discrete manganese mineral has been determined.

Texture/Structure Massive, structureless, extremely fine grained lenticular masses.

Alteration Pyrite, where present, alters to iron oxides.

Ore Controls Commonly occurs in depressions on the surface of basalt flows, in interbeds between basalt flows, in fault-controlled depressions on volcanic breccia, and in lowermost parts of the covering sedimentary-rock sequence.

Weathering Important for manganese enrichment.

Geochemical Signatures Mn, Fe, Ni, Cu, Zn, and Co.

Examples Troulii, Drapia, and Skouriotissa, CYPS (Georgiou and others, 1981).

GPO 585-045/78032