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Origin of Manganese Deposits of Busuanga Island Philippines

by

Ronald Keith Sorem

U. S. GEOLOGICAL SURVEY
OPEN FILE REPORT
This report is preliminary and has
not been edited or reviewed for
conformity with Geological Survey
standards or nomenclature.

Prepared by the U. S. Geological Survey

in Cooperation with

The Philippine Bureau of Mines

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A thesis submitted in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

(GEOLOGY)

at the

UNIVERSITY OF WISCONSIN

The x-ray patterns given on p. 123 are erroneously identified as bementite. This is due to the use of ASTM card 3-0971 as a reference. Actually, the card is wrong, and both patterns are of barite.

In the text, read barite for bementite on pages 60 (line 10), 65 (line 2, and in table III), p. 66 (line 3 of Fig. 25 caption), p. 66 (line 4 of Fig. 26 caption), p. 119 (line 16).

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ABSTRACT

The manganese deposits of Busuanga Island, Palawan, are tabular and broadly lenticular bodies which lie conformably within a thick sequence of deformed chert beds. The purpose of this study is to determine the probable mode of origin of the deposits. Similar deposits in other parts of the world have been described by others as products of several different genetic processes.

Field and laboratory methods of research were employed in the course of the investigation. Detailed geologic mapping was done on the surface and underground, and many samples of rocks and ores were obtained. Later, intensive study of samples from four typical deposits and from the rocks in the surrounding areas was undertaken, using a variety of laboratory techniques. Microscopic study of thin sections and polished surfaces was supplemented by X-ray and chemical work. More than one hundred X-ray diffraction powder photographs were made to identify minerals, and qualitative chemical studies were made of a number of samples by use of the X-ray spectrograph. In addition, quantitative chemical analyses were made of certain samples. Finally, published accounts of the occurrence and geological behavior of manganese and silica were consulted to aid in interpretation of the data at hand.

Cherty layers in the manganese deposits are lithologically similar to the chert wallrocks and country rock beds. Radiolarian fossils are common in the chert and are also found in some ore specimens. Manganese content of the wallrocks and the country rock beds, however, is essentially nil.

The manganese deposits contain mostly psilomelane-type oxides in their near-surface parts, and in the deepest mines this ore grades downward into siliceous protore. In three of the deposits studied, the protore consists mainly of braunite and quartz; in the fourth deposit, hausmannite and the silicate alleghanyite make up the bulk of the protore. Some of the protore is massive, but cherty zones are commonly well layered parallel to the wall rock structure. Grain size is very small, but, like the silica in the chert beds, becomes relatively coarse where the rocks are much deformed. No evidence of large-scale replacement or cross-cutting veins is found in the protores.

It is concluded that the original manganiferous deposits were largely non-clastic or colloidal marine sediments laid down in a reducing environment. The protores were developed from these beds by processes of diagenesis and low-grade regional metamorphism. The protores were in turn altered to black oxide ore by near-surface agencies during the present erosion cycle. Particular interest is attached to the occurrence of alleghanyite and traces of pyroxmangite and hubnerite(?) in the protores.

INTRODUCTION

Busuanga is the northernmost major island in the province of Palawan, in the western Philippines (Fig. 1). Manganese deposits were discovered on the island in about 1936, and since 1937 more than 100,000 metric tons of ore containing approximately 48 percent manganese have been produced. In 1953 most of the commercial-grade ore was exhausted, and mining virtually ceased.

In 1950 the writer was assigned by the U. S. Geological Survey to make a detailed geologic study of the manganese deposits in cooperation with geologists of the Philippine Bureau of Mines. About sixteen months were spent in field work, and a preliminary report was submitted to the Philippine and U. S. Governments in 1955. Results of the work were given in a general way in a brief report written in 1953 and published in 1956 (Sorem, 1956).

The present investigation is concerned with the origin of the deposits. Field data and the results of detailed laboratory studies have been correlated to present a much more complete picture of the deposits than was possible heretofore, and a reasonable hypothesis of origin can be proposed with considerable conviction. The results of the investigation are of academic interest because similar detailed work has not been done previously on these deposits. In addition, deposits of the same general type, although known from many parts of the world, are for the most part inadequately studied and their origin is poorly understood. Locally economic interest is attached to the study, also, for a correct interpretation of the features of the deposits may aid in the search for commercial ore.

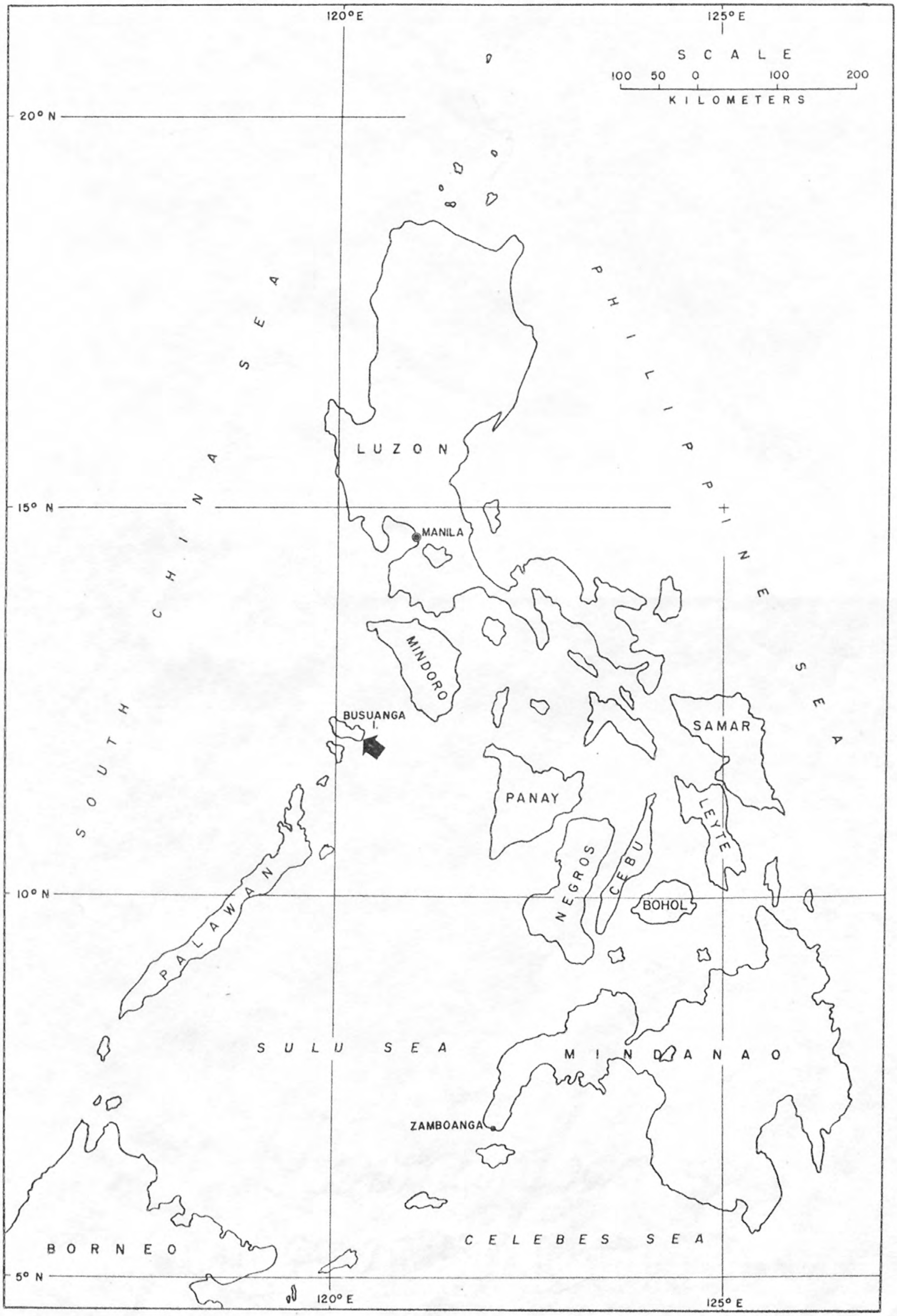


Figure 1.—The Philippines, showing location of Busuanga Island.

PREVIOUS WORK AND ACKNOWLEDGMENTS

Numerous geologists and engineers of the Philippine Bureau of Mines have visited the manganese deposits of Busuanga since their discovery, but little detailed geological exploration was reported before 1951. The most intensive work to this time was done in 1940 and 1941, when a Bureau of Mines field party headed by Ralph W. Marsden began a systematic geological survey of certain deposits and areas around them. Unfortunately, the work was interrupted by the outbreak of the war in 1941, and virtually all of the data were lost. In the years immediately following the wartime occupation of the country by the Japanese, engineers of the Bureau of Mines inspected the mines formerly in operation and recommended that the geologic study be resumed. As a result, a joint Philippine Bureau of Mines-U. S. Geological Survey project was established under the U. S. "Point Four" program to carry out the work.

The writer worked with the following men from the Bureau of Mines: Norberto S. Fernandez, geologist; Demetrio N. Palacio, assistant geologist; Arsenio S. Salazar, assistant geologist; Manuel Lucas, surveyor; and Gavino L. Rosit and Benjamin Villa, technical helpers. Particular acknowledgment is due Fernandez, who did a great deal of topographic map compilation from aerial photographs and assisted ably in the geologic work. Salvador A. Vasquez drafted excellent copies of many of the field maps during periods in 1953 and 1955 when the author was compiling preliminary reports on the project. Vasquez also drafted figure 1 and plate 1 of this report. In May 1955 Miss Visitacion Victorio examined thin sections of some of the rocks.

The field party worked from November 1950 to April 1952, with minor interruptions, carrying out large and small scale surveying and geologic mapping. More than 60 deposits of manganese were studied. About half of these were mapped by plane table methods on the surface on a metric scale of 1:1000 or 1:2000; underground mapping was done by tape and compass on a scale of 1:500. Reconnaissance mapping of the island was done on scales of 1:20,000 and 1:34,000, using for control high-altitude aerial photographs and formline base maps compiled from them by use of a stereocomparagraph. Triangulation by theodolite and some vertical control by aneroid barometer surveys were used in making the small scale maps.

Staffs of the operating mines were cooperative and most cordial during the field work and contributed materially to the progress of the project. Engineer Emilio S. Santos, superintendent of the Luzon Stevedoring Company operations, his family, and his staff were particularly generous in providing truck and boat transportation, temporary lodging, supplies, and in extending many personal courtesies. Many other local residents who were kind enough to offer assistance and hospitality in the field cannot be acknowledged by name, but their kindness is greatly appreciated.

The U. S. Army supplied copies of aerial photographs covering most of Busuanga and in several instances provided transportation by sea. Two of the aerial photographs are reproduced in figure 2. The U. S. Coast Guard furnished air transportation on several occasions. The results of a road survey by Army engineers were made available to aid in compilation of base maps. These forms of aid are acknowledged with thanks.

Ralph W. Marsden kindly furnished copies of field notes and other papers from his files and gave much helpful information through them. Equally valuable information was obtained from him by personal conference and correspondence. Professor S. A. Tyler has shown a stimulating interest in the cherty rocks of Busuanga and has made valuable suggestions regarding the study of them. Professor S. W. Bailey gave helpful advice on X-ray techniques and interpretation of results of the X-ray work. The continued interest and the constructive comments of these men have been encouraging, and it is a pleasure to acknowledge their help.

During the field work the writer was responsible to W. D. Johnston, Jr., Chief, Foreign Geology Branch, U. S. Geological Survey. The laboratory work was done in the geology department of the University of Wisconsin under the direction of Professor E. N. Cameron. The writer is grateful for the aid and encouragement given by these men; without it the investigation could not have been made.

During the writer's employment as geologist by the Geological Survey, funds for the work were provided by the Department of State and, after 1952, by the Foreign Operations Administration. The expenses of other members of the field party were paid by the Philippine Bureau of Mines.

SCOPE OF THE PRESENT INVESTIGATION

The present investigation was planned to correlate detailed field information on the physical character of the manganese deposits with laboratory data on selected ores and rocks in an attempt to arrive at an acceptable hypothesis of origin for the deposits. In order to keep the study to a workable size, it has been necessary to consider the regional geology of the island in detail only in aspects which seem to bear directly on the problem of the origin of the deposits. The general geology of Busuanga is complex and its proper study would constitute a project in itself.

Geologic data obtained in the field suggest certain possibilities as to the origin of the manganese deposits and the enclosing rocks. Significant features common to many of the deposits indicate that the ore zones may be altered sedimentary beds or lenses conformable with the country rock. The cause and nature of the alteration are not clear, however. In addition, important differences are recognized among the ore zones of various deposits. The laboratory work was planned, therefore, to include study of typical materials from deposits representative of the apparently different types. It was hoped that, by studying the mineralogy, paragenesis, and textural features of the ores and wall rocks, it could be determined if more than one type of deposit was indeed present, and that the genetic history of the deposits could be learned.

GEOGRAPHY

TOPOGRAPHY

Steep-sided sinuous hogback ridges and narrow winding stream valleys are the most striking physical features of Busuanga Island (Fig. 2). Elevations are not particularly great, but many ridges approach 350 meters and have relief of about 300 meters. The highest point is Mount Tundalara, or Darala, which is 657 meters above mean sea level and lies just north of Coron town, in the southeastern part of the island (Pl. 1). The trend of the ridges in the east one-fourth of the island is varied, but in the western part parallel alignment of ridge axes is prominent. From the vicinity of the Labañgan River, numerous ridges trend about northwestward as far as the Minuit River, where the principal hills turn to the southwest.

The drainage pattern in the terrain dominated by parallel ridges is characteristically subrectangular or trellis type; but in other parts of the island, streams are dendritic and crudely radial. Plate 1 shows the generalized scheme of the drainage pattern, but many minor streams are not included.

CLIMATE AND VEGETATION

Two principal climatic seasons are experienced on Busuanga Island. From January to July very little rain falls, and temperatures range from about 80° F. at night to 90° or 95° F. during the day. In the period from August to December, however, rainfall is heavy, and

(a)

(b)

Figure 2.--Aerial views of parts of Busuanga Island, from U. S. Government (Air Force) photographs. Altitude 17,000 feet.

a. Eastern Busuanga, looking east-southeast from point above headwaters area of Malamig River.

b. Western Busuanga, looking west-northwest from point above Mapuyawen mine area.

somewhat cooler temperatures prevail. In November and December, when typhoons sometimes pass over the island, the rate of precipitation is probably greatest, and the coolest air temperatures are experienced. Total annual rainfall is commonly greater than 200 cm. Temperatures as low as 65° to 70° F. have been recorded in the early morning during these months. January is commonly dry and relatively cool, and this month consequently is considered one of ideal weather by local residents.

In most parts of the island, moderate breezes from the sea bring some relief from the discomfort of heat and high relative humidity. Strong prevailing winds characteristic of the season are felt throughout the area, from the east and northeast during the dry season, and from the south, southwest, and west during the rainy season. Routes of travel by small boat are generally planned with due regard to direction and strength of the prevailing wind.

Much of Busuanga is densely wooded, but extensive areas have been deforested by agricultural activities and by fire. In the eastern half of the island, flat plains, like that from San Nicolas northwest to Decalachao, are for the most part grassy and devoid of larger growth except along stream courses, and rolling hills bordering the valley plains are also commonly grass covered. In more rugged terrain and particularly in the mountainous, more inaccessible northwest half of Busuanga, forest growth predominates, and cleared areas are found in only a few places.

GEOLOGY

GENERAL

In early writings on the geology of Palawan Province the rocks of Busuanga are commonly referred to as predominantly quartzite (Smith, 1929, p. 255). Marsden and his co-workers were apparently the first geologists to learn some of the details of the stratigraphy, and from Marsden's notes (1940, 1941) it is evident that many chert outcrops were observed and a large number of samples taken. Marsden concluded from his work that the general stratigraphic sequence in southeastern Busuanga consists of poorly bedded quartzite conformably overlain by a great thickness of bedded chert; he tentatively recognized a second massive quartzite bed within the chert sequence._/ In the Maralitin area he found a poorly exposed dark rock, which appeared to be of igneous origin and which he thought may underlie the stratified rocks of the island.

_/ Personal communication, 1952.

The work of the writer and his companions led to conclusions somewhat more detailed but essentially similar to those of Marsden. The principal contributions of the later exploration to the regional geology relate to the distribution of the different rock units over the entire island, to the general geologic structure, and to the presence of limestone younger than the siliceous rocks. The stratigraphic sequence is still poorly known, however. More detailed field work in regional and structural geology is needed to provide a more accurate understanding of the stratigraphy and to correlate results of the intensive studies that have been made in the vicinity of the manganese deposits.

REGIONAL GEOLOGY

The bedded rocks that crop out extensively in Busuanga are predominantly chert, with subordinate amounts of graywacke quartzite, mudstone, and limestone. Basic igneous rocks probably underlie these strata, but no direct evidence of relative age is available. Relationships are commonly obscured by discontinuous outcrops and complex structure.

The oldest unit in the bedded sequence is thought to be a massive quartzite that is 100 meters or more in thickness. The quartzite is overlain by chert beds at least several hundred meters thick, within which are relatively thin clastic beds and the principal manganese ore deposits. These rocks were probably at one time completely overlain by a much younger unfossiliferous limestone bed of which only small outliers are found on the present island surface. Essentially unconsolidated clastic valley fill, which is not extensive except in a few places, is the youngest unit in the section. The stratigraphic column is summarized in Table I.

Table I

	Estimated thickness
Valley fill: clastics	50 meters
—— Unconformity ——————————	
Limestone; massive, unfossiliferous	100 meters
—— Angular unconformity? ——————	
Chert: well-bedded; some minor clastic beds; manganese deposits along bedding planes	1000 meters (?)
Quartzite: massive graywacke; some minor mudstone beds	100 meters
—— Unconformity ? ——————————	
Basic igneous (?) rock; relations obscure	unknown

Basic igneous rock

The supposed igneous rocks noted by Marsden in the Maralitin area, south of Minangas Bay, were investigated in 1952 by N. S. Fernandez. According to Fernandez, the mode of occurrence of these rocks and their relation to chert beds and other rocks in the vicinity are obscured because of the poor exposures. In hand specimen the rock is dark green or gray, fine grained, and appears to consist mostly of ferromagnesian minerals such as pyroxene and chlorite.

Megascopically similar rocks may lie at shallow depths in the settlement of Toob, about 2 kilometers west of the Marcella mine in eastern Busuanga. A medium size boulder was discovered in a plowed field here in 1952.

Graywacke quartzite

Massive graywacke quartzite beds which may have a total thickness of 100 meters or more crop out extensively in parts of Busuanga, forming low rounded hills and flat broad valleys. Fresh outcrops are scarce, and bedding is rarely exposed, but some good exposures are found in small stream valleys. Here the quartzite is generally without mappable bedding, but at places thin shale or mudstone beds show the structure. The fine-grained beds invariably have steep dips.

The structural relation of the quartzite to other stratigraphic units is not everywhere clear. In southern Busuanga, north of Dipulao Cove, bedded chert conformably overlies the clastic beds. Marsden's party measured a section in this area and found that the contact of the chert and quartzite was gradational, and that the chert beds of the ridge east of the Labañgan River definitely overlie the clastic beds in the broad valley east of the ridge. In other areas of quartzite outcrop, however, relations are not well known because of poor exposures, inadequate exploration, and difficulties in correlation.

In hand specimen the rock is typically light to dark gray, fine- to coarse-grained, hard, and consists of poorly rounded mineral grains and rock fragments which are so well cemented that the fresh rock breaks across the grains when fractured. Sorting is poor. In thin section, quartz is the most abundant mineral, but feldspar is fairly abundant in some sections. The sand grains are well packed, and many quartz grains show closely spaced parallel fractures; some grains show a peripheral granulation. The matrix, or cement, which generally makes up only a very small proportion of the rock, consists of fine-grained silica, clay, chlorite, and sericite, with minor amounts of pyrite and brown iron oxide. In some sections, the matrix contains abundant biotite, to the exclusion of the other minerals except pyrite. The biotite grains are commonly irregular in shape and in many places show bent cleavage planes which curve around sand grains. In certain fine-grained specimens the mica shows a crude alignment of the long dimension of the grains parallel to the bedding.

Sparse poorly preserved radiolaria-like fossils are found in some of the fine-grained beds, but no fossils suitable for age determination have been found.

Chert

General

Highly siliceous rocks best described as bedded chert crop out in all parts of Busuanga and are by far the most conspicuous rock type. The manganese deposits lie along bedding planes in these rocks. Total thickness of the beds is difficult to determine because the beds are complexly deformed and greatly eroded, but an estimate of 1,000 meters seems reasonable. In some of the hogback ridges that reach more than 300 meters in elevation, a thickness of several hundred meters is exposed. Mount Tundalara, 657 meters in elevation at the summit, is a complex chert hogback, but perhaps the most striking display of the chert sequence is in a group of parallel ridges that trends northwestward from the Labañgan River, north of Dipulao Cove. In these ridges an accurate minimum thickness of the beds can ultimately be measured if some means is found to determine the thickness of section repeated by folding or faulting. At present this is not known.

The persistence of the chert sequence as a whole throughout the island is shown by the great length of many of the hogback ridges (Fig. 2). Although individual beds commonly cannot be traced more than 100 meters because of poor exposures, it is evident that groups of beds 100 meters or more in thickness have a continuous lateral extent measured in kilometers. Moreover, the continuous nature of the ridge line of many hogbacks suggests strongly that the lithology of the beds is generally uniform along the strike.

In the field several varieties of cherty rocks may be distinguished on the basis of such physical characteristics as color and layering. Color ranges from white to black, with various shades of brown and gray the most common. Marsden_/ suspected that the beds in the lower part of the chert sequence are generally much darker than those in the upper, thicker part of the section. This was not apparent to the writer. It was noted, however, that color of the beds apparently varies with topographic position. Outcrops of chert on hill slopes are generally light in color, but, in most valley exposures, dark colors predominate. In both situations, color is relatively uniform from bed to bed in a given outcrop; color banding is not common.

Layering is well developed in the chert sequence, but thickness of layers varies greatly. Some beds show regular laminae 1 mm or less in thickness (Fig. 3a), but most of the beds are 1 to 5 cm thick (Fig. 3b). Rarely, massive beds as thick as 1 meter crop out. Rhythmic banding is commonly seen in the laminated beds and in outcrops of thin-bedded chert. The rhythm cycles differ greatly in magnitude in these two cases, but the nature of the cycle is similar to the naked eye; relatively thick cherty layers alternate regularly with very thin partings.

_/ Personal communication, 1952.

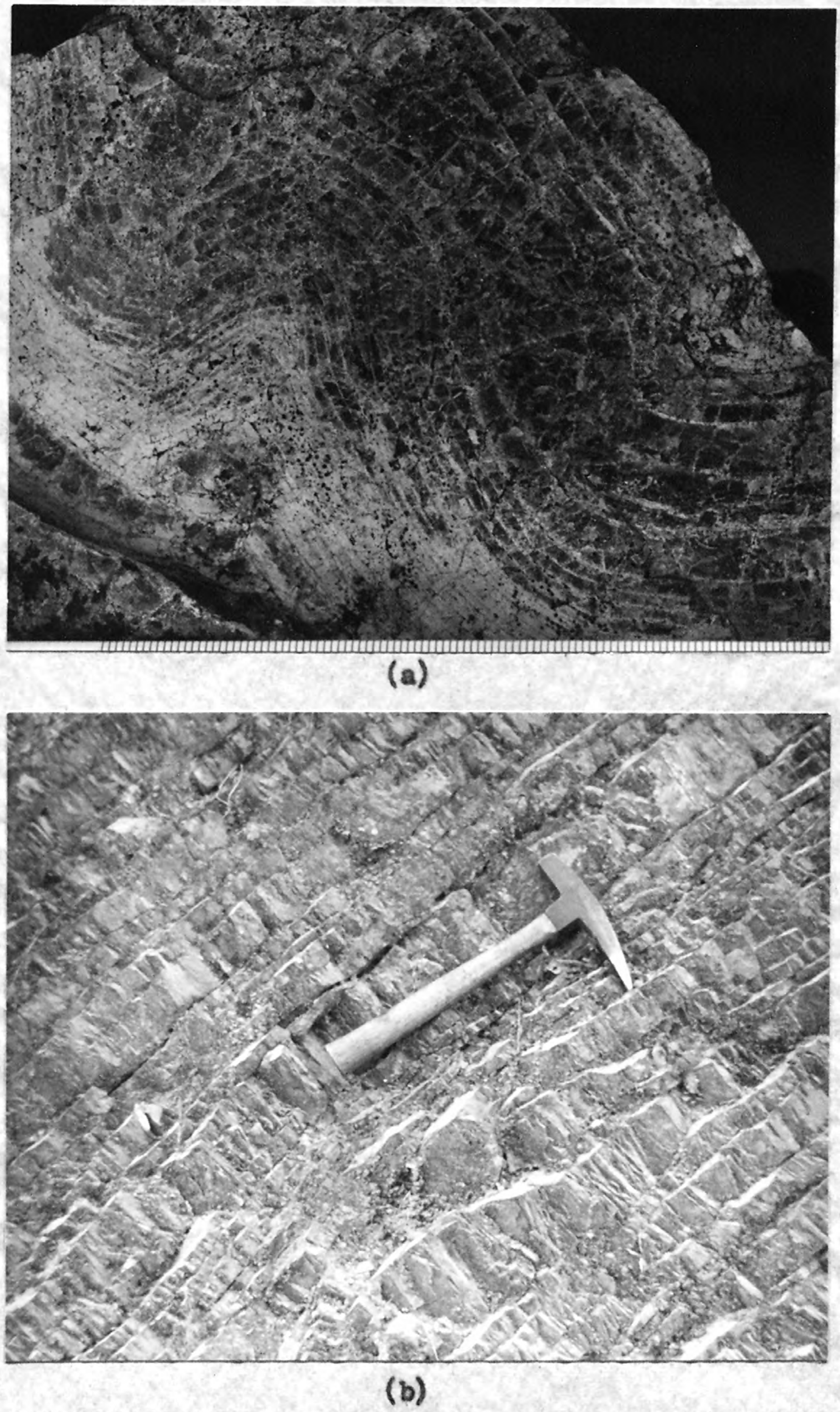


Figure 3.—Layering in chert.

a. Laminated dark gray chert. Folding may be penecontemporaneous in origin. One scale division equals 0.5 mm.

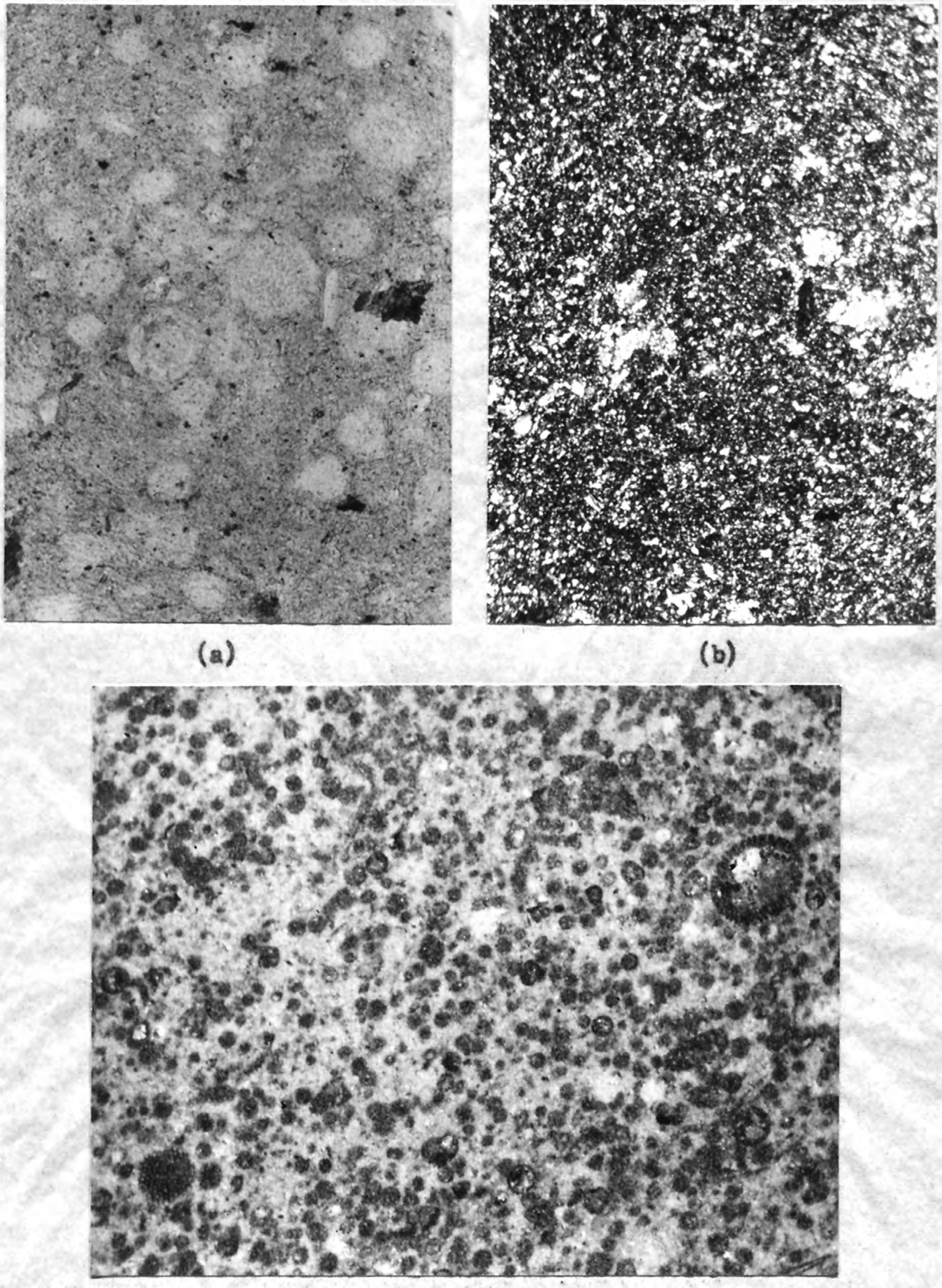
b. Thin-bedded brown chert, near mouth of Labañgan River.

Petrography

Hand specimens of chert commonly have the hardness of quartz. Texture is generally cryptocrystalline and fracture is sub-conchoidal to hackly. Some beds are tougher under the hammer and more resistant to weathering than others, but little difference in texture can be discerned megascopically. Most hand specimens show minute intersecting veinlets of quartz. The beds break easily along bedding planes, except where finely laminated, and jointing along planes roughly normal to the bedding is common.

Thin sections of a number of specimens representative of different types of cherty beds were studied, and several etched surfaces were examined under the microscope in reflected light. It is not implied that an exhaustive petrographic study of the whole chert sequence has been made, but the results of the limited work done serve to indicate the general nature of the rock types most prominent in the field.

The specimens studied are characterized texturally by very fine grain size, a very small proportion of recognizable clastic grains, and irregularly distributed radiolarian fossil remains (Fig. 4). Layering is not commonly evident except in sections of rocks which show good lamination in the hand specimen.



(a) (b)

(c)

Figure 4.—Photomicrographs. Impure chert rich in radiolarian remains.
a. Thin section. Plain light. Magnification 142 x.
b. Same, with crossed polaroids.
c. Polished surface of same specimen etched 20 seconds with HF. Oblique light. Magnification 38 x.

Quartz is by far the most abundant mineral in the sections studied. It forms the matrix of the rocks and fills veinlets and fossil forms as well. In the matrix, grain size is generally very small, and the quartz may be regarded as a cryptocrystalline aggregate in many specimens. In some sections certain bands or patches are essentially isotropic. This material is not opal, for the refraction is commonly greater than that of Canada balsam. The optical properties are similar to those of material termed "isotropic silica" by Goldstein and Hendricks (1953, p. 429), and this term will be used here. Certain thin sections show a faint boxwork structure between crossed polaroids, the central areas being isotropic to cryptocrystalline and grading outward to somewhat coarser quartz along the thin boxwork planes. This structure is scarcely visible in thin sections of the more intensely deformed beds, however, where only scattered small patches of cryptocrystalline quartz are found in an intricate coarse-grained quartz mosaic. The coarse-grained quartz appears to have developed at the expense of the finer-grained quartz.

Quartz filling the circular and oval sections of radiolarian forms is in part coarser than the matrix silica and is relatively free of the minor constituents which are scattered like dust through the cryptocrystalline matrix (Fig. 4a, b). In part, the coarser-grained quartz is somewhat fibrous in nature, but generally the grains form an indistinct mosaic with irregular extinction. The coarse-grained quartz and the matrix quartz react differently to hydrofluoric acid, and light etching of a polished surface with the acid (10 to 30 seconds) brings out details of the texture not visible in thin section (Fig. 4c).

The thin straight veinlets of quartz found in most sections form a random network of varying degrees of complexity. Symmetrical banding in some veinlets indicates that they are probably fracture fillings. In a typical veinlet one or more thin layers of comb-like chalcedonic quartz extend from both walls. Some veinlets have a central area of coarser-grained quartz with mosaic texture. The extinction of the mosaic quartz is less irregular than that of the earlier silica.

Minor constituents in the specimens studied include carbonate, pyrite, iron oxide, clay minerals, and probably organic matter. For the most part these materials are very fine grained and sparsely disseminated, but in some slides local concentrations are found along bedding planes or in irregular aggregates. Except where relatively coarse-grained concentrations of these constituents can be studied, mineral identification is difficult and must be regarded as tentative. Pyrite and carbonate fill radiolarian forms in rare instances, but euhedral grains of these minerals were not found. Clay minerals were not identified as such, but their presence is suggested by the development of sericite flakes in certain coarser-grained chert specimens. The presence of organic material in the chert is suggested by the bleaching effect of weathering (Bramlette, 1946), but a specimen of brown chert dissolved in hydrofluoric acid failed to yield any recognizable organic residue. However, the specimen tested may have been particularly poor in organic matter, just as some beds are devoid of radiolarian remains, and further tests should be made before a conclusion is reached.

The color of the chert beds appears to be due largely to the nature and abundance of the finely disseminated minor constituents. Dark gray and black cherts have a greater proportion of pyrite-like sulfides than the lighter colored cherts and the dark color is probably caused by these minerals. In the brown chert beds, the color is presumably related to the finely divided brown "dust", probably iron oxides, in the rocks. Organic material may be an effective coloring agent in many of the beds.

No manganese minerals were recognized in the chert, and X-ray spectrograph tests made by the writer and chemical analyses performed during Marsden's work (see p. 75) show virtually no manganese in typical chert specimens.

A thin section of well-laminated brown chert was studied to determine the nature of the lamination. In the hand specimen, the layering is marked by scarcely visible partings which look the same in physical character as the laminae. Under the microscope, however, it was found that the silica along the partings is nearly isotropic and much finer grained than that of the laminae. In addition, the partings contain a somewhat greater proportion of finely divided minor constituents than do the intervening laminae (Fig. 5). The index of refraction of the silica appears to be uniform throughout the section, however. It is concluded that the lamination in the specimen studied is due to minor but significant differences in lithology over a very small stratigraphic interval.

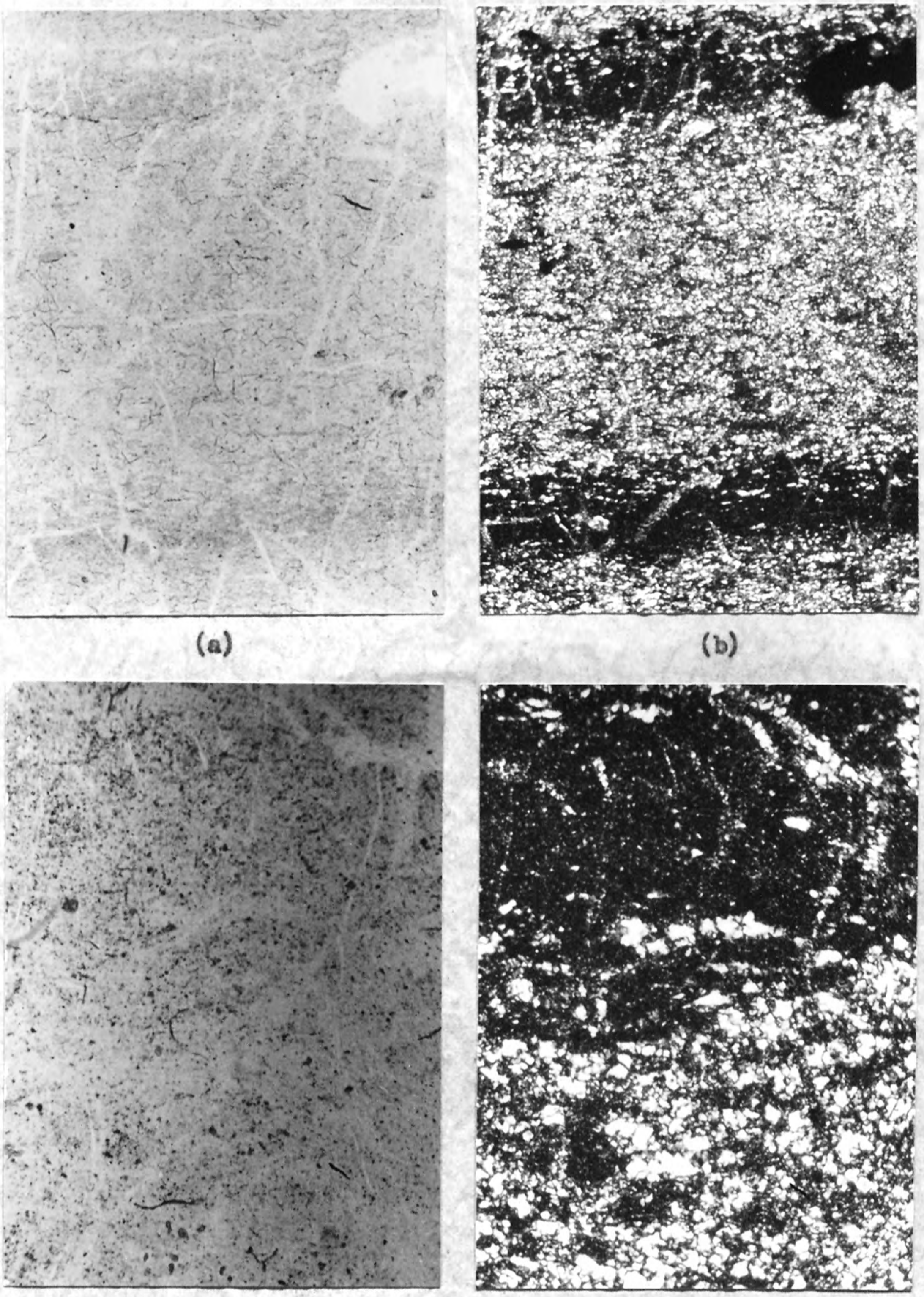
Figure 5.--Photomicrographs. Thin sections of laminated brown chert.

a. Faint thin bands near top and bottom are partings between chert laminae which make up rest of area of picture. Plain light. Magnification 38 x.

b. Same, with crossed polaroids.

c. Contact of parting (upper half of picture) and chert lamina. Note relative abundance of very finely divided opaque material in parting. Plain light. Magnification 142 x.

d. Same, with crossed polaroids. Note very fine grained silica in the parting.



(a) (b)

(c) (d)

Figure 5

The nature of the partings between 1 to 5 cm chert layers in thin-bedded parts of the chert sequence was not studied in the laboratory, but in the field the partings appeared to be clayey or shaly. It is suggested that here the situation is similar to that in the laminated chert beds, except that the bedding units are thicker and the fine-grained non-silica material in the partings predominates over silica. The partings are, therefore, poorly cemented and are disaggregated by weathering with relative ease.

Summary

In this brief description of the major features of specimens of the chert beds, no attempt has been made to correlate the rocks with varietal names like those used by Taliaferro (1934), Pettijohn (1949), and others for highly siliceous rocks. A detailed study and classification of rock types in the Busuanga chert sequence based on modern terminology would be of interest, to be sure, but research of this kind is outside the scope of the present investigation. It has been pointed out that the chert beds are to some extent impure, in the sense that constituents other than silica are present. The proportion of clastic material to non-clastic material in the impurities is not known, however. The shaly partings in thin-bedded chert suggest that clastic material may be more common in the chert than is recognized, and, indeed, a more complete study may reveal silicified mudstones and similar beds in the sequence. Nevertheless, on the basis of the laboratory information and field evidence at hand, it is the writer's opinion that the siliceous rocks of Busuanga consist for the most part of non-clastic silica and the remains of siliceous organisms. Chert seems to be the best inclusive term for these rocks.

The origin of the chert beds is discussed in the section on origin of the manganese deposits.

The age of the chert beds is not known. A number of specimens containing radiolaria were examined by Lloyd Henbest, U. S. Geological Survey, who confirmed the presence of radiolaria and other microfossils but found no material suitable for age assignment._/ Similar rocks in the province of Ilocos Norte and on Panay and Balabac Islands were considered by Smith (1924, p. 72-74) to be of probable Jurassic age, on the basis of lithologic and faunal similarities to supposedly Jurassic cherts in the Moluccas and Borneo, and to the Franciscan cherts of California.

Limestone

Hard, dense, massive limestone crops out in a few places on Busuanga and forms several nearby islands, notably Coron, Tañgat, and Elet. It is commonly gray, coarsely crystalline, and weathers to a craggy, cavernous mass. It is nowhere found in direct contact with the other rocks. In two places thin conglomeratic zones containing cherty rock fragments are exposed, and it is believed that the limestone is younger than and unconformably overlies the other bedded rocks on Busuanga. The limestone does not show bedding or other sedimentary features except the conglomeratic zones and sparse oolitic forms.

The age of the limestone is not known with certainty.

_/ Personal communication from Charles W. Merriam, 1957.

In the conglomerate that crops out in the extreme northwestern part of the island, near Elet Island, marine fauna are found which are classed Miocene or Pliocene in age by Bureau of Mines paleontologists. A limestone float block in central Busuanga yielded a fairly well preserved foraminiferal shell, but paleontologists of the Geological Survey term it not identifiable. Thus it can only be said that the limestone is probably of Late Tertiary age.

Valley fill

Sandy unconsolidated material covers the main valleys, in places to a depth of several tens of meters. Poorly preserved fossils indicate that the fill is probably in part of marine origin, but it is believed to consist in large part of Recent alluvium.

STRUCTURE

Strong deformation is displayed in the rocks of Busuanga in structures which range in size from a few millimeters to kilometers. Intense folding is shown in the bedded cherts (Figs. 3a, 6), and faulting is also evident. Much small-scale folding may be of penecontemporaneous origin.

Two major patterns of folding have been recognized. Close folding along horizontal axes is strongly suggested by the numerous roughly parallel hogback ridges, like those west of the Labañgan River; minor folds with similar orientation are commonly observed. The second system of folds, broader and transverse to the first, is reflected by the sinuous trend of the ridges. The largest fold of this system is a north-plunging major anticline, the axial trace of which extends southward along the Minuit River from the village of Cheey, in northwestern Busuanga. The two fold systems may be products of the same general period of deformation.

The manganese ore zones are folded and faulted in the same manner as the enclosing rocks. There seems to be little question that the rocks which make up the ore zones, or their precursors, were deposited before deformation took place and that they behaved much like the country rocks under stress.

Figure 6.--Close folding in thick- and thin-bedded chert. Road cut on west side of Dipulao Cove.

MANGANESE DEPOSITS

More than 60 separate deposits of manganese ore are known on the island of Busuanga. Nearly all were examined in the course of the field work, and more than 30 were mapped in detail on the surface and in underground openings. The locations of most of the deposits are shown on plate 1. On the map, deposits which have yielded more than 100 metric tons of commercial grade ore are classed as mines; smaller deposits are termed prospects.

Without significant exception, the manganese deposits are tabular or broadly lenticular in shape and follow bedding planes in the chert sequence, even where deformation is intense. The ore zone is commonly 1 meter or less in thickness, and the maximum lateral extent in most places is less than 200 meters. The maximum vertical range through which a deposit has been traced is about 220 meters, in the Singay mine.

MINERALOGY

In most of the deposits, the ore zone at and near the surface of the ground is made up of hard black psilomelane-type oxides, high in manganese content and apparently much the same from deposit to deposit. In many mines of small vertical extent, this ore persists in the lowest working accessible by adit. In several of the deepest mines, however, the black ore gives way at depth to fine-grained siliceous brown and gray protore. Four of these deposits were studied in detail, and in three the protore was found to contain much braunite and quartz; in the fourth, hausmannite and alleghanyite are the main constituents.

In discussing the character and probable mode of origin of these protores, the term "primary ore" will be used synonymously with "protore" to describe what appears to be the earliest mineral assemblage present. The term "original deposit" will be restricted to the hypothetical material thought to have occupied the ore zone before formation of the protore.

The specimens to be studied in the laboratory were selected after careful study of field notes and maps. After megascopic examination of the specimens, many polished surfaces and thin sections were prepared for microscopic study. A few samples were submitted to the U. S. Geological Survey for partial chemical analysis, and several specimens were analyzed qualitatively by use of the X-ray spectrograph.

Both mineragraphic and petrographic examination of the ores and rocks were indispensable in studying the mineralogy and textural features. Where certain minerals could not be identified by optical methods because of fine grain size or lack of diagnostic properties, minute samples were taken from polished surfaces or hand specimens and X-rayed by the powder method. The X-ray diffraction patterns obtained were compared with published mineralogical data to identify the unknown material (see Appendix). Certain minerals could not be identified with certainty, however, by either optical or X-ray methods, and in the text these mineral names are queried. For example, very small needle-like clusters of a brownish mineral associated with braunite and quartz in the Piña deposit appear to have approximately the index of refraction and birefringence of bementite; but an X-ray pattern of a specimen removed carefully from a polished surface showed lines from only quartz and braunite. In the discussion, therefore, the mineral is designated bementite(?). In specimens from the Malamig deposit, however, a late vein mineral is found which gives an X-ray pattern much like a published pattern of bementite(ASTM card 3-0971), and the mineral is consequently listed as bementite. Other examples could be cited.

Mineral formulae given are taken from a recent compilation by members of the U. S. Geological Survey (Hewett, et al., 1956, p. 171), unless otherwise noted.

Braunite protore

General

Two of the braunite deposits, Piña and Siñgay, are less than 2 km apart, and the other, Dimanyang, is about 12 km distant; all are in southeastern Busuanga. The stratigraphic positions of the deposits in the chert sequence may be similar, but inadequate knowledge of the regional geology prevents correlation among the deposits.

The braunite deposits are similar in their principal features, such as mineralogy and paragenesis, relations of the ore to the wall rocks, and the nature of the wall rocks. The deposits differ, to some extent, in proportions of the different minerals, degree of development of layering in the ore, and average grain size of the constituents. These differences are not great enough, however, to warrant a further subdivision of the classification.

The principal minerals of the braunite protore are listed below in approximate order of abundance.

braunite	$3Mn_2O_3.MnSiO_3$
quartz	SiO_2
bementite	$8MnO.7SiO_2.5H_2O$
pyroxmangite	$(Mn,Fe)SiO_3$

Minor amounts of iron oxides, rhodochrosite, hausmannite, alleghanyite(?), and perhaps other manganese silicates are found in certain specimens. Hübnerite(?) was encountered in one specimen from the Siñgay mine.

Grain size of the minerals is generally microscopically small, and in the Siñgay deposit, much cryptocrystalline or amorphous material is encountered.

The proportions of the major constituents, braunite and quartz, are noticeably different, even megascopically, from deposit to deposit, and appear to bear a direct relation to the development of lamination in the ore zone. The Dimanyang protore contains probably less than 5 percent quartz, and lamination is poorly defined because most of the quartz is intimately mixed with braunite (Fig. 7); even thin seams containing much quartz contain abundant disseminated braunite. The Piña protore, however, contains perhaps several times as much quartz as that at Dimanyang, and commonly exhibits good lamination of nearly pure quartz seams with layers made up of braunite, silicates, and quartz (Fig. 8). The Siñgay ore also contains abundant quartz and shows good lamination (Fig. 9).

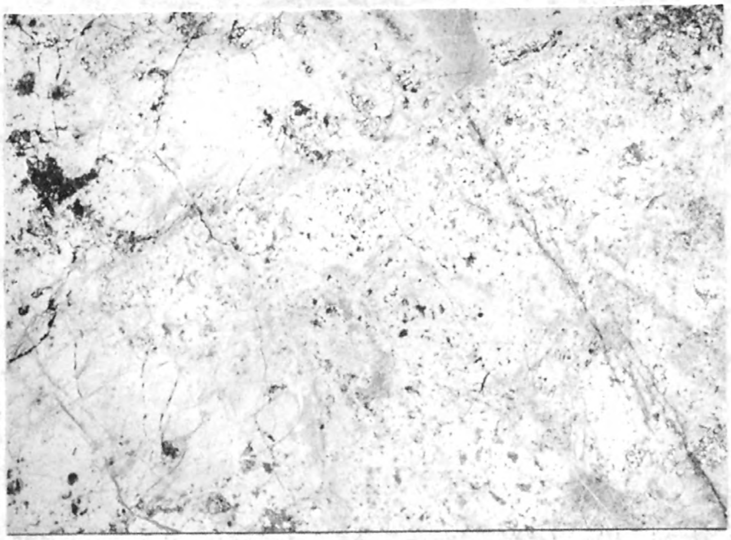


Figure 7.—Polished surface. Massive braunite ore, Dimanyang deposit. Fine-grained aggregates of braunite (light to medium gray) with small proportion of interstitial quartz and silicates (dark gray to black). Plain light. Magnification 6 x.

Figure 8.--Polished surface mounted in plastic. Layered braunite ore, Piña deposit. Cherty layers (medium gray) grade into braunite-silicate-quartz layers (gray flecked with white). Short veinlets of quartz (dark gray) cut some layers. Plain light. Magnification 6 x.

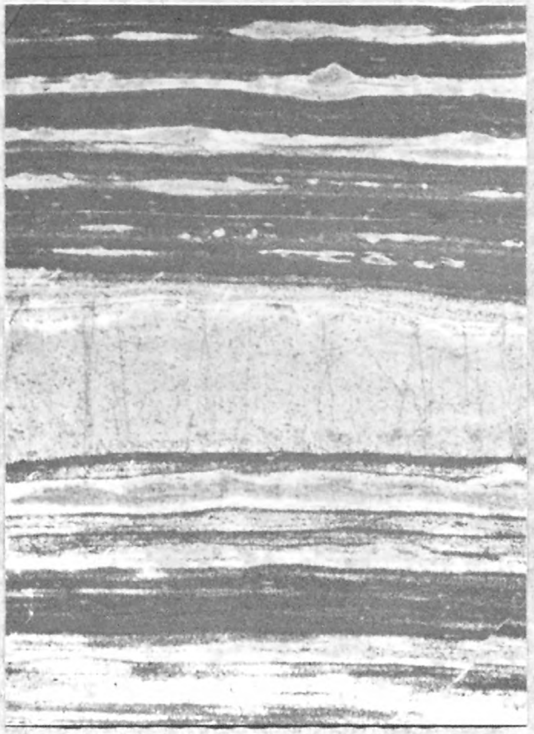


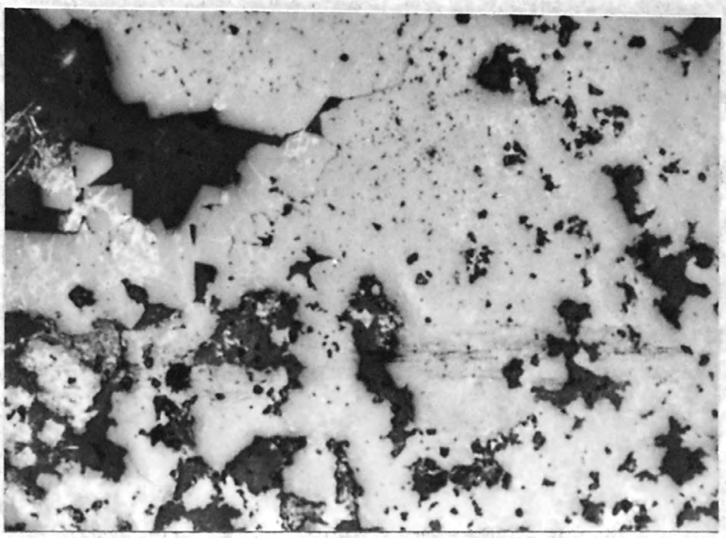
Figure 9.--Polished surface. Layered braunite ore, Siñgay deposit. Braunite layers (light gray) contain appreciable amount of disseminated quartz-silicate-carbonate gangue. Quartz-silicate-carbonate(?) layers (dark gray) contain a small amount of fine-grained braunite. Plain light. Magnification 6 x.

The minor constituents nowhere are abundant enough to form well-defined layers, but concentrations of bementite(?), pyroxmangite, and iron oxide at places impart a distinctive color to braunite or quartz layers. In the Piña deposit, braunite layers have a patchy light brown aspect where bementite(?) is relatively plentiful; where pyroxmangite is present locally, a faint red to purple color is visible. Where braunite is lacking, seams of pyroxmangite impart a delicate pink tint to quartz. At the Siñgay mine, as well as at Piña, very finely dispersed iron oxide in cherty layers gives the layers an orange or light brown hue.

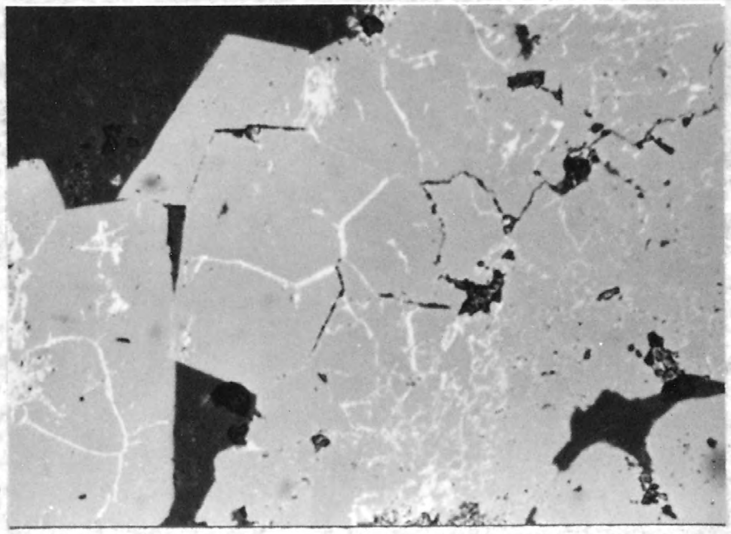
Braunite layers

The layers and massive ore made up largely of braunite are the dominant features of the protores. Without exception they consist of granular aggregates of braunite and a minor proportion of interstitial non-opaque minerals which include silica, silicates, and, to a lesser extent, carbonate (probably rhodochrosite). In general, the braunite grains are somewhat larger than grains of the other minerals.

Relations within the braunite layers are best shown in the Pina deposit. The braunite is typically in irregular aggregates (Fig. 10a) in which individual grains generally range from 0.005 mm to 0.05 mm in size. Larger subhedral grains not uncommonly surround relatively large quartz areas (Fig. 10b). In certain places where clusters of small pyroxmangite crystals border the braunite layer, some small braunite aggregates have a rudely tabular outline not unlike the shape of pyroxmangite crystals. Fine-grained mosaic quartz with



(a)



(b)

Figure 10.--Photomicrographs. Polished surface of braunite ore, Dimanyang deposit.

a. Braunite (light gray) is mostly in irregular granular aggregates, with interstitial quartz (dark gray). Note subhedral braunite grains in upper left corner of picture. Plain light. Magnification 90 x.

b. Detail of subhedral braunite grains and adjacent irregular braunite aggregates. Note alteration to cryptomelane(?) (white) along grain boundaries. Plain light. Magnification 385 x.

strongly wavy extinction separates the braunite aggregates. At many points clusters of very fine grained needle-like crystals of a yellow-brown mineral (bementite(?)) radiate from the braunite and cut the quartz without regard for grain boundaries (Fig. 11).

The same general relationships of braunite aggregates to gangue are found in the ore at Dimanyang, but the gangue is of somewhat different character. Appreciable quantities of fine-grained silicates and rhodocrosite are closely associated with the mosaic quartz. The carbonate is of particular interest, for in certain places where it is in irregular patches and rude veinlike bodies of small extent, the braunite aggregates are made up of particularly coarse and well-formed grains. In the same deposit, one specimen was found to contain intimately related hausmannite and alleghanyite as well as the typical braunite aggregates. The relation of the two ore types is not clear, for the contact between the two is irregular and gradational. The same specimen showed thin bementite veinlets associated with minor veinlike hausmannite.

At the Siñgay mine, braunite-rich layers are also composed of granular aggregates of braunite and intimately intergrown gangue, but the ore is so fine grained that only the braunite and cryptocrystalline quartz could be identified with assurance. Minor amounts of silicate(?) and carbonate are mixed with the quartz, but the minerals could not be determined by optical or X-ray methods.

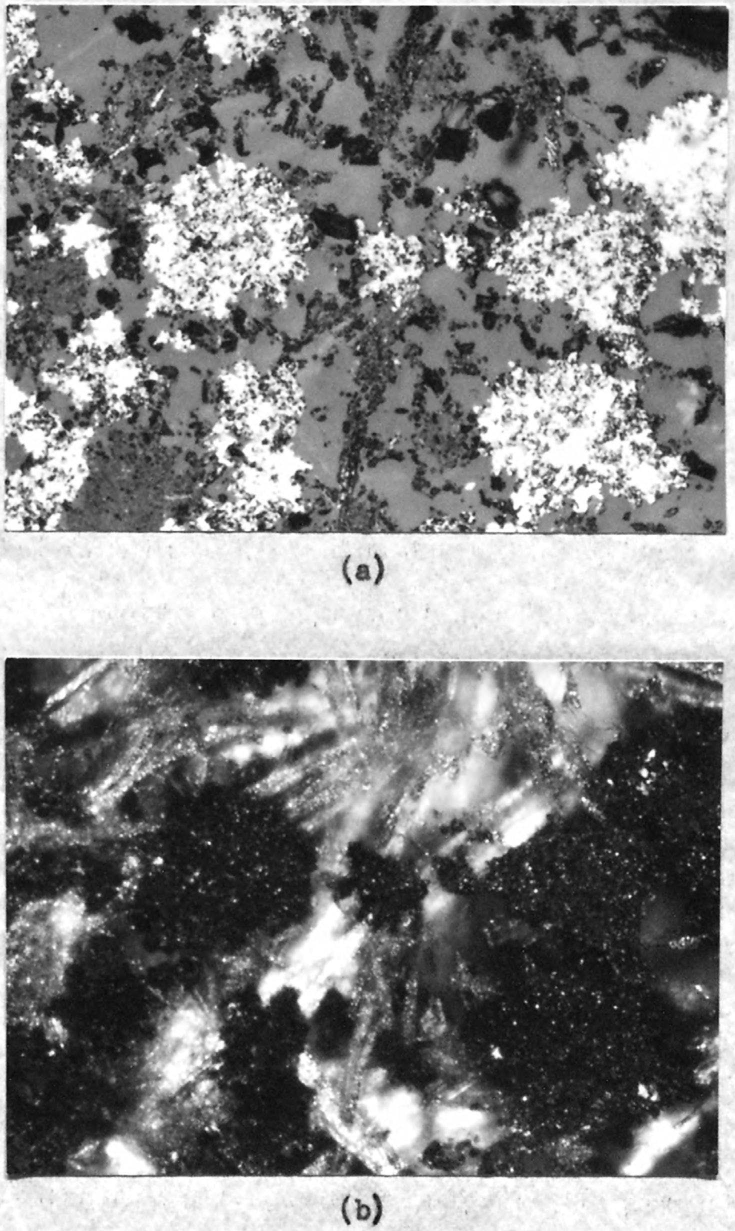


Figure 11.—Photomicrographs. Polished surface of braunite ore, Piña deposit. Very fine grained aggregates of braunite (white to light gray), with interstitial quartz and acicular bementite(?) crystals. Magnification 385 x.

a. Plain light.
b. Crossed polaroids.

Internal structure of the braunite-rich layers is for the most part massive or irregular, or coffined to a vague layering parallel to the lamination of the ore zone as a whole. It is significant, however, that in each deposit one or more specimens show circular or ovoid quartz areas in the braunite-rich layers, much like the sections of radiolarian shells common in the chert beds. In the ore, braunite grains fringe the quartz but ordinarily do not penetrate the forms to a great extent (Fig. 12).

Non-opaque layers

Well-defined layers made up chiefly of non-opaque minerals alternate with braunite-rich layers in both the Piña and Siñgay deposits. The layers are predominantly quartz, but in some specimens appreciable amounts of iron oxide and unidentified fine-grained silicate(?) and carbonate(?) accompany the silica. In certain layers, disseminated grains and small granular aggregates of braunite are sparsely distributed parallel to the bedding (Fig. 9); the general range of grain size is about the same as in the associated braunite-rich layers. Outlines of radiolarian forms are common (Fig. 13).

The internal features of the non-opaque layers are best studied in the relatively coarse-grained ore zone at Piña. Although the color is variable from layer to layer, ranging from nearly white to gray and orange-brown, the chief constituent in all is fine-grained quartz, with mosaic texture and pronounced wavy extinction. Radiolarian forms commonly enclose somewhat coarser grained quartz and are outlined by peripheral accumulations of minor fine-grained constituents.

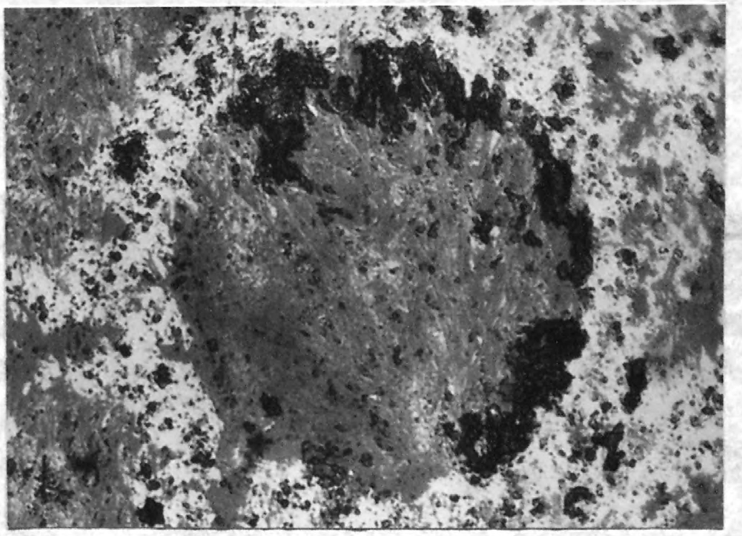


Figure 12.--Photomicrograph. Polished surface of braunite ore, Siñgay deposit. Fine-grained braunite aggregates (light gray) form rim around radiolarian form. Quartz and silicate make up remainder of area shown. Plain light. Magnification 385 x.

Figure 13.--Polished surface. Cherty, low grade part of braunite ore zone, Piña deposit. Note abundant radiolarian forms in both the chert layers (medium gray) and the manganiferous layers (dark gray). Braunite grains (light gray) are disseminated in the manganiferous layers. Plain light. Magnification 6 x.

The minor constituents in these cherty layers are poorly studied. For the most part they are so fine grained that identification by optical means, even using a magnification as high as 1970x, is impossible. In certain white chert laminae, to judge from indirect evidence, disseminated "dust" may be in part manganese-bearing. In the laminae in question, a thin selvage of pyroxmangite crystals lies between the chert and adjacent braunite layers. The "dust", which in the main part of the chert layer is relatively common, particularly around ovoid fossil forms, decreases in abundance at certain places near the pyroxmangite selvage where scattered colorless needle-like crystals lie at random in the quartz. The crystals could not be identified, but their proximity to the pyroxmangite suggests that they may be manganiferous, and the lack of "dust" in their vicinity suggests that they may have formed at the expense of the "dust."

In brown chert laminae, the principal minor constituent is very finely divided iron oxide. Small amounts of fine-grained silicates and carbonate are admixed locally, as in some parts of the Siñgay ore zone. It is noteworthy that some layers of this type at Siñgay contain sparse, very finely disseminated braunite, and that only quartz is recognized immediately next to the wispy braunite aggregates (Fig. 14). It seems likely that the braunite developed at the expense of the fine-grained silicates and carbonate.

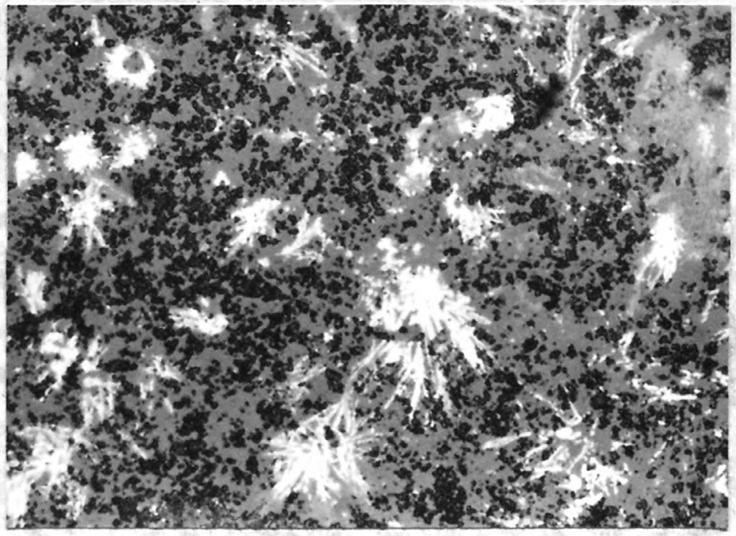


Figure 14.--Photomicrograph. Polished surface of cherty, low-grade part of braunite ore zone, Siñgay deposit. Wispy aggregates of braunite (white, light gray) in cherty matrix (dark gray). Well-polished areas of matrix are essentially pure quartz; pitted areas consist of quartz, silicate, and carbonate. Plain light. Magnification 385 x.

The pyroxmangite selvage is, as far as known, a feature peculiar to the Piña deposit, where it is found in specimens of the protore from one tunnel. The selvage is actually a thin seam of pyroxmangite crystals, no more than 1 millimeter or 2 millimeters thick, between white chert layers and braunite-rich layers (Fig. 15). The crystals are smaller, clearer, and less closely packed at the chert contact than at the braunite contact. Chert-like mosaic quartz lies interstitial to the silicate crystals, and in a few places radiolarian forms are recognizable.

Irregular short quartz veinlets much like those commonly observed in the chert country rock cut the various layers of the protore. Grain size is somewhat larger than that in the chert and braunite layers, and wavy extinction is common, as in the finer-grained quartz. Of the other minerals, only bementite(?) needles transect the grains of the vein quartz.

An unusual vein mineral which gives an X-ray pattern similar to that of hübnerite ($MnWO_4$) cuts across the layers of cherty braunite ore in one specimen from the Siñgay deposit. In polished surfaces the mineral has low reflectivity, strong anisotropism with deep red internal reflections, and a yellow-brown streak. It may well be a tungsten-bearing mineral, but its significance is not clear because of its limited occurrence.

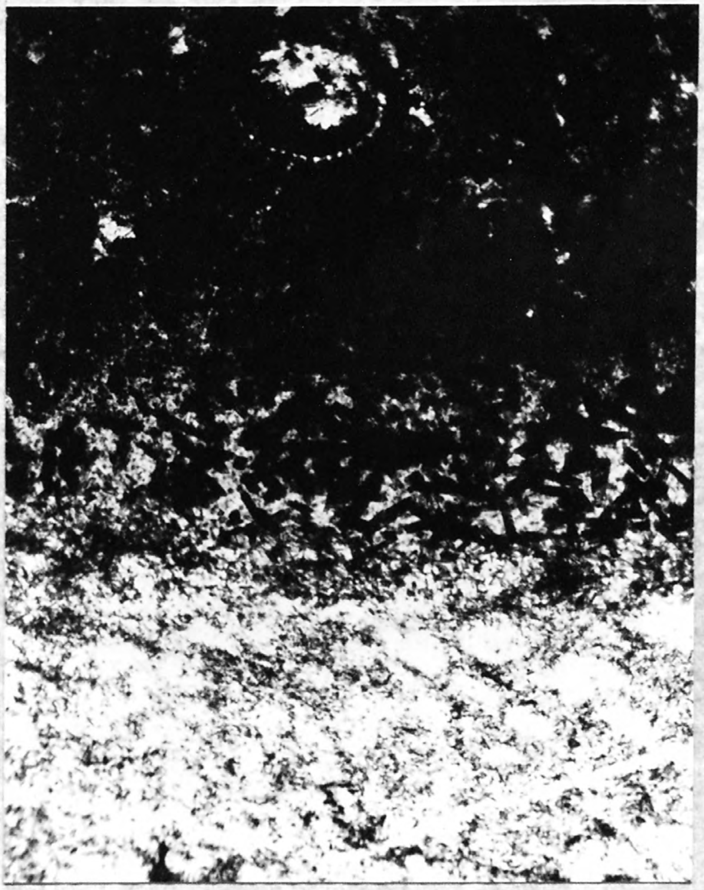


Figure 15.--Photomicrograph. Thin section of cherty braunite ore zone, Piña deposit. Thin seam of tabular pyroxmangite crystals across middle of picture separates cherty layer below from braunite layer above (black). Transparent minerals largely quartz. Note radiolarian form in braunite layer (top). Plain light. Magnification 142 x.

Paragenetic sequence

The mineral assemblages of the various types of layers in the braunite protores evidently developed by recrystallization, essentially in place, of siliceous manganiferous sediments. There is no evidence, such as cross-cutting veins or partly replaced older beds, to indicate post-depositional introduction of manganese. A correlation of the crystalloblastic sequence of mineral formation from layer to layer is difficult to establish, but within a given layer certain age relationships are clearly shown by the textural features. Those features considered significant with regard to paragenesis are summarized below, but it should be kept in mind that, in general, mineral formation is thought to have been a continuous, progressive process. Coincidence and overlap of times of mineral formation were probably the rule rather than the exception.

The earliest stage of recrystallization is recognized in the cherty layers of the Siñgay ore zone. Here wispy, dendrite-like braunite aggregates appear to have formed by recrystallization of fine-grained silicates and carbonate disseminated in the cherty matrix. A by-product of this reaction was evidently the development of relatively coarse grained quartz around the braunite aggregates. In the more highly metamorphosed deposits, braunite aggregates are coarser and more abundant, and coarse-grained quartz with mosaic texture fills the interstices and makes up the remainder of the rock. In the associated pyroxmangite seams, tabular crystals of the silicate also appear to have formed earlier than the quartz mosaic which encloses them. The abundant bementite(?) needles in some braunite layers, on the other hand, evidently formed later than the quartz and the braunite.

The rare hausmannite, alleghanyite, and veinlike bementite and rhodocrosite in the braunite ore at Dimanyang may have formed at about the same time as the braunite aggregates, for these components seem to be mutually penetrating. The thin veinlet of hübnerite which cuts the cherty braunite layers in one specimen of the Siñgay protore is clearly later than the other minerals in the rock, but its origin is uncertain.

In summary, it is emphasized that the age difference of associated minerals in the braunite protores is probably not great. This is because the age difference in most instances is related closely to the reactions which took place during recrystallization and to the rate of the reactions. The reactions probably involved a reorganization of constituents of earlier minerals, and proceeded at a slow rate; the resulting manganiferous and non-manganiferous products would be expected to form at the same general time.

Hausmannite protore

General

The one known deposit of hausmannite protore is at the Malamig mine, in northwestern Busuanga. The deposit is more than 20 km from the braunite deposits described, and the stratigraphic relations between the two are not known.

The principal minerals identified in the hausmannite protore are listed below in approximate order of decreasing abundance.

hausmannite	$MnMn_2O_4$
Alleghanyite	$Mn_5(SiO_4)_2(OH,F)_2$
rhodochrosite	$MnCO_3$
manganosite	MnO

Other minerals found rarely are quartz, jacobsite(?), braunite, and questionable bementite and millerite.

Mineral relations

The minerals are without exception microscopically to submicroscopically fine grained, and for the most part are intimately mixed. The dominant component is made up of hausmannite blebs finely dispersed in very fine grained alleghanyite, which for convenience will be referred to as hausmannite-alleghanyite (Fig. 16). Small amounts of coarser grained hausmannite, mangamosite, bementite(?), and rhodochrosite are commonly associated closely with this component. The rare braunite and jacobsite(?)($MnFe_2O_4$), where encountered, are similarly related. Rhodochrosite also forms massive granular ore.

Recognizable layering is rare in the hausmannite protore. Widely spaced partings parallel to the wall rock contacts are found in the ore zone in certain mine openings (Fig. 17), and these may represent bedding planes or joints controlled by original ore structures. But in hand specimens, mineral distribution and relations are

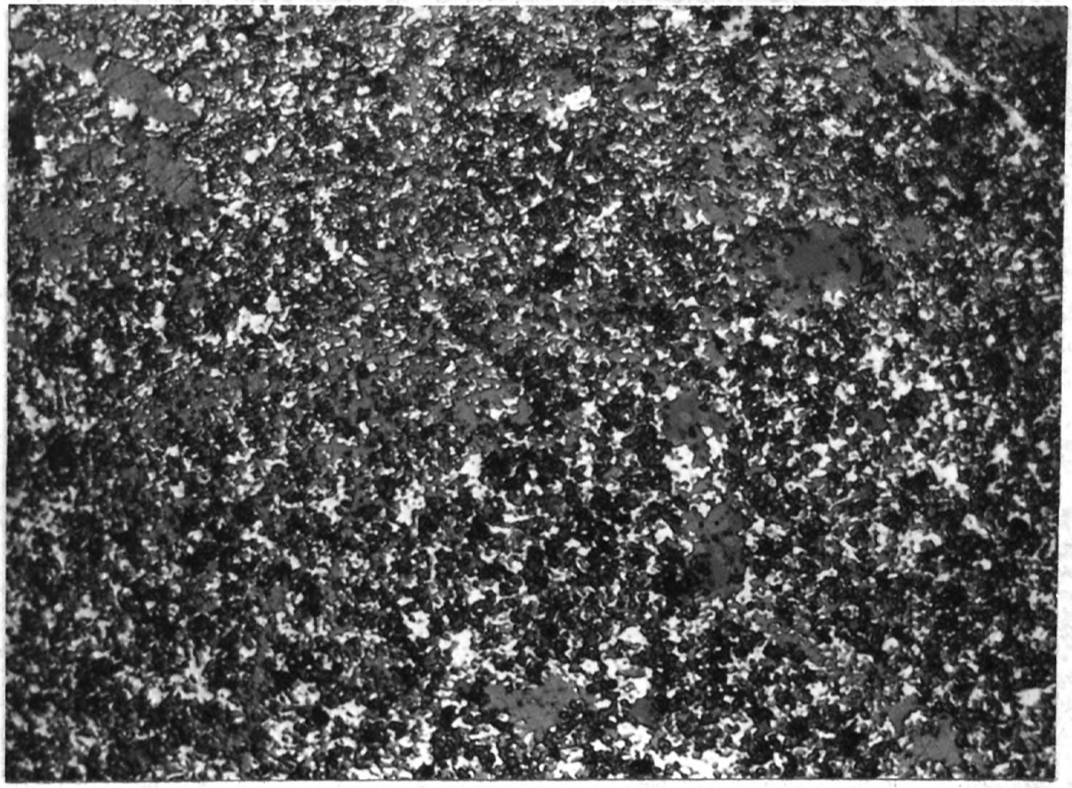


Figure 16.—Photomicrograph. Polished surface of hausmannite-alleghanyite ore, Malamig deposit. Very small blebs of hausmannite (light gray) are disseminated in very fine grained alleghanyite matrix. Plain light. Magnification 385 x.

Figure 17. Ore zone exposed at end of old open cut, Malamig deposit. Note ore zone parting parallel to steeply dipping wall rock structure near man.

irregular, and no regular layering is discernable (Fig. 18). The massive rhodochrosite ore, according to E. S. Santos,_/ who gave the specimens to the writer, forms a layer at the top of the ore zone in the lowest tunnel, but the hand specimens show no evidence of bedding.

The relationships of the principal minerals in the hausmannite protore are not consistent, even within the area of one polished surface. For example, relatively coarse-grained hausmannite aggregates appear to be earlier than the hausmannite-alleghanyite which penetrates them along fractures and encloses them (Fig. 18), but in certain areas where rhodochrosite is abundant, veinlike hausmannite looks particularly fresh and well formed and appears to be later than the hausmannite-alleghanyite (Fig. 19). Similarly, manganosite is enclosed and corroded by coarse-grained hausmannite in some areas (Fig. 20), but elsewhere in the same specimen it appears to have a veinlike form that transects the hausmannite (Fig. 18). In some specimens, narrow veinlets cutting hausmannite-alleghanyite contain rhodochrosite or, less commonly, alleghanyite (Fig. 21).

In one surface coarse-grained hausmannite appears to replace partly small areas of granular braunite, but elsewhere braunite is not found. In another surface from the same tunnel, sparse veinlets of jacobsite(?) thread through a matrix made up largely of silicates. The jacobsite(?) is closely associated with irregular patches of rhodochrosite.

_/ Personal communication, 1952.

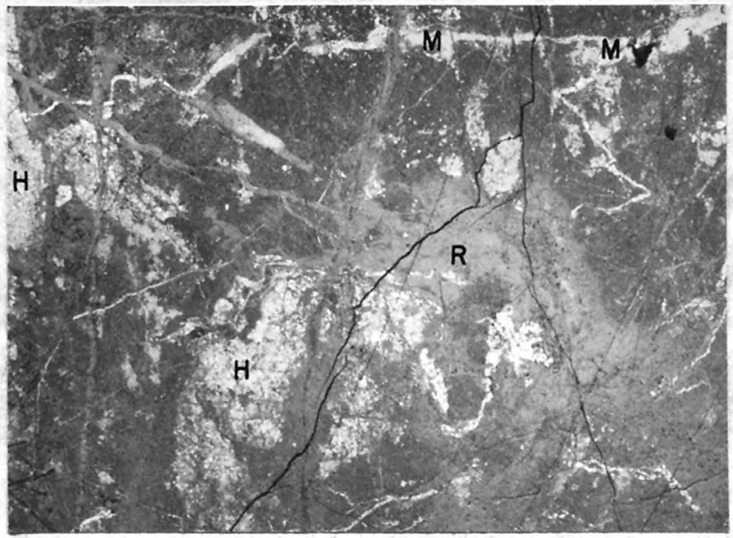


Figure 18. Polished surface. Hausmannite protore, Malamig deposit. Alleghanyite (dark gray) contains finely disseminated hausmannite. Relatively coarse grained hausmannite (H) and rhodochrosite (R) are in irregular aggregates and veinlets. Manganosite (M) forms one prominent veinlike mass. Plain light. Magnification 6 x.

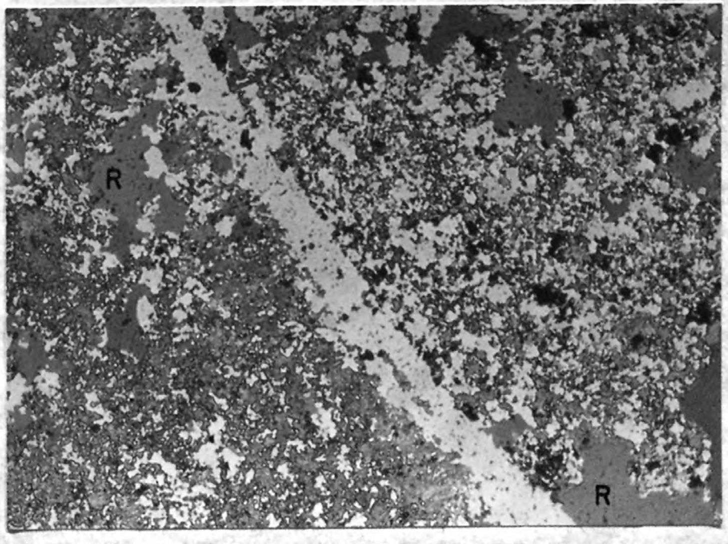


Figure 19. Photomicrograph. Polished surface of hausmannite protore, Malamig deposit. Coarse-grained veinlike hausmannite (light gray) associated with rhodochrosite (R) appears to cut matrix of hausmannite-alleghanyite. Plain light. Magnification 160 x.

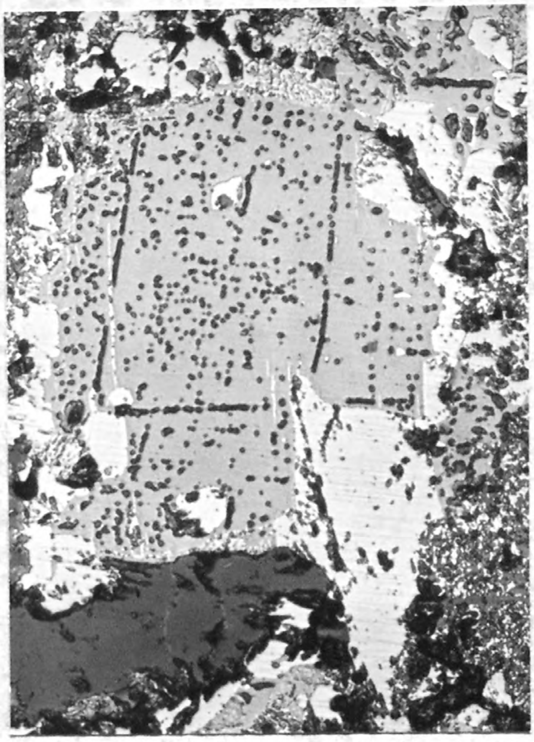


Figure 20. Photomicrograph. Polished surface of hausmannite protore, Malamig deposit. Manganosite (medium gray, center) corroded by hausmannite (light gray). Groundmass is mostly hausmannite-alleghanyite. Some bementite may be present (dark gray, bottom left). Plain light. Magnification 210 x.

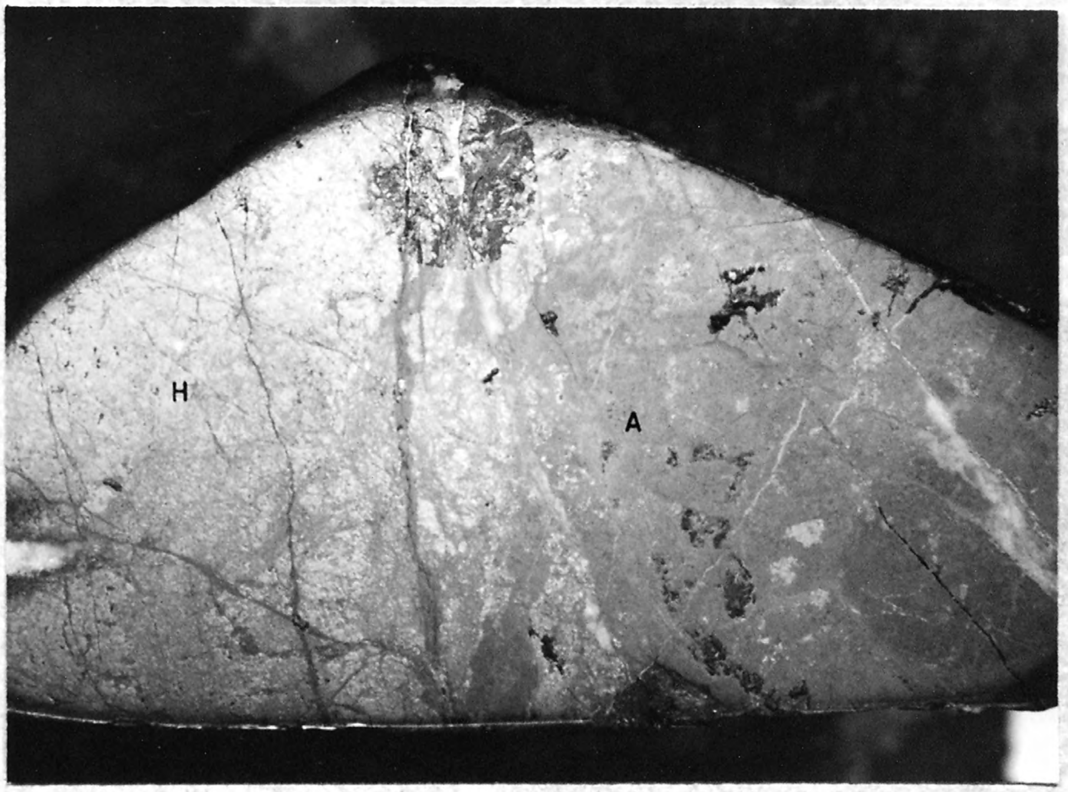


Figure 21. Polished surface. Hausmannite protore, Malamig deposit. Two principal components are relatively coarse grained hausmannite with minor alleghanyite and manganosite (H), and alleghanyite with minor fine-grained hausmannite and manganosite (A). Alleghanyite and rhodochrosite veinlets cut the specimen. Plain light. Magnification 6 x.

The massive carbonate rock under the microscope shows what appears to be a breccia structure. Dark brown carbonate fragments are cut by lighter colored, coarser-grained carbonate. Both varieties give a good X-ray pattern of rhodochrosite. Minor quartz is disseminated in the carbonate, as are sparse minute grains of a yellowish anisotropic opaque mineral, which may be millerite(NiS). Thin veinlets of quartz cut the carbonate matrix, and one or more unidentified semi-opaque minerals fill small irregular fractures.

Paragenetic Sequence

In general, the minerals of the hausmannite protore have mutual relations texturally, and a definite sequence of mineral formation cannot be recognized for the protore as a whole. Evidence is lacking for introduction of manganese after lithification of the ore and wall rocks, and it appears that the minerals have formed more or less in place from a fine-grained manganiferous sediment.

how?

The great bulk of the minerals evidently developed by recrystallization during metamorphism of the beds. Hausmannite, alleghanyite, manganosite, rhodochrosite, and bementite(?) formed extensively during this period, their abundance and precise sequence of formation at a given place probably determined largely by local features such as original textures and bulk chemical composition. Locally, in rare instances, braunite formed at an early stage and was partially replaced by later hausmannite, and jacobsite(?) veinlets were developed in early manganese silicates.

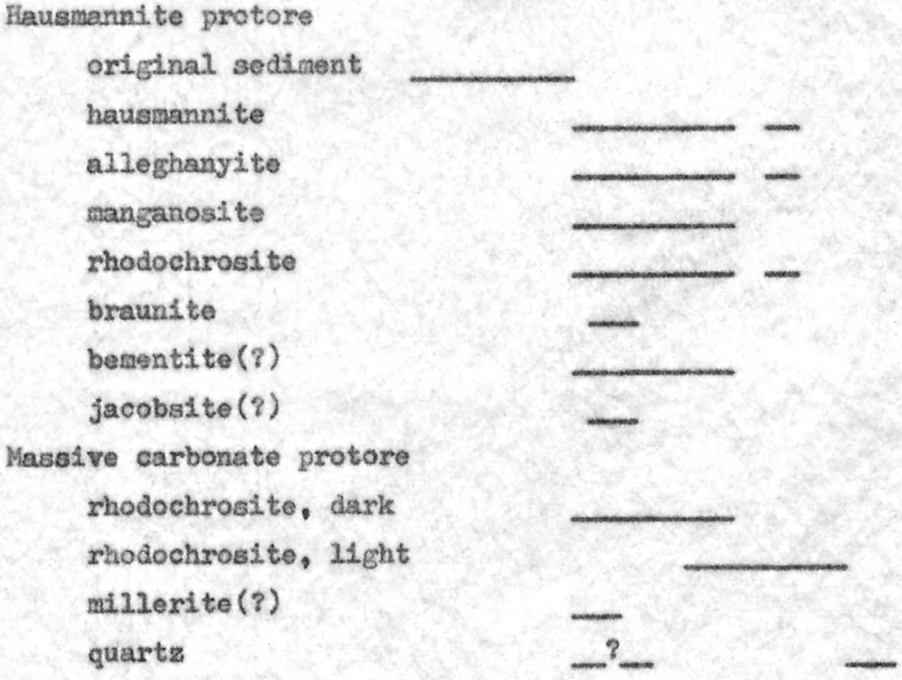
heat? or pressure which?

Solution

The small veinlike bodies of rhodochrosite, hausmannite, and alleghanyite found in some protore specimens are believed to have resulted from redistribution of minor amounts of manganese and other constituents during the last stages of deformation. Presumably these materials filled small fractures which developed at that time. The possibility that the late veinlets are related to supergene processes cannot be discounted completely, but no evidence to support this view was found. Similar veinlets were searched for but not found in specimens of the wall rocks.

The massive carbonate ore probably recrystallized at the same time as the hausmannite ore, but it is treated separately in table II, because relations between the two ore types are poorly known.

Table II. Paragenetic relations of minerals in hausmannite and massive carbonate protore.



Psilomelane-type ore

General

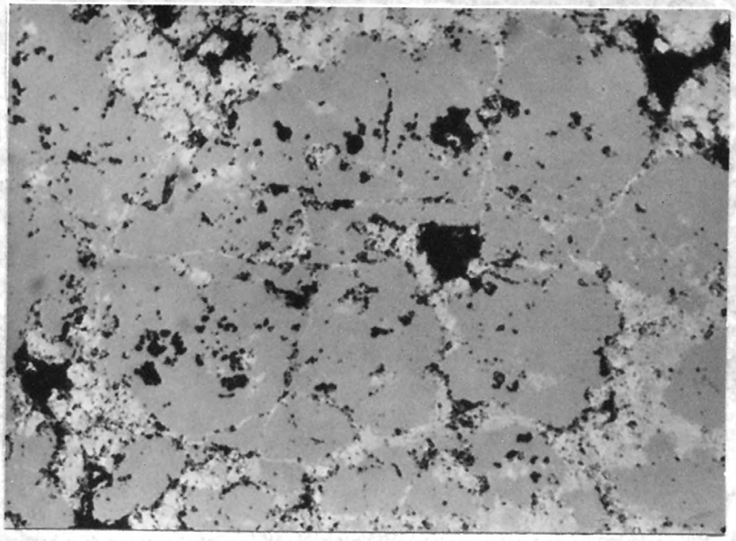
A complete study of the near-surface ore in the various deposits has not been made, but in studying the transition from protore to the black ore, some details of the mineralogy have been discovered. Minerals identified include:

cryptomelane	near KMn_8O_{16}
manganite	$Mn_2O_3.H_2O$
gamma MnO_2	MnO_2
~~bementite~~ barite	$8MnO.7SiO_2.5H_2O$

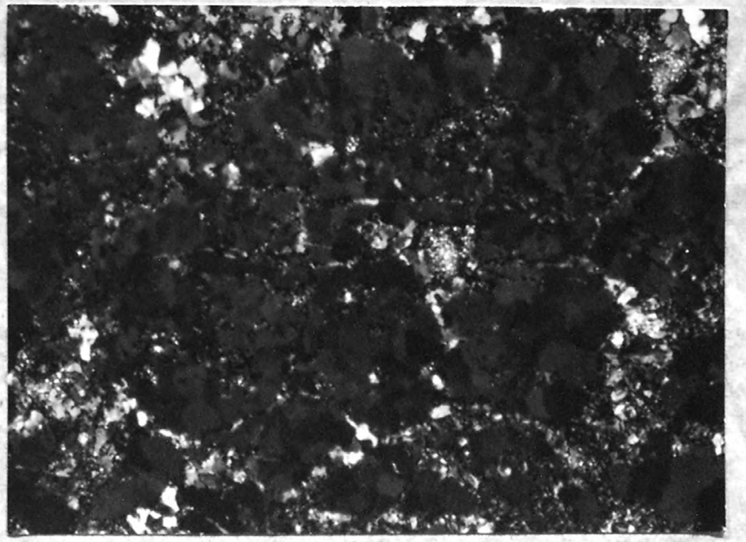
Other oxides of manganese are undoubtedly present. An unidentified mineral which forms by alteration of the hausmannite-alleghanyite protore is abundant in the upper part of that deposit.

Relations to protore

In the braunite deposits, manganite is generally the first mineral of this group encountered as the protore is followed toward the surface. It forms narrow veinlets and thin rims around grains of earlier minerals (Fig. 22). In places it is in larger patches which uncommonly show an internal structure much like that of the earlier minerals. Cryptomelane is in similar veinlets, generally in much greater abundance and complexity of pattern, which cut manganite as well as the protore minerals. In larger irregular areas cryptomelane may be massive or banded or may preserve earlier structures (Fig. 23). Where gamma MnO_2 has been identified by optical properties in the braunite deposits, it forms fibrous to massive fine-grained veinlets in the cryptomelane ore.



(a)



(b)

Figure 22. Photomicrographs. Polished surface of braunite protore, Dimanyang deposit. Magnification 385 x.

a. Plain light. Granular aggregates of braunite (dark gray) partly altered to manganite (lighter gray) along grain boundaries. Black areas are gangue.

b. Crossed polaroids. Note weak anisotropism of braunite and strong anisotropism of manganite.

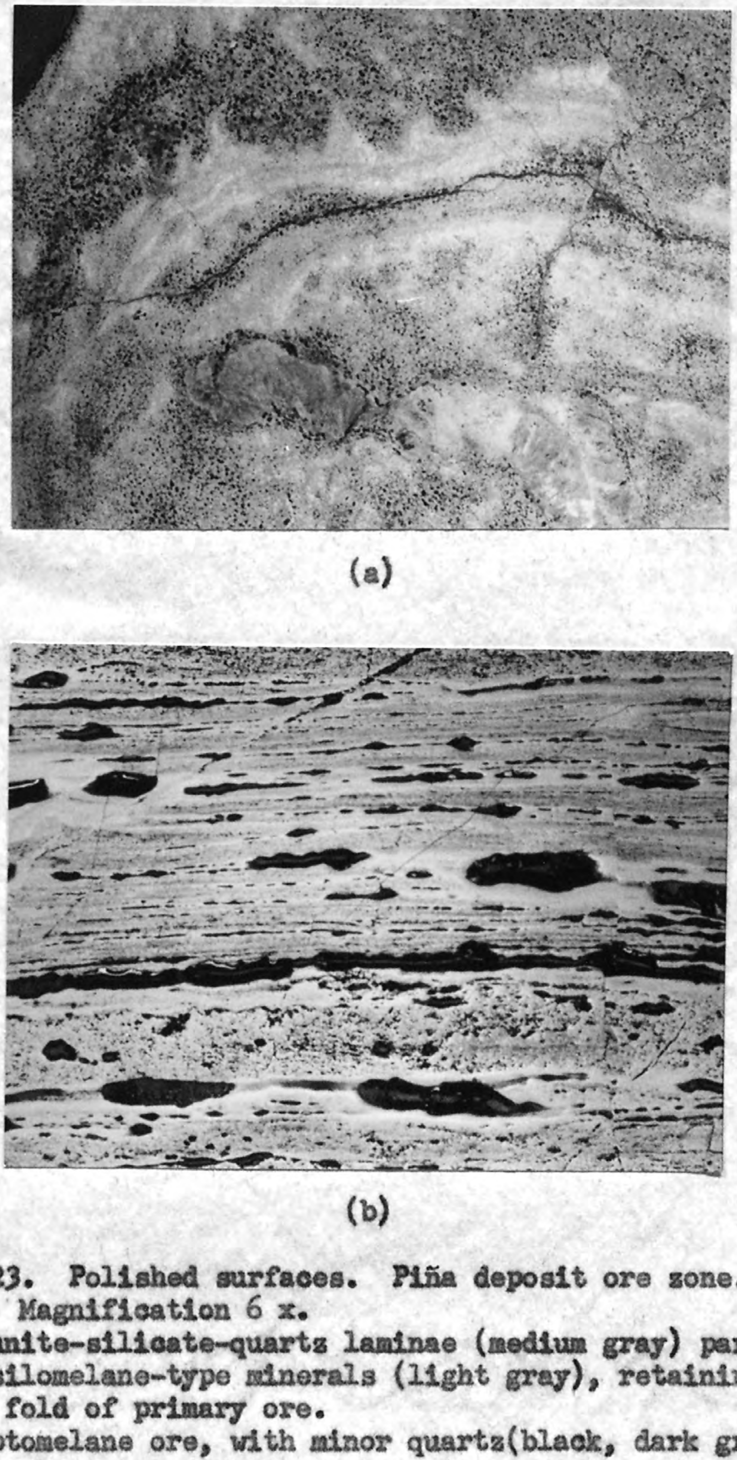


Figure 23. Polished surfaces. Piña deposit ore zone. Plain light. Magnification 6 x.

a. Braunite-silicate-quartz laminae (medium gray) partly altered to psilomelane-type minerals (light gray), retaining layering and fold of primary ore.

b. Cryptomelane ore, with minor quartz(black, dark gray), showing relict layering of primary braunite protore.

In the hausmannite deposit, the transition from protore to surface ore is somewhat more complex. The unidentified mineral termed mineral X is quite clearly the earliest alteration product of the hausmannite-alleghanyite, for it penetrates that component and is cut by veinlets of the other late minerals. Mineral X has a dark brown powder and is regarded as an opaque mineral, but its reflectivity is only slightly greater than that of alleghanyite, in polished surface. In plain light it can best be distinguished by minute surface pits, in places showing traces of rectangular patterns arranged at random. It is much more easily distinguished from hausmannite-alleghanyite between crossed polaroids, for it has a very dark color in contrast to the bright orange-red internal reflections common to alleghanyite and fine-grained hausmannite (Fig. 24). Another characteristic feature of mineral X between crossed polaroids is an intricate mesh of small tabular weakly anisotropic grains, many of which show lamellar twinning much like that of hausmannite. In spite of the features described, and in spite of numerous attempts to obtain an X-ray powder pattern, identification of the material has not been possible. The X-ray pattern is weak and cannot be assigned to any known mineral. Several faint lines have d-spacings similar to those of certain lines of the hausmannite pattern; these may be due to dispersed relict hausmannite in the X matrix.

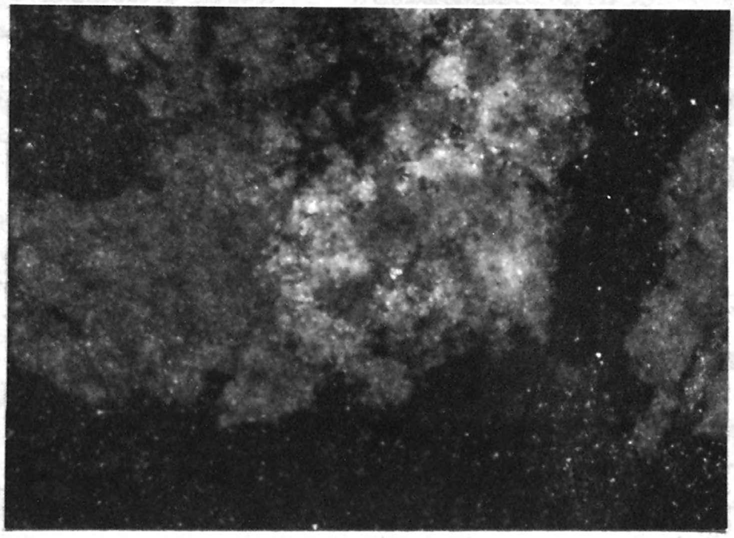


Figure 24.—Photomicrograph. Polished surface, hausmannite ore, Malamig deposit. Fine-grained hausmannite-alleghanyite (gray) partly replaced by mineral X (black).

Crossed polaroids. Magnification 168 x.

Massive mineral X is commonly traversed by thin veinlets made up of cryptomelane, manganite, ~~bementite~~ barite, and minor hausmannite(?) (Fig. 25). Many of the veinlets show a rudely circular cross section in polished surface, but some are more sheetlike in form. Manganite commonly borders the veinlets and encloses a central area of bementite. Cryptomelane forms veinlets in the manganite and bementite and encloses grains of the earlier minerals (Fig. 26).

In both hausmannite and braunite deposits, the ore at and near the surface is made up of massive and laminated minerals of the psilomelane type, and no vestige of the earlier minerals remains. In some near-surface ore, irregular, rounded pore-spaces trace original lamination in the protore (Fig. 23, b), indicating the removal of certain constituents, probably silica, at a late stage of alteration.

Paragenetic sequence

Paragenetic relations of minerals in the psilomelane-type ore are summarized in table III.

Table III. Paragenetic relations in psilomelane-type ore derived from braunite and hausmannite protores

Mineral X	———			
Manganite		———		
Hausmannite(?)		———		
~~Bementite~~ Barite			———	
Psilomelane-type minerals _/				———

_/ The term "psilomelane-type minerals" includes cryptomelane and similar minerals forming massive very fine-grained ore, a usage suggested by Fleischer and Richmond (1943, p. 271).

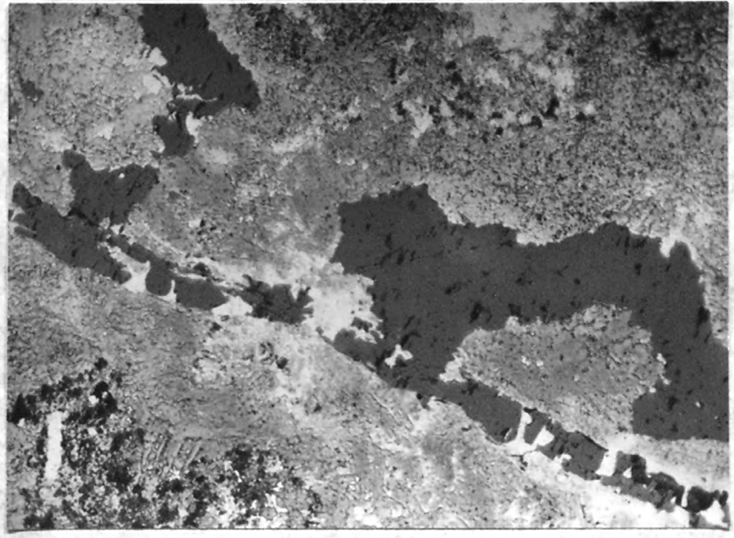


Figure 25.—Photomicrograph. Polished surface, ore zone of Malamig deposit. Mineral X matrix (medium gray) cut by irregular veinlets of ~~bementite~~ barite (dark gray, smooth) and cryptomelane (light gray). Plain light. Magnification 168 x.

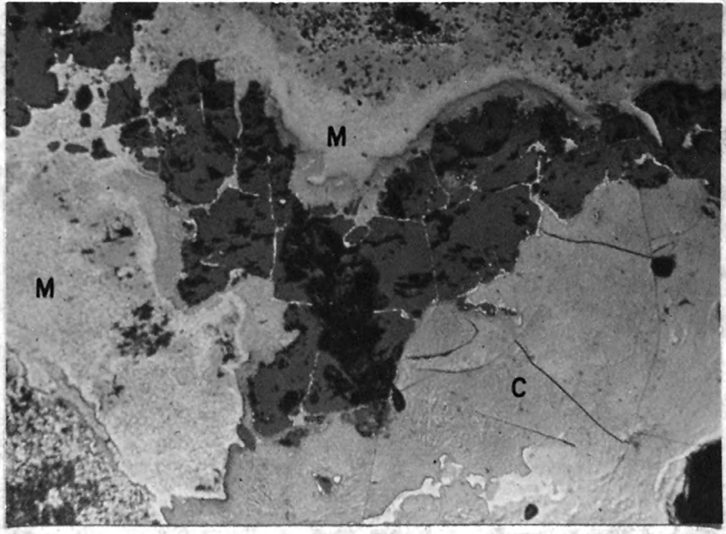


Figure 26.—Photomicrograph. Polished surface, Malamig deposit ore zone. Complex veinlet in mineral X matrix. Fine-grained manganite (M) forms outer band of veinlet and is enclosed in places by cryptomelane (C). Cryptomelane invades ~~bementite~~ barite (dark gray) along grain boundaries. Plain light. Magnification 132 x.

CHEMICAL NATURE OF THE ORES

The amount of quantitative chemical data available is limited, for a detailed chemical study of the ores was not attempted. The results at hand, however, give a general picture of the composition of representative samples of several types of ore. The partial analyses which are presented in table IV show particularly the high silica content of the protores and the low content of iron and alumina in all varieties of ore. The measurable quantities of the minor constituents TiO_2, P_2O_5, BaO, Cu, and Zn are also of interest.

Table IV. Partial chemical analyses of ore samples, Busuanga

(Analyses by L. E. Reichen and S. M. Berthold, U. S. Geological Survey.)

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	MnO	BaO	Cu	Zn
1._/	9.63	1.71	0.67	.14	.39	66.1	2.1	.04	.04
2.	5.36	1.60	.82	.06	.40	71.3	2.4	.04	.03
3.	3.49	.59	1.26	.14	.13	71.4	.7	.01	.04
4.	10.21	1.07	1.44	.12	.20	75.2	0.0	.05	.04
5.	.66	1.30	.46	.05	.31	74.3	.4	.01	.06

_/ 1. Piña mine. Much cryptomelane, appreciable quartz.
2. Piña mine. Much braunite, minor quartz, silicates, manganite, cryptomelane.
3. Malamig mine. Hausmannite-alleghanyite, minor manganite.
4. Malamig mine. Hausmannite-alleghanyite, some rhodochrosite.
5. Dimanyang mine. Cryptomelane, etc.

In addition to the quantitative analyses, qualitative analyses were made by X-ray spectrograph of several selected ore samples. The object of this work was to learn what minor elements are present in the ores. It was found that samples from the protore zone of each of the four deposits studied in detail contained similar minor amounts of Sr, Zn, Cu, Ni, and Co. In addition, Ba was found in the samples from Siñgay and Piña, and Ti was found in the Siñgay sample. It should be pointed out that the chemical analyses listed in table IV show Ti to be present in samples from the other three deposits and, as well, corroborate the spectrographic determination of Cu and Zn.

The manner of occurrence of the minor elements in the protores is not known, but certain possibilities exist. Divalent ions of Cu, Zn, Ni, and Co, have radii (Evans, 1952, p. 171) of 0.96A., 0.83A., 0.78A., and 0.82A., respectively, and may substitute for divalent Mn, radius 0.91A., in the manganese minerals containing Mn^{+2}. Ni^{+2} is quite small for this substitution, however, and may substitute for Fe^{+2}, radius 0.83A., or it may form unrecognized nickel silicates or other minerals. Carbonate ore at Malamig contains minute grains of a yellowish opaque mineral which may be millerite (NiS). At Dimanyang, an ore sample was once found to contain more than 1 percent Ni,_/

_/ G. B. Fexer, personal communication, 1951.

but no unusual minerals were noticed in the hand specimen. Trivalent Ti (0.67A.) may well substitute for trivalent manganese (0.70A.) in the manganese minerals. Ba and Sr, with divalent ionic radii of 1.43 and 1.27 A., respectively, are too large to substitute diadochically for Mn ions, and they are presumably in certain large sites in the lattices of certain protore minerals, as is Ba in hollandite (Bystrom and Bystrom, 1950). Traces of Ba are not uncommon in analyses of braunite and hausmannite (Palache, et al., 1944, p. 553, 714).

The significance of the presence of minor amounts of these elements in the protores is discussed in the section on transportation and deposition of the original manganiferous material.

FEATURES OF THE WALL ROCKS

General

The wall rocks of the manganese deposits have been studied with three principal aims in mind: to determine their general petrographic character, to determine their mode of origin, and to find what genetic relationships exist, if any, between these rocks and the ore zones. The braunite deposits are enclosed by rocks somewhat different from those which enclose the hausmannite ore, and the contrasting features of the wall rocks are discussed separately.

Braunite deposits

In the braunite deposits, well-bedded brown chert forms the hangingwall and red to brown jasper the footwall. The chert is for the most part finely crystalline silica, with grain size similar to that of cherty layers within the ore zone. In general aspect it is identical to the country rock chert. The color is due to finely divided iron oxide and possibly minor fine-grained organic debris. Circular and ovoid forms of radiolarian tests are common, generally with a core of relatively coarse-grained quartz and a rim of somewhat concentrated iron oxide. There is no indication of the presence in the chert of the manganese minerals recognized in the protore. Scattered sharp-walled veinlets of psilomelane-type minerals are found, however, in the upper parts of the deposits.

The jasper breccia footwall bed is remarkably similar from one braunite deposit to another. Specimens from deep workings commonly show dark chert fragments, much like ordinary dark brown chert, veined and cemented by gray to white coarse-grained chalcedonic quartz. The brown chert fragments contain radiolarian forms in some specimens, but in only one instance has a form of this kind been found in the cement. No evidence of granulation is found in the breccia, nor do the fragments appear to be rotated to any extent. Commonly, in fact, the fragments are not entirely separated, but are penetrated by narrow wedgelike quartz veinlets which grade outward to larger quartz veins.

It seems likely that the breccia is of post-depositional origin, in view of the virtually complete absence of fossils in the silica cement. It is more likely a diagenetic feature than a tectonic feature, however, to judge from the lack of granulation and fragment rotation. Perhaps the fracturing was due to dessication and shrinkage of a sediment rich in colloidal silica soon after burial on the sea floor, and cementation took place shortly thereafter as silica-saturated solutions penetrated the bed. This view finds some support in the results of a simple experiment which Marsden performed in the laboratory in Manila._/ He prepared a saturated solution of silica, added red coloring matter, and allowed the preparation to dry out. He then poured melted paraffin into the container to cement the dried sediment and obtained a "breccia" that looked remarkably like the jasper breccia bed.

The color of the chert fragments where the breccia bed is near the surface is distinctly red, and it was this feature that led earlier workers and miners to refer to the rock as jasper. It is thought that the change in color is due to the oxidation of iron disseminated in the chert to the ferric state, but other changes may also take place. Tests by X-ray spectrograph show that other brown chert beds also contain small amounts of iron, but none turn red upon weathering as the breccia bed does. The minerals which contain the iron are not known, but it seems likely that those in the jasper oxidize to hematite, whereas those in the chert oxidize to limonite or mixtures of iron oxides.

_/ Personal communication, 1952.

Hausmannite deposit

In the hausmannite deposit at Malamig, rocks on both sides of the ore zone are dark gray to black bedded chert. A massive outcrop of jasper breccia lies a short distance west of the workings, apparently on the footwall side of the ore zone, but the rock is not found in contact with the ore. The footwall rock exposed in one tunnel is unlike most dark cherts in that it is very brittle under the hammer and in hand specimen shows poorly defined banding and minute fractures coated with a chlorite-like mineral. Specimens of this rock and of the hangingwall rock were studied and analyzed in the laboratories of the U. S. Geological Survey in 1952. The chemical analyses are given in table V.

Two brief reports on the laboratory work were written by Charles Milton. Milton believed that the footwall rock is probably of volcanic origin, judging from both chemical and petrographic data. He wrote, in part: _/

_/ Personal communication, 1952.

> " ... The sample consists of two types of layered material, in broad bands of varying darkness; both are extremely fine grained. The essential difference appears to be in the presence in one of a good deal of extremely minute silicate particles, largely chlorite(?). Little can be said beyond noting that it is not by any means a simple chalcedonic 'chert'. Under high magnification, wisps of fibrous chlorite(?) of low birefringence are numerous; aggregates of such wisps into knots appear isotropic. An X-ray of the 'heavy' fraction of the rock showed chlorite, biotite, and quartz to be present, with presumably other minerals that could not be identified."

Table V. Chemical analyses of wall rock samples, Malamig deposit

(Rapid method analyses by S. M. Berthold and C. C. Alexander, U. S. Geological Survey.)

	I*	II	III
SiO_2	85.9	54.8	97.9
Al_2O_3	4.3	14.9	.48
Total Fe as Fe_2O_3	2.0	7.4	.48
MgO	.92	5.8	.15
CaO	.86	1.7	.05
Na_2O	.19	.22	.12
K_2O	1.5	4.8	.07
TiO_2	.23	.62	.01
P_2O_5	.47	1.1	.02
MnO	3.2	6.3	.26
Ignition**	1.2	3.1	.78
Sum	101	101	100
FeO	1.5	5.7	.31
Fe_2O_3	.33	1.1	.14
S			.34

* I Footwall "gray chert", light-colored part.

II Footwall "gray chert", dark part.

III Hangingwall black chert.

** Includes gain due to oxidation of FeO.

Milton also suspected the presence of minor amounts of garnet and rhodochrosite on the basis of certain lines in the X-ray patterns, and thought that the chlorite may be an alteration product of the garnet.

The chemical analysis of the darker layers of the footwall rock was interpreted by Milton to indicate a rhyolitic or related composition, which, he wrote, " ... May well be interpreted to signify a volcanic ash ... the rock is ... almost certainly of volcanic origin."

Milton's interpretation of the origin of the footwall rock deserves serious thought, but it should be pointed out that the chemical composition of the darker layers of the rock is not greatly different from that of certain shales (Clarke, 1924, p. 552). In fact, the K_2O/Na_2O ratio is more similar to that in shales than to that in many rhyolites and andesites (Clarke, 1924, p. 439, 458).

Milton recognized that the hangingwall rock, which contains nearly 98 percent SiO_2, was recrystallized but declined to speculate upon the nature of the original rock. He found no fossils in the specimen he examined, but in other specimens of the rock the writer has found scattered radiolarian forms.

Manganese content

A number of wall rock specimens were tested for metal content by use of the X-ray spectrograph. No manganese was identified with certainty in any of the specimens. It is believed that the manganese in the Malamig footwall specimens analyzed by the Geological Survey was in the form of thin rhodochrosite veinlets, which are found in some thin sections of this rock. The X-ray spectrograph revealed the presence of minor amounts of iron in all samples tested, as well as Ba and Sr in several samples. Zn was found in one jasper breccia specimen, along with iron.

Marsden reported_/ that detailed chemical studies were made of a suite of carefully selected wall rock and country rock samples from the Siñgay deposit during his work, in an effort to determine manganese content of rocks associated with the manganese ore. The chemical analyses showed no manganese in most samples and only a trace in others; no regular variation in metal content was found.

_/ Personal communication, 1958.

Summary

In summary, it may be pointed out that the hangingwall rocks of the manganese deposits are essentially identical to chert beds of similar color in the country rock, but the footwall rocks show marked differences. The jasper breccia bed, which is peculiar to the braunite deposits, has a distinctive color as well as an internal structure unlike that of the average chert bed. The tuffaceous or shaly footwall rock of the hausmannite deposit at Malamig is a type unrecognized elsewhere on the island, but its close association with a chert bed suggests that it may be merely a fine clastic layer within the chert sequence, similar except in thickness and degree of lithification to the partings commonly found between chert beds.

The relation of the footwall rocks to the manganese deposits is discussed further in the section on origin of the deposits.

SUMMARY OF DATA ON THE DEPOSITS

The factual evidence pertinent to a discussion of the possible mode of origin of the deposits may be summarized in outline form.

The country rocks and wallrocks:

1. The country rocks contain abundant marine fossils.
2. Wallrocks of the deposits are lithologically similar to the country rocks and commonly also contain fossils.
3. Grain size of chert in the wallrocks is similar to that of the cherty layers in the ore zones and is generally coarser where deformation is more intense.
4. There is virtually no manganese in the wallrocks or country rocks.

The protores:

5. The ore zone follows the structure of the wallrocks, even where deformation is complex.
6. Fossils similar to those in the wallrocks are preserved equally well in the ore zone.
7. The deposits are associated with only fine-grained siliceous beds and in three of four cases have similar footwall rocks.
8. Layers in protore follow the wallrock structure and are generally uniform laterally in mineralogical character and thickness.
9. There is no veining of consequence between layers.
10. Grain size is generally smaller in braunite deposits that have been moderately deformed than in those that have been intensely folded.
11. No granulation of minerals is evident.
12. Free quartz is common in braunite deposits and absent in the hausmannite deposit.

13. Textural relationships are best explained by more or less simultaneous recrystallization of different minerals from a very fine-grained original sediment.

14. Minor elements in the protores include Sr, Zn, Cu, Ni, Co, Ba, and Ti.

15. The footwall rock at Malamig is shaly or tuffaceous.

A satisfactory hypothesis of origin must explain or be consistent with these data, and, as well, must provide for a source and means of transport and deposition of the manganese and the silica.

ORIGIN OF THE DEPOSITS

Possible modes of origin

Two principal categories are commonly distinguished in the discussion of the genesis of ore deposits: those deposits formed contemporaneously with the enclosing rocks, or syngenetic deposits, and those introduced into rocks formed earlier, or epigenetic deposits. Classifications of manganese deposits recently published (Park, 1956; Hewett, et al., 1956), although dissimilar, show this basic breakdown. The logical first step in discussing the origin of the deposits under investigation, then, is to determine to which of these categories the deposits belong, on the basis of observed features of the deposits.

Five features common to the Busuanga manganese deposits, which support a syngenetic origin, may be listed:

a. The ore zone and its internal layered structure are without exception conformable with the enclosing rocks.

b. Both the ore zone and the enclosing rocks contain marine fossils in approximately the same state of preservation.

c. The lithologic character of even the thinnest chert laminae in the ore zones is much like that of the wall rock and country rock chert.

d. The primary ore minerals are not related to veins or other discordant structural features.

e. The wall rocks and country rocks contain virtually no manganese.

In considering the possibility of epigenetic origin, it must be pointed out that bedding plane deposits of introduced ore minerals are not uncommon; but the complete lack of cross-cutting features in the Busuanga deposits, as well as the absence of evidence of large-scale replacement, is strong negative evidence against epigenetic origin. The data which tend to support epigenetic origin of these deposits are largely mineralogical. For example, alleghanyite has only been reported, as far as the writer is aware, in high-temperature hydrothermal veins (Hewett, et al., 1956; Lee, 1955). Rhodonite, and the closely related mineral pyroxmangite, are also known as hydrothermal minerals, as well as products of medium- to high-grade metamorphism, according to Hewett, et al., and Lee (*loc. cit.*), as well as Dorr, Soares, and Horen (1956), and others. If these minerals are, indeed, formed only under conditions of elevated temperature and pressure, then the deposits in question must have been subject to these conditions at some time. Nevertheless, the evidence for syngenetic deposition of the original manganiferous material seems compelling, and it is concluded that the ore zones were deposited conformably with the enclosing beds in a sedimentary basin.

The marine fossils in the country rocks, wall rocks, and the ore indicate that the basin of deposition was marine, and the presence of similar-appearing chert beds above, below, and within the ore zone suggests strongly that the environment remained relatively constant during the period of deposition of the ore and the enclosing rocks. The tuffaceous(?) bed below the Malamig ore zone may indicate an exception to this generalization and is discussed in the following section.

Source of manganese and silica

General

There is little direct evidence in the chert sequence of Busuanga that bears on the source of the manganese and silica. Indirect evidence is found in the stratigraphic section as a whole, however. The gradational contact of the chert sequence with the thick graywacke beds below shows that the transition from a period of dominantly clastic deposition to one of largely chemical, or non-clastic, deposition was gradual. Silica deposition began somewhat haltingly as clastic deposition decreased, but finally became widespread and uniform for a long period. The gradual decrease in the supply of clastics to the sedimentary basin suggests that the source area of this material was reduced to topography of low relief. Intense chemical weathering in a humid climate of low terrain of this nature would be expected to provide silica in amounts somewhat greater than normal to rivers draining to the sea, as well as to yield minor amounts of clay-size debris. Whether or not the silica thus derived would be adequate to form a thick sequence of bedded chert like that of Busuanga can only be speculated upon.

It seems significant that the manganese deposits are associated solely with the chert sequence, and a genetic relation between the two is likely. The great disparity in the volume and extent of the cherts and of the manganese deposits indicates, however, that silica was supplied to the sedimentary basin in large amounts over a long period of time, whereas the manganese may have been much more restricted in areal distribution as well as in time. No significant stratigraphic break in the chert sequence is known, and the period of periods of manganese deposition are best regarded as minor special events during a long, continuous period of silica deposition.

The only suggestion of an unusual source of the manganese is given by the altered tuff(?) footwall bed at the Malamig deposit, which indicates that volcanic activity occurred just preceding the deposition of the Malamig ore zone. The extent of the activity is unknown, for such beds can only be recognized by laboratory study. It is not implied that the tuff(?) bed itself supplied the manganese, but the alteration of related rocks formed during the activity, or emanations attendant to the activity, may have yielded manganese. However, the minor extent and uncertain origin of the tuff(?) bed make more elaborate speculation hazardous. In any case it seems likely that the source of the silica was more general and enduring than that of the manganese, to judge from the much greater extent of the cherts.

Published data on similar deposits

Descriptions of the manganese deposits and the enclosing rocks in the Franciscan formation (Jurassic?) of the Coast Ranges of California (Taliaferro and Hudson, 1943) disclose many features similar to those of the Busuanga deposits. Max D. Crittenden, Jr._/, declared that typical hand specimens of the rocks and ores from Busuanga were very much like those from the Franciscan deposits which he has studied. The Franciscan deposits are siliceous, contain much carbonate rock, and lie conformably in the bedded cherts almost without exception. Taliaferro and Hudson believed that the source of the silica and manganese and the associated iron as well, was directly related to the basic volcanic rocks commonly found in the formation. They pointed to the essential contemporaneity of the cherts and the volcanic rocks, and the direct relation between the abundance of chert and the abundance of flows and tuffs. They concluded that submarine hot springs were the most likely immediate source, because the constant relation of the manganese deposits to particularly thick chert lenses in the sequence was thought to indicate that rapid additions of silica, sometimes with manganese, often had taken place.

_/ Personal communication, 1952.

The Monterey formation(Miocene) of California was studied in detail by Bramlette (1946), and his conclusions regarding the origin of the great thickness of cherty rocks in that formation are of particular interest. He considered the Monterey cherts much like the Franciscan formation cherts, but much fresher, because they have undergone a good deal less metamorphism. He concluded that the beds were primarily due to the accumulation of the skeletal remains of diatoms and radiolaria in a quiet basin over a long period of time. The large supply of silica which nourished the organisms may well have been derived from tuffaceous sediments by submarine alteration, according to Bramlette, but formation of the immense deposits of very high silica content was most likely a result of the drifting of siliceous organisms into certain favorable basins of deposition.

Bedding plane deposits of manganese in chert sequences of the Chichibu Complex, Japan, on the other hand, are thought by Lee (1955) to have formed by the hydrothermal replacement of certain chert beds. In the absence of detailed information on field relations, Lee based his conclusion on detailed mineralogical and chemical work on the ores. He considered that the almost complete lack of hydrous minerals as primary constituents of the ores and the presence of minerals like hubnerite and galaxite strongly suggest formation at moderately high temperatures. He believed that the presence of small amounts of monazite, hubnerite, and allanite in the ores indicates derivation of the ore-forming solutions from a granitic magma.

Other deposits different in many features from the Busuanga and Franciscan occurrences but also characterized by the intimate association of manganese and highly siliceous rocks have been studied in considerable detail by other workers. Park (1956, p. 90) described manganese deposits, like those of the Olympic Peninsula, closely associated with impure limestones, argillites and cherts, and particularly with submarine lava flows. He thought that the manganese and silica were both derived from the lavas by hot acid solutions rising upward through the flows immediately after their extrusion. In the same paper, Park discussed the work of James (1954) on the iron and manganese deposits of the Cuyuna range and that of Dorr (1945) on the Morro du Urucum deposits in Brazil. According to Park the results of these investigations showed that the manganese and iron in these deposits were derived by subaerial weathering from older rocks, and that the metals were transported in river waters to marine basins of deposition. Grout and Wolff (1955, p. 30ff) supported the sedimentary origin of the Cuyuna Range manganese, but they believed that temporary volcanic emanations and other hot sources may have yielded significant quantities of manganese to the sea water.

In Aroostook County, Maine, manganiferous beds within a sequence of highly folded ferruginous slates are thought to be of sedimentary origin (Miller, 1947). The beds contain much silica and iron, as well as abundant fine clastic material. Braunite is the chief manganese mineral recognized, and minor constituents bearing manganese include bementite and pink carbonate. In the Maple Mountain and Hovey Mountain deposit, Pavlides (1952, p. 8) reported that the minor minerals also include spessartite, rhodonite, pyrophanite, stilpnomelane, neotocite, and others. Miller believed that the earliest manganese mineral is braunite, and that it may well be primary (sedimentary) in origin. He concluded that the deposits represent accumulations in a shallow marine environment of manganese derived by subaerial weathering of volcanic rocks lying somewhere east of the outcrop area.

Experimental data

The hypothesis of derivation of manganese from volcanic rocks has been investigated recently by Krauskopf (1957). He showed by experimental work that manganese and iron can, indeed, be derived from volcanic rocks of intermediate composition, and that both sea water and surface waters are effective solvents, given enough time. He pointed out, however, that the resulting solutions would contain 50 times more iron than manganese, and that hypotheses proposing the derivation of manganese from volcanic rocks in this manner must account for the disposal of the iron as well.

Krauskopf also considered the possibility that manganese in certain sedimentary deposits could be derived from pre-existing rocks by well-known processes of weathering. Both manganese and iron are dissolved in the zone of weathering by weakly acid solutions. The manganese concentration of the resulting solutions is low, perhaps 1 to 40 parts per billion, but long continued weathering could liberate a large total amount of manganese. Separation of the iron in solution from the manganese is not so great a problem as it is in solutions related to volcanic activity, for much of the iron is precipitated in the soil zone near the source. The processes involved are discussed further in the section on transportation and deposition of manganese.

Summary

The cherty rocks of Busuanga may well have formed by a process similar to that envisioned by Bramlette to have formed the Monterey formation. Abundant siliceous fossils are recognized, but the Busuanga cherts are similar in character to those of the Franciscan formation because of metamorphic modifications, and most of the primary features are obliterated. The source of the silica remains in doubt, however. It seems likely that rivers draining a deeply weathered area of low relief contributed silica as well as clayey sediments to the basin of deposition. Silica content of the sea water may have been increased by submarine alteration of volcanic ash beds, or, locally, by emanation of silica-rich solutions from hot springs, but evidence for these sources is lacking.

The source of the manganese is more in doubt than that of the silica, but it seems logical, as evidence to the contrary is lacking, to suppose that the manganese was derived from the same general source as the silica. Obviously the fact that the manganese is concentrated only at one of several stratigraphic levels must be explained, but this can be done by assuming temporary unusual conditions in either the source area or on the sea bottom, or both. The problem is discussed in the section on transportation and deposition, which follows. Local sources such as volcanic emanations appear to have been unimportant, to judge from the lack of evidence of volcanic activity, although it is tempting to call upon such sources to explain the apparently sporadic distribution of the deposits.

Transportation and deposition

Several features of the rocks and manganiferous zones of Busuanga indicate that the original sediments were laid down by means other than clastic deposition. In the first place, clastic materials are rare in the chert sequence. In addition, the heterogeneous very fine-grained nature of the ore zones, particularly those at Malamig and Dimanyang, suggests original intricate mixtures of non-clastic material. Third, the presence in all of the manganese deposits of numerous minor metals indicates that negatively charged manganese sols and gels may have been present in the original sediments (Rankama and Sahama, 1949, p. 650). These observations suggest that the original sediments were deposited as precipitates or colloids, or both, but little can be said of the means of transport of material and probable mechanisms of deposition without more data. In this connection, the work of others on similar problems is of interest.

Silica

Bramlette's research on the origin of the Monterey cherts and other siliceous rocks (1946) has been previously discussed (page 84). He postulated essentially a mechanical accumulation of siliceous shells to account for extensive deposits of radiolarian and diatomaceous sediments. Local dissolution and reprecipitation of silica were called upon to provide the siliceous matrix.

Experimental work by Krauskopf on the solution and precipitation of silica (1956) led him to conclusions which substantiate and amplify Bramlette's ideas. He stated that sedimentary chert beds could not generally be explained as products of direct inorganic precipitation, except where local sources of abundant silica exist, as in the immediate vicinity of volcanic activity. This is so because silica in sea water, which he showed to be in true solution generally, is commonly present in amounts far below the equilibrium solubility, and is precipitated with difficulty unless the solution becomes supersaturated in some way. On the other hand, diatoms and radiolaria have the ability to use silica from undersaturated solutions to build their opaline shells; after death, the opal is subject to dissolution, but the rate is so slow that the many shells reach the sea floor and form large accumulations. Krauskopf believed that most sedimentary cherts can best be explained as such accumulations, modified by partial dissolution and redeposition of the silica in an amorphous form during diagenesis.

Taliaferro and Hudson (1943, p. 273) emphatically stated that only chemical precipitation of the silica could account for the observed features in the Franciscan cherts, and indicate that contraction features show that the precipitate was a silica gel.

The radiolarian nature of the Busuanga chert beds, their wide lateral extent, and their apparently great thickness appear to be adequately explained by an hypothesis of origin like those proposed by Bramlette and Krauskopf. Environmental conditions were evidently uniform over a long period of time, during which slow subsidence of the basin of deposition prevented the modification of the deposits by wave action and maintained the proper bottom conditions for deposition.

The alternation of thin chert beds with shaly partings, common in the Busuanga sequence, has been noted and studied by others. Taliaferro and Hudson (1943, p. 233) believed that sharp contacts between chert and shale laminae in the Fmanciscan formation can be explained by the exclusion of impurities as the original silica colloid passed to the gel stage. Bramlette (1946) was inclined to believe that rhythmic layering of organic and clastic beds in the Monterey formation is the result of annual cycles, in the case of thin laminae, and very long climatic cycles, in the case of beds measured in inbhes. An attempt to resolve this problem lies outside the scope of the present paper, but the extremely regular character of the partings in a specimen of laminated chert studied in thin section suggests to the writer that minor variations in the supply of fine clastics to the basin adequately explain the observed features.

Manganese

Possible means of transportation and deposition of manganese in various environments are discussed in detail by Krauskopf (1957). In the zone of weathering, manganese and iron in rock-forming minerals may be dissolved by a weakly acid solution, such as water containing carbonic acid. Much of the iron thus dissolved may be precipitated in the alkaline B soil horizon in the immediate vicinity, but the manganese, which is less sensitive to a small increase in pH, remains in solution. At any point en route to the sea, however, the manganese and the remaining iron may be precipitated if the pH should rise above 8, or if copious quantities of anions like silicate or carbonate are added to the solution. Certain bacteria may also effect the precipitation of one or both of the metals. Nevertheless, river waters containing 1 to 40 parts per billion, or more in favorable instances, may eventually reach the sea. Upon mixing with sea water, the solution is made more alkaline and the manganese and iron are precipitated as silicates, carbonates, and probably as oxides.

According to Krauskopf (1957, p. 79):

"Such a process would be most effective where manganese is supplied to meteoric water in amounts slightly greater than normal, say by the weathering of volcanic material or glacial debris, but abnormality of supply is probably not essential if the necessary pH gradient is maintained for a long time."

The delta-type deposits postulated are not the kind of manganese concentration commonly found in bedded chert, however, and an explanation of the formation of the bedded deposits requires further speculation. Krauskopf pointed out that the manganese minerals once deposited can be redissolved upon appropriate reduction in Eh and perhaps in pH of the bottom waters, conditions not unlikely in the deltal area of sluggish streams, and redistribution of the manganese to areas more favorable to deposition is possible. This process also causes a further separation of manganese and iron, partly because of the insoluble character of iron compounds compared with manganese compounds and partly because some iron commonly combines with sulfur to form pyrite, which is stable. The cycle of deposition, solution, transportation, and redeposition of manganese may be repeated several times before a deposit of stable manganese compounds results.

The chemical nature of the sedimentary manganese deposits formed by these general processes may be of two types, according to Krauskopf, depending upon the conditions at the site of deposition. If the Eh of the bottom waters is negative when the manganese-bearing solution is neutralized, divalent manganese ions will form insoluble compounds with available anions, such as silicate and carbonate, and settle out. If the Eh is positive however, the divalent manganese ions will oxidize to form trivalent and quadrivalent ions, and insoluble oxides and hydroxides of these ions will form the precipitate.

The validity of the foregoing hypothesis as an explanation of the mode of formation of the original Busuanga ores may be tested to an extent by re-examining the present mineralogy of the deposits. In the protore of the Siñgay deposit, which apparently has suffered less recrystallization than the other deposits studied, very fine grained silicates and carbonate dispersed in the cryptocrystalline silica appear to have given rise to braunite upon recrystallization. Generally only quartz surrounds braunite grains and aggregates. If the assumption is correct that the proportion of braunite increases with recrystallization, it seems likely that the first minute dendritic braunite grains formed during diagenesis, perhaps as a result of reaction between dehydrating manganese hydroxides and manganese silicates and carbonate. These considerations suggest that in the mass of hydrous material precipitated and buried on the sea floor a certain amount of variation in Eh existed from place to place, so that compounds of both divalent and trivalent manganese were formed locally. Eh values necessary to form Mn^{+4} evidently were not attained.

In the Malamig deposit, where intimately mixed hausmannite and alleghanyite appear to be the principal primary minerals, the original sediment likewise apparently contained both trivalent and divalent manganese compounds. A major difference between this sediment and those of the braunite deposits is indicated, however, by the lack of free silica in the protore. Evidently silica was relatively deficient and was totally utilized in the formation of manganese silicate, with the consequence that the non-siliceous oxide hausmannite and manganosite (MnO) formed along with alleghanyite upon diagenesis and metamorphism. At the last stage of manganese deposition, silica was quantitatively subordinate to carbonate and much rhodochrosite was precipitated. At this stage the Eh of the solutions was uniformly negative, to judge from the absence of manganese oxides. A minor amount of sulfide, probably millerite (NiS), in the carbonate rock supports this view.

The deposition of the original manganiferous sediments as colloidal precipitates, at least in part, is suggested by the content of minor metals in the protores, as has been noted. Commonly, ions of these metals (Sr, Zn, Cu, Ni, Co, Ba, and Ti) are said to have been adsorbed by sols and gels of quadrivalent manganese oxide and hydroxide, which are negatively charged. This explanation requires modification, however, in the case of the Busuanga deposits, in view of the lack of recognized primary compounds of quadrivalent manganese. Perhaps adsorption of the metal ions by hydrous silica gel, which is negatively charged (Rankama and Sahama, p. 236), accounts for a certain amount of the minor metal content. However, the presence of the same metal ions in the Malamig deposit, which contains no free silica, suggests that primary manganous silicate precipitates and hydrous compounds of trivalent manganese may also be negatively charged and thus be capable of adsorbing cations.

Summary

The hypothesis of derivation of manganese from pre-existing rocks by weathering, and subsequent concentration of the manganese by deposition in a marine environment, appears to explain adequately the features of the Busuanga deposits. A serious question remains, however. Did the rather special phenomenon of manganese concentration take place more than once during deposition of the chert sequence? An unequivocal answer cannot be given because of difficulties of stratigraphic correlation of the deposits, as discussed earlier in this report. The deposits could well have been formed contemporaneously, however, for similar conditions of formation are suggested by the mineralogy of the protores and by the virtually constant association of the jasper breccia bed with the deposits. Thus it seems likely that manganese deposition on a large scale took place during only one relatively short interval during the period of chert deposition. The manganiferous sediments were probably fairly continuous over a large area, but the specific nature of the sediments evidently varied locally to some extent, as shown by the difference in character of the protores of the deposits studied. Local differences in pH, <u>Eh</u>, and ion concentrations in the sea water probably were responsible for the variations in composition of the original deposits.

Conditions which led to the abrupt inception and cessation of manganese sedimentation are not known. The jasper breccia bed, which is found only in close association with the manganese deposits, suggests that a minor change in bottom conditions occurred just preceding manganese deposition. Whether this change and the period of manganese

[illegible]

sedimentation were in response to erosional evolution of the source area, changes in sea currents, or to some other events can only be speculated upon, with the data at hand. In any case, the special conditions were of a temporary nature, and deposition of highly siliceous beds free of manganese concentrations was resumed abruptly at the close of manganese sedimentation. Outside the areas of manganese sedimentation, no evidence of interruption of the deposition of highly siliceous beds is recognized.

Modification after deposition

General

The cherty rocks and manganese protores of Busuanga have been formed from the original sediments by progressive textural, structural, and mineralogical changes resulting from diagenesis and metamorphism. Processes involved included compaction, dehydration, crystallization, and recrystallization. Recrystallization was evidently the latest phase and was particularly pervasive in the nonclastic rocks during regional metamorphism. Under the microscope these rocks show a general increase in grain size with increasing metamorphism, as reflected by bedding deformation, but the individual grains exhibit little evidence of deformation except wavy extinction. Little preferred orientation of mineral grains is recognized except in some impure cherts, where sparse minute sericite flakes are rudely aligned. Certain specimens of graywacke show a similar orientation of biotite formed by recrystallization of the clayey cement; some of these rocks show minor granulation of individual grains as well.

Diagenesis and metamorphism of manganiferous sediments

The mineral assemblages in the different protores may be considered the end products of the general reactions that took place in the original manganiferous sediments during diagenesis and metamorphism, if it is agreed that there has been no substantial introduction of manganese nor much migration of the metal within the zone since deposition. The evidence for this assumption has been given in the discussion of syngenetic versus epigenetic origin (p. 78).

The braunite ore evidently developed from original sediments containing manganese in divalent and trivalent forms and abundant silica. Textural evidence indicates that the braunite formed early, and that quartz recrystallized interstitial to the granular braunite aggregates; however, it seems likely that the minerals formed at the same general time as reorganization of the primary sediments proceeded. Needle-like crystals of bementite(?) formed clusters near the braunite after the quartz recrystallized, presumably developing from sparse amounts of hydrous silica and Mn^{+2} ions which remained after the braunite formed. Rarely Mn^{+2} ions were concentrated and combined with Fe^{+2} ions and silica to form pyroxmangite crystals.

The minerals of the hausmannite protore evidently developed by recrystallization of original sediments similar to those cited above but lacking in abundant silica. The hydrous silicate alleghanyite and hausmannite formed at the same general time, the proportions and textural features depending upon the distribution of local concentrations of Mn^{+2} and Mn^{+3} ions, silica, and oxygen in the sediments. The random distribution and intimate relationships of the minerals, and their chemical differences, suggest that the original material may have been an intricate mixture of hydrous compounds of a colloidal nature. Original minor beds containing predominantly manganese carbonate simply recrystallized to granular rhodochrosite.

Supergene alteration of the protores

After long-continued erosion of an unknown but probably great thickness of overlying beds, the protores were exposed at the surface in some areas and subjected to alteration in the zone of weathering. Gradually the compounds of divalent and trivalent manganese were converted to oxides of quadrivalent manganese, and the various anions in the primary minerals were removed in solution. To a large extent the primary minerals appear to have been altered in place. Lack of significant movement of manganese during the alteration is shown by the preservation of original bedding features in the near-surface ore, as well as by the limited penetration of manganese oxide veinlets into the wallrock near the surface. Enrichment of the ore zone near the surface is common, however, as a result of removal of deleterious components, but where the protore originally contained more than 50 percent manganese, the enrichment is quantitatively minor.

The massive psilomelane-type ore formed as a final product of supergene alteration of the protore commonly forms hard, tough, resistant ledges far superior in durability under weathering to the average bedded chert in the country rock. This ore shows in an impressive way the stability of compounds of Mn^{+4} in the presence of atmospheric oxygen.

Summary and conclusions

The results of detailed field work and laboratory investigations strongly indicate that the manganese deposits under study were formed by the modification of manganiferous marine sediments containing silica. The manganese and silica are thought to have been derived from pre-existing rocks by weathering in a humid climate over a long period of time. Weathering solutions and river waters carried the manganese and silica in solution and transported them to the sea, where they were eventually deposited in basins relatively free from the inflow of clastic material and of sufficient depth to permit accumulation of sediments free from the effects of wave action.

The manganese compounds were probably deposited by inorganic reactions, but the silica now found as discrete layers within the ore zones and in the chert sequence was presumably deposited largely through the action of radiolaria and other organisms. It seems likely that the original manganiferous sediments were more or less colloidal in nature, but post-depositional mineral changes obscure the original mineralogical character. The sediments varied in chemical composition on a microscopic scale and likewise over large distances, both vertically and laterally. These variations were due largely, perhaps, to non-uniform conditions of Eh, pH, and ion concentrations in the manganese-bearing sea water.

Mineralogical changes were probably continuous and progressive through diagenesis and metamorphism. The degree of development of the braunite, hausmannite, and associated minerals was evidently dependent upon local bulk chemical composition and appears to have proceeded by gradual recrystallization of the original sediments with little change in the principal sedimentary structures.

Finally, supergene alteration, apparently above the present day water table, converted the bulk of the earlier manganese to a variety of oxides of Mn^{+4}. Most of the original silica was removed in solution during this process, producing the massive, somewhat porous high-grade ore at and near the surface which led to the original discovery of the deposits.

Particular interest is attached to the occurrence of pyroxmangite, alleghanyite, and hübnerite(?) in the deposits. These minerals have not been reported previously as products of low-grade metamorphism, but rather as minerals characteristic of deposits formed at relatively high temperatures and pressures (Lee, 1955; Hewett, et al., 1956). Pyroxmangite and hübnerite(?) appear in very small amounts and in only two places, and it is possible that they represent restricted "hot spots" developed during regional metamorphism. Alleghanyite, however, is abundant in the hausmannite deposit. There is no evidence of its formation by processes other than those of regional metamorphism, and it must be regarded as a low-grade metamorphic mineral in this occurrence.

Certain fundamental problems which remain unsolved or only poorly explained should be pointed out. Perhaps the principal difficulty in the entire investigation has been the satisfactory identification of intimately mixed fine-grained components. For example, the identity of the bementite(?) in the braunite ores, the "dust" in the interlayered cherty beds in that ore, and the coloring matter in the chert beds as a whole are all problematical. Much chemical data could be desired as well, particularly in the detailed study of the chert country rock and the wall rocks of the deposits. The questionable hübnerite at Siñgay deserves more attention, as does the so-called mineral X at Malamig. It can only be hoped that these problems and others related to the origin of the deposits can be studied further by other investigators, with the present data as a background.

The results of the investigation contribute much new data on the manganese deposits of Busuanga, in spite of the obvious unsolved problems. Knowledge of the mineral assemblages not only provides a basis for the hypothesis of origin of the deposits, but also indicates complexities that must be considered in any attempt to make commercial use of the protore. In addition, the hypothesis of origin, if correct, suggests that undiscovered deposits of manganese may exist at the same general level in the stratigraphic section as the known deposits. It is improbable that every deposit laid down when the known deposits were formed has been discovered.

DESCRIPTIONS OF DEPOSITS

PIÑA DEPOSIT

General

The Piña deposit is about 3 km east-southeast of the village of San Nicolas and is reached by a 5.3-km truck road from the village. The workings consist of several open cuts and tunnels, from which several thousand metric tons of commercial grade ore has been mined since the deposit was opened in 1940. The manganese content of the ore was 42 to 50 percent, and in 1952 nearly all minable ore of this quality was exhausted; reserves consisted mostly of siliceous, low-grade material.

Topography and geology

The mine workings are on the lower northeast slope of a roughly pyramid-shaped hill which rises some 120 meters above the valley floor to an elevation of about 180 meters. The hill forms part of a well-dissected foothill ridge which lies several hundred meters north of the main high ridge that borders the valley on the south. A moderate growth of grass covers the rubbly slopes. Small cliffed outcrops dot the surface, and in a few places there are large rock exposures.

A thickness of more than 100 meters of bedded rocks is exposed in the area mapped. The beds are dominantly light-colored chert, but some shaly or slaty beds which seem to be of minor extent are included. The ore zone follows the bedding and rests on a footwall of red jasper breccia. The breccia is cemented by gray to white quartz and is probably several meters in thickness. In places underground, however, the footwall is massive dark brown chert which shows little brecciation. The hanging wall of the ore zone is well-bedded gray to buff chert. The ore zone and the jasper breccia are the only beds that can be traced for a considerable distance with certainty.

The entire sequence of beds is highly deformed. The major structure in the vicinity of the workings is a large complex asymmetrical syncline which plunges moderately east-northeast. The fold is not well exposed as a unit but is mappable by following rubbly jasper outcrops away from the mine workings to the southwest, where the trough is exposed on the upper slope of the hill. The general dip of the limbs is steep and in places the beds are overturned. Minor folds, which are best exposed in the underground workings, commonly plunge 20° to 55° east-northeast. The folds are usually sharp, asymmetrical, and overturned to the north. Where the crest is very sharp, some folds pass into high-angle faults of small displacement. Major faults probably strike northeast, complicating the structure and cutting off the ore zone on the northwest.

Ore zone

In the workings accessible in 1951 and 1952 the ore zone could be well studied only on the south limb of the major fold. From the highest part of the narrow open cut to the lowest tunnel, the ore is exposed discontinuously over a vertical distance of about 60 meters. The longest strike distance exposed in one tunnel is about 55 meters.

The ore zone is stratiform and is from 1 meter to 2 meters in thickness. It is conformable at all places to the layered rocks above and below. The zone contains relatively massive dark gray high-grade manganese ore and well-layered low-grade siliceous ore, locally called "black rock". The siliceous ore, or protore, which is made up of dark brownish black layers separated by thin brown and gray cherty seams, is best exposed in the deeper mine workings. The high-grade ore is best developed at and near the surface of the ground, where the entire ore zone is commonly of rich ore over a distance of many meters. But in certain underground exposures, as at the nose of a sharp, steeply plunging fold or where vertical fractures cut the ore zone, the high-grade ore has a podlike form within the siliceous ore. These steeply dipping ore shoots evidently have formed where ground water was afforded particularly easy access to the ore zone at depth. This near-surface ore passes gradually, with increasing distance from the surface or from controlling structures, into the low-grade siliceous ore along the same stratigraphic zone. The transitional stage between the near-surface ore and the protore consists of interfingering high-grade and low-grade ore layers and is commonly difficult to distinguish from good ore megascopically.

The protore is hard and tough and is characterized by braunite-rich layers from 5 to 75 cm thick which are separated by relatively thin seams of chert. The braunite is in fine granular aggregates with varying proportions of interstitial quartz and bementite(?). The chert layers are in part impure, containing minor amounts of finely disseminated iron oxides and probably manganese silicates. Rarely a thin selvage of pyroxmangite separates chert and braunite layers.

Approaching the surface, manganite appears in thin veinlets and along grain boundaries in the braunite aggregates, and to some extent it replaces bementite(?) and pyroxmangite. The manganite and other minerals are cut by scattered veinlets of psilomelane-type oxides. At and near the ground surface the oxides predominate and the earlier minerals are virtually absent. Cryptomelane is common in this ore.

The near-surface ore in places shows good lamination which is evidently inherited from the protore, to judge from the presence of unreplaced seams of chert between layers rich in manganese oxides. Some specimens show elongate cavities, in part coated with sooty pyrolusite(?), as a result of partial solution of the chert seams.

Summary

The high-grade near-surface ore of the Piña deposit evidently was derived from the siliceous protore by supergene processes which involved oxidation of the manganese and removal of much of the silica in solution. In the unaltered protore, manganese content is high in some layers, but abundant quartz and silicates intimately associated with the braunite lower the grade of the zone as a whole. Nevertheless, if substantial reserves of the protore can be proved by exploration, a product of fair quality could probably be obtained by separating the cherty layers from the braunite layers by selective mining and simple ore-dressing techniques. However, if silica content less than, say, 15 percent were required, very fine grinding and more elaborate beneficiation methods would be required to liberate the braunite from the interstitial quartz.

DIMANYANG DEPOSIT

General

The Dimanyang mine is about 11½ km northwest of Coron town, on the eastern side of the Balulo River Valley. The mine is reached by a truck road about 2½ km long that follows the valley southeast and joins the national road at about kilometer 12. Development was begun in about 1938, and more than 20,000 metric tons of commercial ore, much of which contained more than 50 percent manganese, was produced by 1952. Mining was stopped at that time because of high production costs.

Topography and geology

The Balulo River flows southeastward to Port Uson between parallel steep-sloped wooded ridges which reach a maximum elevation of about 300 meters above sea level. The ridges are moderately dissected by intermittent streams but are generally straight and continuous, trending northwest. The Dimanyang workings are at elevations of 115 to 180 meters, in a small tributary valley on the lower west slope of the eastern ridge.

Most of the rocks in the vicinity of the mine are light-colored thin-bedded chert and similar appearing beds which may be very fine grained clastic sediments. The thickness is great but has not been measured. The manganese ore zone lies within these beds on a massive layer of jasper breccia interlayered in the chert as a probably continuous stratum. Thickness of the ore zone is from 1 meter to 3 meters or more, depending upon local intensity of deformation.

The rocks generally strike north-northwest and dip steeply northeast, but the structure in the area is complex. Axes of minor folds commonly plunge steeply northeast and north, and a similarly plunging major sigmoidal fold is suggested by poorly exposed structures north and south of the mine. Faulting on large and small scales is evident in numerous places, but the displacement is noted more commonly than the actual fault plane. Cross-faults and shearing and faulting nearly parallel to the bedding are both apparent.

Ore zone

During the first years of production, ore was well exposed in open cuts, but ore at the surface was rapidly mined and in 1951 and 1952 ore could be seen only in a few of the underground workings. Many of the upper tunnels were partly caved and inaccessible, and only in the lower levels were exposures extensive.

As a whole, the zone is highly deformed by folding and faulting and varies greatly in thickness, both vertically and laterally. In some folds the zone is markedly thicker at the crest and trough. The entire thickness of the zone generally consists of high-grade ore, but the appearance of the ore is not uniform throughout. In the upper levels, according to Marsden,_/ black hard massive and partly laminated ore was mined in large amounts. Brown massive hard ore was encountered at depth in one of the lower tunnels, interfingering with the black ore. The ore zone exposed in the tunnels open in 1952 was dominantly massive brown ore with minor black lenses. The Amalgamated Minerals, Inc., reported that the approximate manganese content of this ore, which is thought to be the true protore of the deposit, was 52 to 55 percent and the silica content about 8 percent.

_/ Personal communication, 1952.

The dark brown protore is composed largely of closely packed granular aggregates of braunite and a small proportion of interstitial quartz with mosaic texture. Minor constituents include hausmannite, rhodochrosite, and unidentified manganese silicates. The protore alters to black ore along fractures and bedding(?) planes with the development of manganite, which replaces braunite along grain boundaries. Manganite is in turn veined and replaced by psilomelane-type minerals, which evidently make up the bulk of the ore near the surface. Representative specimens of the near-surface ore were not available for study.

Summary

In the Dimanyang deposit black near-surface ore was probably only a little if any higher in manganese content than the braunite protore. This is not surprising, considering that the protore contains very little gangue and that the manganese content of pure braunite is considerably greater than that of pure pyrolusite (braunite: 71.5 percent manganese; pyrolusite: 60 to 63 percent manganese), according to Rankama and Sahama (1949, p. 642). It seems likely, therefore, that ore containing 50 percent manganese or more and 8 to 10 percent silica could be produced from deep parts of the Dimanyang deposit if difficulties in following the ore zone can be overcome. In the past, structural complexities and the added cost of water pumping in deep workings have discouraged attempts to carry mining below adit levels.

SIÑGAY DEPOSIT

General

The Siñgay deposit lies about 4½ km east-southeast of San Nicolas on the north side of a steep-sloped sinuous ridge. By truck road the mine camp is about 5 km from the village. A total of about 28,000 metric tons of ore containing 48 percent manganese or more was produced from about 1938 to 1954, when the ore of commercial grade was exhausted. In terms of ore produced, Siñgay is the largest deposit thus far discovered on Busuanga.

Topography and geology

The wooded hogback ridge on which the mining has been done is a large spur on the west side of the Mount Tundalara-Debaquet divide. Although erosion of the divide is fairly deep, the Siñgay spur is not greatly dissected laterally and is fairly continuous for several kilometers. Maximum elevation is about 350 meters, and relief is greater than 250 meters.

The rocks in the vicinity are principally bedded chert, but coarse- to fine-grained clastic beds also crop out. Vegetation is dense, and outcrops are poor, and relation of the different rock types is not clear.

The thickness and character of the clastic beds are particularly poorly known because outcrops are low and generally highly weathered. On a fairly fresh surface the rocks are gray and brown in color; bedding is poorly evident. Soft, highly weathered bedded rocks which look like slate or mudstone are exposed in the lowest adit stratigraphically above the ore zone and apparently in conformable contact with bedded chert which overlies the ore. Thickness of the beds is several tens of meters. The beds become harder as distance from the ground surface increases, however, and they may be altered chert rather than true clastic beds. Several hundred meters west of this tunnel coarse-grained graywacke crops out in a shallow gully, but the relation of this rock and the supposed mudstone is not known. Boulders of graywacke have been found in several small valleys north of the tunnel, but the rock here has not been found in place.

The chert is thin bedded and probably more than 100 meters thick, although no actual measurement has been attempted. It is exposed in the accessible tunnels, in some old open cuts on the slope, and on the crest of the ridge, and in small cuts along an abandoned road that traverses the ridge west of the workings, as well as on the steep south slope of the ridge. Color of the beds varies from buff, red, and brown to black; darker colors seem to predominate where weathering has been slight. The ore zone lies near the top of the sequence, commonly resting on a footwall of massive jasper breccia and overlain by bedded red to brown chert. In some places the jasper breccia is several meters in thickness.

The beds are folded and faulted, but the gross structure is a complex homocline which strikes west to northwest and dips steeply north. Overturned and recumbent minor folds were mapped several hundred meters east of the workings in a stream valley which cuts the ridge transversely, and similar deformation was observed locally in the ore zone and wall rock during mining, according to Marsden (1940) and others. Complex folding and faulting is well exposed along the old road west of the workings, but no structural pattern has been recognized.

Ore zone

It is reliably reported_/ that ore was mined more or less continuously from the summit of the ridge down the dip to the north through a vertical range of more than 220 meters. Old caved workings along the slope bear this out and show also that mining extended as much as 200 meters along the strike. Production evidently came mostly from tunnels and stopes higher than 150 meters in elevation during pre-war operations. These workings were largely caved and inaccessible in 1950, and the ore zone could be studied only in the Zero Level Tunnel, elevation about 150 meters, and in a winze down the dip from this level.

_/ E. S. Santos, personal communication, 1950.

Most of the ore produced was hard layered psilomelane-type oxide ore, which lay as a bedlike body 1 meter or more thick on a massive jasper breccia footwall (Marsden, 1940, 1941; Ferrera, 1945). Marsden also reported irregular manganese oxide veins in the jasper breccia in one open cut but observed that this ore was not banded like the main ore zone and was probably of secondary origin. In the Zero Level winze the ore zone exposed in 1950 contained interlayered high-grade and low-grade ore and manganiferous chert. The high-grade ore was in layers about 15 cm thick containing interlaminated black oxides and very dark brown slaty rock 1 mm to 3 mm thick; these layers contained more than 50 percent manganese. The low-grade ore contained about 45 percent manganese and was dense, very dark red-brown to nearly black in color. In places this material was closely associated with dirty yellow to straw-brown hard, dense chert which was in stringers, laminae, and irregular masses. At a depth about 20 meters below the Zero Level the average grade of the ore zone was below commercial quality and the zone was limited laterally by steep cross-faults.

The mineralogy of the high-grade ore in the upper part of the deposit was not studied because of the lack of representative samples. Several hand specimens examined were compact, fine-grained masses of psilomelane-type minerals. Minor veinlets of manganite cut the low-grade ore just below the Zero Level, and it appears that the near-surface ore developed from siliceous ore like that now found at depth by processes of supergene alteration in which manganite was an intermediate product.

Braunite is the chief manganese mineral recognized in the protore, which on the whole is particularly fine-grained and difficult to study. The dark brown zones of the protore consist of fine granular aggregates of braunite and small amounts of interstitial quartz, with traces of carbonate(?) and silicate(?). The lighter colored zones contain very minor amounts of braunite as minute, scattered grains in a matrix of chert. The chert also contains a small proportion of finely disseminated impurities including iron oxides and probably manganese carbonate and silicates. Certain buff colored cherty layers are apparently almost free of impurities.

Summary

Except for reserves of near-surface ore which may be discovered along the strike of the deposit, the potential of Siñgay for yielding additional amounts of ore of commercial grade lies in the protore zone. If large tonnages of this material can be found by intensive exploration, simple methods could be employed, as at Piña, to produce a rough concentrate by separating cherty layers from those rich in braunite. More elaborate beneficiation processes could be used to produce a relatively pure braunite concentrate, containing perhaps 10 percent silica, if the tonnage of material available is large enough to warrant the added expense. If mining were carried below the Zero Level, constant water pumping would be necessary.

MALAMIG DEPOSIT

General

The Malamig deposit is in the northwestern part of Busuanga near the small settlement of Malamig, several kilometers southwest of the coastal village of Cheey. A truck road about 4½ km long connects Malamig to the coast at a point just northwest of the mouth of the Minuit River. From 1947, when active mining was begun, to 1953, a total of more than 5,000 metric tons of commercial ore (46 percent manganese or more) was produced from the Malamig deposit and smaller deposits in the vicinity. Mining was stopped in 1953 because of high costs and depletion of the near-surface ore.

Topography and geology

The terrain in the vicinity of the Malamig deposit is wooded and hilly. The principal topographic feature is a dissected northeastward-trending ridge, which in the vicinity of the workings is crossed by the eastward-flowing Malamig River and is flanked on the north by Loñgon Creek. The Malamig workings are on the steep south slope of the ridge in the river gorge, and other less extensive workings are on the ridge to the northeast and to the southwest. Relief is more than 200 meters, and the maximum elevation is greater than 200 meters.

Bedded chert and fine- to coarse-grained clastic rocks are exposed in and near the Malamig River Valley where it cuts the main ridge. In the vicinity of the workings clastic beds are lacking, and most of the rocks are dense well-bedded light- and dark-colored chert. The manganese ore zone is roughly tabular and lies between chert beds that are dark gray to black in color; in places the footwall chert looks quartzose and shatters under the hammer into small brittle fragments. A short distance west of the portal of tunnel T-185, a large outcrop of jasper breccia seems to lie stratigraphically below the footwall black chert, but a continuous section is not exposed and the relationship is not certain. The entire chert sequence is probably about 100 meters thick.

About 120 meters south of the Malamig deposit the valley widens, and approximately north of the main ore bin graywacke quartzite crops out poorly in the stream bed. No bedding was seen in the quartzite, and the contact with the chert beds was not located. Chert beds just north of the clastic beds dip steeply north, indicating that the quartzite underlies the chert, but it is not known if the dips observed are overturned. Quartzite also crops out poorly on the slope north of the workings, and here the stratigraphic sequence is equally uncertain.

In general the chert beds strike N. 80° W. to N. 45° E., more or less following the trend of the ridge crest. Complex folding and faulting is common, however. Minor fold axes are parallel to the regional strike, and major folding of a similar orientation is indicated, particularly in the ore zone exposed in the workings. The manganiferous zone dips steeply southward in most of the drifts, but in the highest tunnels it flattens and finally dips gently north and northwest. Several low chert outcrops north of the workings also dip northward, and it is likely that a major anticlinal axis passes roughly along the ridge crest.

A major syncline may lie between the workings and the quartzite beds near the ore bin, to judge from the many northward-dipping beds south of the workings; but the absence of recognizable marker beds makes the true nature of the structure difficult to determine.

Faulting is common in the ore and wall rock exposures underground, and some chert outcrops are cut by faults, causing small cliffs in places. Strike faults are numerous and vary from nearly horizontal to vertical; displacement of the ore zone is generally small along these faults. An extensive fault probably follows the north contact (footwall) of the ore zone in tunnel T-215 and lower levels, to judge from the clayey crushed chert zone 10 to 20 cm thick which commonly lies between the ore and the hard chert footwall. In some places the fault cuts the ore zone at a low angle and causes irregularities in the thickness of the ore.

Cross faults do not appear to be of major importance in the underground workings except at the east end of the ore body, where the ore is lost at a complex fault zone. The fault zone is not well exposed but may be related to two steep northeastward-striking faults located on the surface south and east of the workings.

Ore zone

In 1952 the ore zone was exposed in drifts from 50 to 100 meters in elevation and along a strike length of more than 60 meters. The zone varies from a thin fissile seam to a massive layer one meter or more in thickness and is generally high in manganese content throughout. In the workings above tunnel T-215 the ore is relatively thin bedded and fissile, and layers are mostly broken and imbedded in clay; the clay must be cleaned from this ore to maintain a grade of 46 percent manganese or more. The massive ore, which is principally on the T-215 level and below, contains 48 to 55 percent manganese. The average manganese content is somewhat lower in the lowest workings, however.

Hard black oxide ore composed of psilomelane-type minerals and tough brown ore that consists largely of hausmannite and silicate are found in intimate association in the deposit. So far as is known, only black ore is found above the T-250 level, but in T-250 and lower workings black and brown ore together make up the ore zone. In places the contact between the two is rather sharp and often parallel to the wall-rock contact; in other places, however, the contact is very irregular and appears to be gradational. In some places the black ore forms thin sheets in the brown ore more or less parallel to the wall-rock contact. The proportion of black ore to brown seems to decrease with depth, but it is difficult to make a quantitative statement because only pillars could generally be sampled, and the character of the bulk of the ore mined is not known.

Under the microscope the brown ore is found to be a complex intergrowth of fine-grained alleghanyite and fine-and coarse-grained hausmannite and rhodochrosite. Minor amounts of manganosite are associated with the other minerals, and traces of braunite and jacobsite are found. In the deepest tunnel, a layer of massive rhodochrosite rock 10 to 20 cm thick lies at the top of the brown ore. The alteration of the brown ore to black ore evidently began with the replacement of the hausmannite-alleghanyite intergrowth by a soft black unidentified mineral termed mineral X, and proceeded with the development in this mineral, and to a lesser extent in the remaining primary minerals, of veinlets of barite ~~benentite~~, manganite, hausmannite, and cryptomelane. These minerals formed in approximately the order listed. Finally, massive black ore made up largely of cryptomelane, gamma MnO_2, and other forms of manganese dioxide developed by intense veining and replacement of all of the earlier minerals.

Summary

The near-surface ore at Malamig contains a greater percentage of manganese than the protore because of the removal of silica from the silicates and the concentration of manganese by processes of supergene alteration. Nevertheless, the protore probably contains an average of more than 40 percent manganese, and as much as 55 percent where hausmannite predominates, and thus may be worthy of considerable effort in exploration. If adequate extensions of the protore can be found, a commercially profitable operation may still be possible. In deep workings, water pumping would be necessary at all times. Beneficiation of the protore would improve the grade of the material, but a limit to silica removal would be reached because of the extremely fine-grained nature of much of the hausmannite-alleghanyite intergrowth.

APPENDIX

Representative X-ray diffraction powder patterns obtained from specimens of the manganese ores studied are tabulated alphabetically in this section. For comparison purposes, patterns for the same minerals are listed from recently published reports. Unless otherwise noted, patterns were obtained using Fe radiation filtered with Mn, and intensities were estimated visually.

Minor discrepancies between the patterns of Busuanga minerals and those listed for comparison are common and may be due to several causes. First, errors in interpretation and measurement of lines may result where patterns are weak or represent mineral mixtures. In the present work, special effort was made to obtain mono-mineralic samples, with the result that in many instances only a very minute sample was used, and patterns were commonly weak. Nevertheless, many samples turned out to be mixtures, and identification of the component minerals had to be made from films containing lines characteristic of two or more minerals. Secondly, disagreement of patterns may be due to actual compositional or structural differences in the minerals X-rayed by different investigators. Dissimilarities in published patterns of minerals said to be the same are common and indicate that these problems are widely encountered in work with manganese minerals as well as with other species. A detailed mineralogical investigation to resolve problems of this sort is highly desirable but is not within the scope of the present work.

ALLEGHANYITE

I(a)		II(b)	
I/I$_o$	d(A.)	d(A.)	I/I$_o$
5	5.00	5.1	10
Tr(c)	4.37	4.4	5
Tr	4.09	4.1	5
Tr	3.90	3.92	5
Tr	3.73		
70	3.61	3.62	30
Tr	3.50	3.5	10
		3.3	5
80	3.14	3.14	25
		3.01	5-
		2.97	5-
90	2.85	2.87	70
40	2.77	2.78	10
40	2.74	2.75	20
		2.68	15
90	2.61	2.62	30
5-	2.53	2.55	5
30	2.42	2.43	20
30	2.39	2.40	10
30	2.36	2.35	30
30	2.34		
		2.21	5
Tr	2.12	2.13	5
Tr	2.04	2.03	5
Tr	1.93	1.95	5
Tr	1.89	1.88	10
Tr	1.87		
100	1.81	1.82	100
10	1.75	1.76	10
5	1.71	1.72	5
15	1.69	1.69	20
Tr	1.65	1.66	5
5	1.64	1.64	5
5	1.61	1.61	5
5	1.59	1.59	5
20	1.564	1.57	30
20	1.557		
20	1.547	1.54	30
Tr	1.51	1.50	?
Tr	1.48		
15	1.46	1.46	20
Tr	1.44	1.44	5
		1.40	5-
15	1.39	1.39	10

(Higher 2θ reflections omitted)

(a) Alleghanyite from Bald Knob, North Carolina (Lee, 1955, p. 13)
(b) Alleghanyite from Malamig deposit, Busuanga.
(c) Tr = trace

BARITE
~~BEMENTITE~~

I(a)		II(b)	
I/I_o	d(A.)	d(A.)	I/I_o
4	4.43	4.32	10
8	3.92	3.9	25
		3.73	5
34	3.60	3.58	25
50	3.45	3.43	50
24	3.32	3.32	40
44	3.11	3.08	60
34	2.83	2.82	30
34	2.73	2.71	30
12	2.62		
10	2.56		
8	2.46	2.48	5
		2.32	5
10	2.21	2.2	5
100	2.11	2.11	100
6	2.05	2.05	5
4	1.93	1.93	5-
12	1.85	1.86	5
		1.78	5-
4	1.76	1.76	5
		1.72	5-
32	1.64	1.67	10
32	1.61	1.63	5
		1.58	5
10	1.52	1.53	10
		1.50	5-
		1.47	5
		1.45	5-
14	1.42	1.42	10
6	1.40	1.40	5-
		1.38	5-
		1.36	5
		1.35	5-
		1.32	5
		1.30	5
10	1.26	1.26	20
2	1.22	1.215	5
2	1.20	1.19	5-
2	1.15	1.145	5
4	1.10	1.095	10
		1.06	5-
		1.05	5-
		1.03	5-
		1.01	5-
		0.99+	5-

(a) Barite ~~Bementite~~, (ASTM card 3-0971 Mo radiation, lambda = 0.70926)
(b) ~~Bementite~~ Barite from Malamig deposit, Busuanga

BRAUNITE

I$^{(a)}$		II$^{(b)}$		III$^{(c)}$	
I/I_o	d(A.)	I/I_o	d(A.)	d(A.)	I/I_o
				7.0	5
5-	4.65			4.7	5-
15	3.47	w$^{(d)}$	3.50	3.5 d(?)$^{(e)}$	20
				2.99	20
100	2.70	vs	2.72	2.71	100
25	2.35	m	2.36	2.34	50
15	2.15	s	2.15	2.13	60
15	2.14				
5	1.87	vw	1.88	1.87	5-
5	1.81	vw	1.82	1.82	5
5	1.74	vw	1.74	1.73	5-
60	1.66	vs	1.66	1.66	80
5	1.54	w	1.54	1.54	5
5	1.52	vw	1.50	1.50	5-
5	1.47	vw	1.47	1.47	5
40	1.42	s	1.42	1.42	40
20	1.41			1.41	40
5-	1.37				
10	1.36	m	1.36	1.355	10
5-	1.28				
5-	1.27			1.27	5
5	1.18	vw	1.18	1.18	5
10	1.17	w	1.17	1.17	10
5-	1.15	vw	1.15	1.15	5
20	1.08	s	1.08	1.078	20
10	1.05	m	1.054	1.05	10
		vw	1.046		

(a) Braunite from the Hamayokokawa mine, Japan (Lee, 1955, p. 14).

(b) Braunite from Tifernine, Morocco (Ramdohr, 1956, p. 39).

(c) Braunite from the Dimanyang mine, Busuanga.

(d) vs = very strong; s = strong; m = medium; w = weak; vw = very weak.

(e) d = doublet.

CRYPTOMELANE

I(a)		II(b)		III(c)	
I/I_o	d(A.)	I/I_o	d(A.)	d(A.)	I/I_o
m(d)	6.84	90	6.863	7.0	50
vw	5.83				
m	4.85	80	4.892	4.9	10
vw	4.02				
vw	3.47	30	3.445	3.5	10
s	3.09	100	3.105	3.15	60
		30	2.445		
vs	2.38	70	2.387	2.41	100
		10	2.305	2.25	10
		40	2.183	2.17	40
s	2.14	50	2.145		
vw	1.99	10	2.097	2.05	5
		10	1.961		
vw	1.91	20	1.917		
m	1.82	50	1.820	1.84	10
w	1.63	40	1.633		
		40	1.618		
		10	1.544	1.55	10
m	1.53	60	1.528		
m	1.42	20	1.423	1.43	20
vw	1.39	5	1.385		
w	1.35	50	1.347	1.36	5
w	1.29	10	1.289		
vw	1.24	5	1.23		
		5	1.209		
		5	1.190		
vw	1.15	5	1.135		
vw	1.08	10	1.073		
		10	1.052		

(a) Cryptomelane from Hollerter Zug Siegen, Germany (Ramdohr, 1956, p. 56).

(b) Cryptomelane from Mowry mine, Patagonia district, Arizona (Fleischer and Richmond, 1943, p. 280).

(c) Cryptomelane from Malamig deposit , Busuanga.

(d) vs = very strong, s = strong, m = medium, w = weak, vw = very weak.

GAMMA MnO_2

I[a]		II[b]	
I/I_o	d(A.)	d(A.)	I/I_o
M[c]	3.89	3.8	70
		2.6	20
M	2.42	2.4	100
M	2.09	2.1	50
?	1.80	1.8	10
M	1.614	1.63	80
VW	1.416	1.50	10
VW	1.349		
VW	1.305		

(a) Glemser, quoted in Cole, Wadsley and Walkley, 1947, p. 141

(b) Gamma MnO_2-type mineral from Malamig mine, Busuanga. Pattern obtained using Cu radiation filtered with Ni. All lines diffuse.

(c) M = medium, VW = very weak.

HAUSMANNITE

I(a)		II(b)	
I/I_o	d(A.)	d(A.)	I/I_o
Trace	7.3	7.0	15
15	4.93	4.95	15
25	3.08	3.08	30
5	2.87	2.89	10
90	2.76	2.76	40
100	2.48	2.48	100
20	2.36	2.34	15
20	2.04	2.03	15
5	1.83	1.82	5
20	1.79	1.78	15
5	1.70	1.70	10
5	1.64	1.63	5
40	1.57	1.58	15
60	1.54	1.53	40
5-	1.47		
15	1.44	1.44	10
5-	1.38		
5-	1.35		
15	1.28	1.27	5
10	1.24	1.22	5-
5-	1.19	1.19	5-
5-	1.18	1.17	5-
Trace	1.13		
10	1.12	1.12	10
Trace	1.10	1.10	5-
5	1.08	1.08	10
5	1.06	1.06	5-
5	1.03	1.03	5
5	1.02	1.02	5
5+	0.984	0.984	5

(a) Hausmannite from the Hamayokokawa mine, Japan (Lee, 1955, p. 40)

(b) Hausmannite from the Malamig mine, Busuanga

HÜBNERITE(?)

I(a)		II(b)		III(c)	
I/I$_o$	d(A.)	I/I$_o$	d(A.)	d(A.)	I/I$_o$
15	5.76	10	5.72		
		5	5.28		
80	4.82	70	4.83	4.75	60
		5	4.11		
70	3.77	60	3.77	3.87	50
60	3.69				
		10	3.28		
100	3.00				
100	2.95	100	2.965	2.96	100
25	2.87	5	2.87	2.85d(?)(d)	5
		5	2.74	2.72	30
				2.68	30
				2.56	40
50	2.49	40	2.49	2.45	30
10	2.41	10	2.41	2.38	30
10	2.24				
15	2.20	10	2.22	2.18B(d)	20
5	2.05	5	2.05	2.1 B	10
5	2.02	5	2.02		
5	1.92			1.92	5
5	1.88	5	1.885		
5	1.85	5	1.845	1.86	5
15	1.78	10	1.785		
15	1.75	10	1.745	1.73	10
15	1.72	10	1.715		
				1.67	5
(Higher 2θ reflections omitted)				1.63	20
		10	1.600	1.58	10
				1.56	20
		10	1.525	1.52	20
		5	1.47	1.49	10
		10	1.38		
		5	1.325	1.32 B	5-
				1.27 B	5-
				1.25 B	5-
		5	1.225		
		5	1.198		
				1.14	?
				1.11	?
				1.09	?

(a) Hübnerite from Renge mine, Japan (Lee, 1955, p. 50).

(b) Hübnerite from Silverton, Colorado (Harcourt, 1942, p. 86; intensities re-scaled).

(c) Hübnerite(?) from Siñgay deposit, Busuanga.

(d) d = doublet; B = broad.

MANGANITE

I$^{(b)}$		II$^{(a)}$		III$^{(c)}$	
I/I$_o$	d(A.)	I/I$_o$	d(A.)	d(A.)	I/I$_o$
		1	3.700	3.7	10
vs$^{(d)}$	3.41	10	3.385	3.4	100
		1	3.096	3.1	5
		1	2.883		
m	2.64	9	2.616	2.64	20
w	2.52	2	2.506	2.51	5
m	2.41	6	2.406	2.40	20
		0.5	2.359	2.38	5
		0.5	2.310		
m	2.26	7	2.263	2.28	10
m	2.18	3	2.186	2.18	5-
s	1.77	6	1.771	1.78	5
w	1.70	5	1.694	1.70	5
s	1.66	9	1.661	1.67	10
w	1.63	5	1.629	1.63	5-
m	1.50	5	1.493	1.51	5-
m	1.43	1	1.428	1.43	5-
		4	1.424		
		1	1.414		
m	1.32	4	1.316	1.32	5-
vw	1.29	2	1.287		
vw	1.28	1	1.275		
vw	1.26	1	1.257		
vw	1.24	2	1.239		
vw	1.21	1	1.208		
m	1.18	4	1.179	1.18	5-
m	1.16	4	1.152		
s	1.13	8	1.130	1.13	5-
m-w	1.11	4	1.109		
m-w	1.10	3	1.094		
m-w	1.08	3	1.076		
m	1.03	1	1.052		
		8	1.024		
		2	1.022		
m	1.01				
m	0.990				

(a) Manganite from Ilfeld, Harz, Germany (Fleischer and Richmond, 1943, p. 281)

(b) Same (Ramdohr, 1956, p. 41, 42).

(c) Manganite from Malamig deposit, Busuanga. Weak pattern; lines from minor hausmannite in original pattern omitted.

(d) vs = very strong, s = strong, m = medium, w = weak, vw = very weak.

MANGANOSITE

I$^{(a)}$		II$^{(b)}$	
I/I_o	d(A.)	d(A.)	I/I_o
62	2.568	2.57	60
100	2.223	2.22	100
58	1.571	1.57	50
21	1.340	1.34	20
13	1.283	1.28	30
11	1.1112	1.11	10
10	1.0198	1.018	10
18	0.9938	0.992	20
15	0.9074		
13	0.8554		
4	0.7857		

(a) Synthetic MnO (ASTM card #7-230).

(b) Manganosite from the Malamig deposit, Busuanga
(Lines in original pattern due to hausmannite omitted)

RHODOCHROSITE

I(a)		II(b)	
I/I_o	d(A.)	d(A.)	I/I_o
35	3.66	3.63	40
100	2.84	2.86	100
20	2.39	2.40	20
27	2.172	2.18	25
23	2.000	2.01	20
12	1.829	1.84	15
30	1.770	1.78	50
33	1.763	1.77	50
1	1.556	1.56	5
13	1.533	1.53	15
1	1.452	1.46	10
<1	1.423	1.425	5
10	1.379	1.385	10
<1	1.306	1.320	5
<1	1.248	1.258	5
3	1.221	1.228	10
1	1.146	1.155	10
1	1.1014	1.106	10

(Higher 2θ reflections omitted from table)

(a) Rhodochrosite, "precise determination" (ASTM card 7-268).

(b) Rhodochrosite from Malamig deposit, Busuanga (Lines from unidentified minor impurities in sample not tabulated).

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