CHROMITE DEPOSITS OF THE NORTH-CENTRAL ZAMBALES RANGE, LUZON, PHILIPPINES

by

D. L. Rossman
U. S. Geological Survey

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ABSTRACT

Peridotite and gabbro form an intrusive complex which is exposed over an area about 35 km wide and 150 km long in the center of the Zambales Range of western Luzon. The Zambales Complex is remarkable for its total known resources, mined and still remaining, of about 15 million metric tons of chromite ore. Twenty percent of Free World production was obtained from this area between 1950 and the end of 1964; in 1960 production reached a high of 606,103 metric tons of refractory-grade ore, mostly from the Coto mine near Masinloc, and 128,426 metric tons of metallurgical ore from the Acoje mine. The United States imports 80 to 90 percent of its refractory-grade chromite from the Philippines, and its basic refractory technology has been designed upon the chemical and physical characteristics of Coto high-alumina chromite ore. Continuation of this pattern will depend upon discovery of additional ore reserves to replace those depleted by mining.

The Zambales Ultramafic Complex is of the alpine type in which lenticular or podiform deposits of chromite lie in peridotite or dunite, mostly near contacts with gabbroic rocks. Layered structures, foliation, and lineation commonly are well developed and transect boundaries between major rock units, including chromite deposits, at any angle. Accordingly, these structures cannot be used as guides in exploration and mining as

they are used in stratiform complexes such as the Bushveld, where chromite layers extend for many miles. Probably 90 percent of the known deposits in the Zambales Complex are located in two belts in its northern part. One zone containing high-aluminua refractory-grade deposits extends northeast from the Coto mine and Chromite Reservation No. 1 along a peridotite contact with olivine gabbro, and another of high-chromium metallurgical grade chromite extends south through the Zambales and Acoje properties, and swings westward around the south side of Mount Lanat along a peridotite contact with norite. The textures of ores, association of chromite with dunite as gangue and as halos, and the transecting nature of the layering, foliation, and lineation in relation to chromite, are similar in all deposits regardless of composition of the chromite mineral itself. Textures in chromite ores, and structural relationships between chromite deposits and country rocks, show that layering and related foliation and lineation were formed or modified by flowage. Gabbro is believed to form the upper part of the Complex in general.

Geophysical methods have been rather unsuccessful in finding chromite in the Zambales Complex. Gravity surveys, in order to be successful, must correct for all features influencing gravity except for the chromite itself. Too often the uncertainties in position of rock units and in knowledge of rock densities or position of hidden geologic features (dikes, zones of alteration) preclude the possibility of making adequate corrections. Magnetic surveys have failed to reveal any magnetic patterns attributable to the presence of chromite.

Exploration for chromite should be guided by the knowledge that chromite occurs only in certain geologic environments. Thus because nearly all known chromite deposits in the Zambales Complex lie in peridotite near the gabbro contact, search for chromite should be concentrated there. Likewise it is evident from structural evidence presented here that there is little relation between layering and distribution of either major rock units or chromite deposits. Thus one is not justified in using the layered structure to predict either the position or attitude of major rock unit contacts, or presence or position of chromite deposits.

In such a productive complex it is geologically certain that unknown deposits still remain undiscovered. The most promising areas for exploration are near known groups of large deposits like Acoje and Chromite Reservation No. 1. Underground drilling has been very successful in finding buried tabular ore bodies at the Acoje mine, and comparable exploration down the plunge of the ore zone on Reservation No. 1 is indicated.

Reserves of refractory or high-alumina chromite were estimated to be 10 million metric tons in 1966, including about 1.4 million tons of fines at Coto. Systematic exploration might be expected to find 2 to 3 million tons more of ore. Reserves of metallurgical or high-chromium ore in the Acoje mine in 1966 were reported to be 2,279,750 metric tons.

INTRODUCTION

History of mining

Mining of metallurgical-grade chromite ore began in the Philippines at the Acoje mine in 1933, and four years later mining started at the giant refractory-grade chromite deposit at Coto, near Masinloc. From 1933 to the end of 1964, Philippine production of both ore types is believed to have totaled approximately 9,800,000 metric tons (m.t.). Between 1950, and late 1964, the Republic produced about 8,015,000[1/] m.t. of chromite out of a free world total of 42,640,000 m.t., or 18.8 percent. In the 6-year period 1959-1964, 650,807 m.t. of metallurgical chromite were produced and 2,832,997 m.t. of refractory ore, for a total of 3,483,804 m.t. Peak output of 606,103 m.t. of refractory ore and 128,426 tons of metallurgical ore was attained in 1960. All but about 5 percent of the chromite came from deposits in the Zambales Complex, Zambales Province. Since 1950 the rates of shipments and mining have reflected demand and consumption primarily in the United States, but to an increasing extent in Japan and western Europe.

Geography and access

The Zambales chromite area (fig. 1) is on the west side of Luzon between lat 14°40'N. and lat 16°00'N. National Highway No. 7 is the chief access route into the area, and from it mine and logging roads extend into the Zambales Range. Native trails are widespread but poor.

[1/] All figures are from U. S. Bureau of Mines, Minerals Yearbook and Mineral Trade Notes.

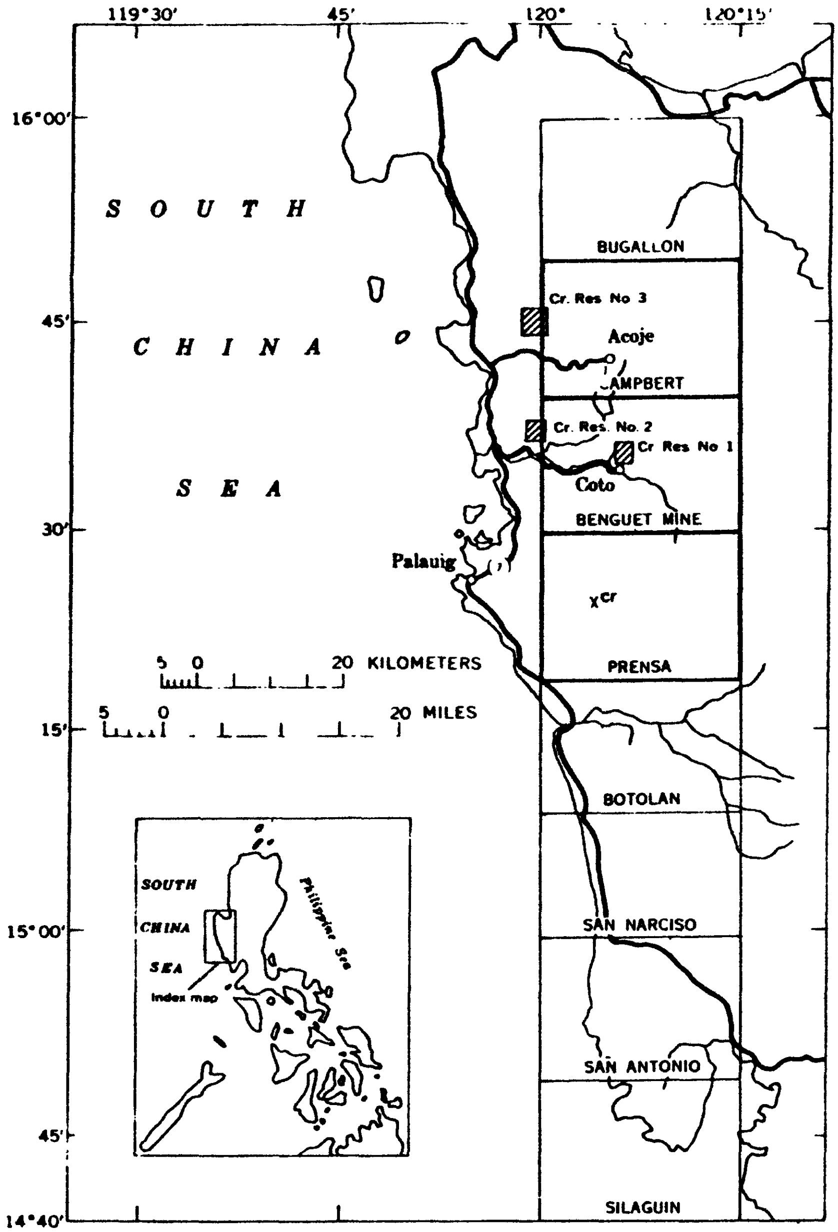


FIGURE 1.--Index map showing location of Campbert, Benguet Mine, and Prensa quadrangles.

The Zambales Range is a rugged mountainous area with many slopes of 45° or more. Rock exposures are abundant, particularly along streams, but flatter areas are covered with laterite and afford fewer outcrops. Vegetation reflects underlying rock types. Gabbro supports dense forests; at low altitudes peridotite generally supports only brush or cogon, a tall coarse grass, but above 800 m pine is common on peridotite. Burning after logging is rapidly deforesting the area and hunting is extermininating the wild life.

The main crest of the Zambales Range is a gentle domal high surface which is best preserved on High Peak in the Prensa quadrangle and in a high area in the eastern part of the Benguet Mine quadrangle. Streams are deeply incised and erosion has been so severe that this surface has been destroyed over much of the mapped area. The piedmont area west of the range has in profile a smoothly sloping surface that can be projected seaward across the offshore islands. Streams flowing across the piedmont are eroded almost to base level and most lie in flat valleys several miles wide. Beach ridges occur as much as 1 km inland in the lower ends of these stream valleys.

The area has a pronounced rainy season which lasts from June to November, and a hot dry season from March to June; the other months are relatively cool. Along the coast the annual rainfall averages about 4.5 m. Rainfall data for the higher altitudes are not available, but above 1,800 m rain falls frequently in all seasons. Temperatures range from 20° to 33°C near sea level, and never reach the freezing point even on the highest peaks.

Previous investigations

Early geologic work in the Zambales Range was concerned primarily with the chromite deposits and no attempt was made to map the geology of the area systematically. Corby (1951) included a description of the sedimentary rocks along the Zambales coast. W. C. Stoll (1958) published a geologic description of the Coto deposit which contains considerable petrographic data on the rocks of the area. Neither reported at any length on rocks composing the Zambales Complex as a whole.

Field work and acknowledgments

The present investigation of the chromite resources of the Philippines was started by the Philippine Bureau of Mines in 1955 under the general supervision of J. W. Peoples, U.S. Geological Survey, under the auspices of the International Cooperation Administration (now Agency for International Development), U. S. Department of State. By 1957 the Coto deposit, part of Reservation No. 1, and parts of the Benguet Mine and Campbert quadrangles had been mapped geologically. Drilling and other exploration of chromite deposits in Reservation No. 1 began in 1955, and in 1957 an interim report was published (Peoples and others, 1957). The present writer assumed responsibility for the investigation in September 1957 and exploration on Reservation No. 1 was completed in 1958 (Rossman and others, 1959). Subsequently geological mapping was continued in the Campbert and Benguet Mine quadrangles. All quadrangles included in this report were mapped and completed by 1963.

Initial geologic mapping was largely reconnaissance of semi-detailed, and it was not realized that layered structure was not a reliable guide to rock distribution or position of ore deposits. By 1959 it became evident that an understanding of the geology of the chromite deposits required more detailed mapping, so much of the Campbert, Benguet Mine, and the western part of the Prensa quadrangles were re-checked or remapped.

The geologists of the Philippine Bureau of Mines who did much of the field work are listed in table 1. The section of the current report describing the chromite deposits near Palauig was originally written by Mr. Zoilo Zepeda. Mr. Mauricio Marcelo did much of the petrographic work, and Mr. Narciso Bautista was responsible for the final drafting. Numerous other members of the Philippine Bureau of Mines also participated in the work represented in this report.

GEOLOGY OF THE ZAMBALES COMPLEX

Essentially, the Zambales Range is a broad anticline or arch of peridotite and gabbro flanked by younger bedded rocks of Tertiary and Quaternary age. The name "Zambales Complex" is given to interrelated gabbroic and peridotitic rocks exposed over a north-south distance of 150 km and a width of approximately 35 km.

Laterite formed by weathering of peridotite mantles gentle slopes or areas where erosion is not severe. Steep slopes normally retain only relatively small areas and patches of laterite. Vegetation inhibits erosion and laterite deposits are usually thicker under heavy vegetation than elsewhere. Laterite as much as 10 m thick and several square kilometers in area mantles a ridge immediately west of the Acoje Mine; laterite also

Table 1.--Philippine Bureau of Mines personnel assigned to geologic mapping of the Zambales Complex.

Name	Period of activity	Type of work
Abarquez, O.	2/58-6/60	Reconnaissance mapping, Bugallon quadrangle.
*Abiog, D.	1956-61	Reconnaissance and detailed geologic mapping. Responsible for mapping of most of the quadrangles south of Benguet Mine quadrangle. Some geologic mapping in Campbert and Benguet Mine quadrangles.
*Andal, D.	1/58-6/58	Reconnaissance and detailed mapping, largely in Benguet Mine and Prensa quadrangles.
Biscocho, N.	7/60-4/61	Reconnaissance and semi-detailed mapping.
*Crispin, O.	1955-61	In overall charge of mapping.
Encina, D.	2/58-60	Reconnaissance mapping in Bugallon quadrangle.
Fajardo, D.	3-6/56	Detailed mapping in eastern Campbert quadrangle.
*Fernandez, N.	1955-57	Reconnaissance and detailed mapping in Campbert and Benguet Mine quadrangles.

Table 1.--Philippine Bureau of Mines personnel assigned to the geologic mapping of the Zambales Complex--Continued.

Fontanos, C.	1955-57	Detailed mapping on Reservation No. 1
*Fortuno, P.	1959-60	Reconnaissance and detailed mapping Bugallon quadrangle.
Gorriceta, A.	7/12/59	Detailed mapping Palauig deposit.
Ligayu, M.	4/60-3/61	Campbert, Camiling, and Benguet Mine.
*Malicdem, D.	2/58-6/60	Reconnaissance, Bugallon, Benguet Mine.
Marceno, B.	4/60-3/61	Reconnaissance. Campbert, Benguet Mine.
Montero, P.	4/60-3/61	Reconnaissance. Campbert, Benguet Mine.
Pacis	1958	Reconnaissance, Benguet Mine and Prensa quadrangles.
*Palacio, D.	5/60	Detailed mapping. Bugallon quadrangle.
Ramos, F.	3/60-4/61	Semi-detailed and reconnaissance mapping. Benguet Mine quadrangle.
Raval, L.	9/59-3/60	Reconnaissance mapping in Silanguin, Benguet Mine quadrangles.
*Roxas, R.	3/58-6/61	Reconnaissance and detailed. Northern end of Zambales Range.

Table 1.--Philippine Bureau of Mines personnel assigned to the geologic mapping of the Zambales Complex--Continued.

*Samaniego, S.	1954-56	Semi-detailed and detailed. Campbert and Botolan quadrangles.
*Santiago, J.	1/58-6/60	Reconnaissance and detailed. Bugallon quadrangle.
Velasquez, C.	1959-61	Detailed, Dasol, Pangasinan, Botolan quadrangle.
Yap, A.	1955-56	Detailed, Bugallon quadrangle.
*Zepeda, Z.	1/58-6/61	Reconnaissance and detailed mapping over much of Zambales Range.

*Party chief.

covers a mountain top west of this ridge with a mantle 2 to 7 m thick. Residual peridotite blocks are abundant near the base of the laterite. No large areas of laterite are known south of the Benguet Mine quadrangle.

Unconsolidated gravels are found in beds of the major stream valleys and also in outwash that covers the sediments along the foot of the range. Gravels cemented by magnesium carbonate lie along valley flanks as much as 400 m above the valley floor. Exposures present on nearby islands to the west show that the gravels extended to them and well beyond the present shoreline.

The lower east and west sides of the Zambales Complex are overlain unconformably by a conglomerate which obviously was eroded from the peridotite and gabbro. The conglomerate disappears to the north in the Bugallon quadrangle but its extent is otherwise unknown.

The youngest consolidated rocks are bedded, shallow-water marls which contain shells of middle late Miocene age. These lie conformably upon the massive lower Miocene limestone and underlie alluvial deposits in the low coastal areas. The marls are gently folded and tilted up against the Zambales Range. They appear to be only a few hundred meters thick. The limestone rests upon sandy sedimentary rocks, which in turn overlies volcanic rocks that contain pillow structures. These grade downward into an extensive dike swarm which appears to radiate from the upper part of the gabbro.

General relationships of the rocks

The Zambales Complex of mafic and ultramafic rocks crops out over more than 2300 sq km and is one of the largest bodies of its type mapped in the world so far. Undoubtedly the exposed rocks represent only a part of a much larger mass. Further effort is needed before the general disposition of the gabbros and peridotites is proved, and it is premature to postulate an origin for the complex based upon material included in this report.

The large size and excellent exposures of the complex show many highly consistent relationships not heretofore recognized, and much new material is available for study on ultramafic rocks and chromite genesis. Petrologists interested in such problems will find considerable material in the Zambales Complex bearing upon the genesis of ultramafic rocks and chromite deposits.

All chromite deposits of the Zambales Range occur in peridotite, which is related to gabbroic rocks. Several lines of evidence indicate that the peridotite, gabbro, and chromite are genetically interrelated and probably were emplaced as integral parts of a major intrusion (pls. 1, 2, 3). These rocks together with small amounts of apparently closely related dioritic rocks are collectively named the Zambales Complex. The most abundant rocks are gabbro (both noritic and olivine-bearing), saxonite, dunite, and other varieties of peridotite. In this report, to conform to local usage, rocks composed of olivine and enstatite or bronzite are termed saxonite rather than harzburgite. The term peridotite as used in this report refers collectively to all olivine-rich rocks containing little or no feldspar.

The saxonite is assumed to be the basement rock. It grades upward into dunite which nearly everywhere forms a zone lying between the saxonite and the gabbro. Locally however the saxonite is in contact with the gabbro, and in these areas the saxonite intrudes and assimilates the gabbro. The bulk of the gabbro is noritic and lies in contact with peridotite, but in Dalayap Hill near Coto (Benguet quadrangle) the peridotite is in contact with olivine gabbro which grades upward into norite. The norite in many parts of the Complex grades into a micro-diorite dike swarm. These dikes in turn intrude volcanic rocks. The relationship is similar to that described by R. A. M. Wilson for an ultramafic complex on the Isle of Cyprus (Wilson, 1959).

Saxonite

Saxonite outcrops are typically brown and have a rough surface which is due to pyroxene grains that stand out in relief. The rock is typically massive but commonly has a mineral banding that is most clearly seen at moderate distance (a few hundred meters) from the dunite contact. At several kilometers from the dunite contact the layering becomes indistinct or indiscernible, and the saxonite has a uniform texture.

Olivine composition (Fo_{92-94}) in saxonite is notably uniform everywhere. The orthopyroxene on the other hand varies widely in composition, grain size, and abundance, and closely reflects its positional relation to dunite or chromite deposits. In each case the pyroxene decreases in amount, becomes richer in iron, and smaller in grain size, as the dunite or chromite respectively is approached. Composition ranged from En $_{75-95}$

but generally is En_{88-95}. Figure 2 shows these relations for one area located at the chromite deposits lying due east of Palauig, Prensa quadrangle. In general the texture in saxonite is clearly discernible and xenomorphic-granular, and even highly serpentized saxonite commonly contains relict pyroxene grains. Clinopyroxene lamallae are common in the orthopyroxene.

Saxonite is normally separated from gabbro by a dunitic zone, but an atypical contact between saxonite and norite extends southwesterly from the eastern part of the Campbert quadrangle to a point on the South Lawis River about 3 km west of Coto. Locally saxonite along this contact has intruded norite and both units show evidence of recrystallization. South of the Lawis River the contact becomes more "normal" and dunite lies between the norite and saxonite.

Dunite

Most of the dunite occurs in a zone between saxonite and gabbro and in aureoles around chromite deposits. Dunite shown on the map, especially in the eastern part of the Campbert quadrangle, includes material containing as much as 5 percent pyroxene. Most dunite is a massive, uniform rock that consists entirely of olivine and accessory chromite. Where interlayered with gabbro or along shear zones, dunite may weather to an ash-gray color and characteristically contains thin seams of magnetite. All the dunite is dark green on fresh surfaces and weathers light brown.

Along gabbro contact zones the gabbro or troctolite and dunite are interlayered over distances of a few meters. Although isolated dunitic

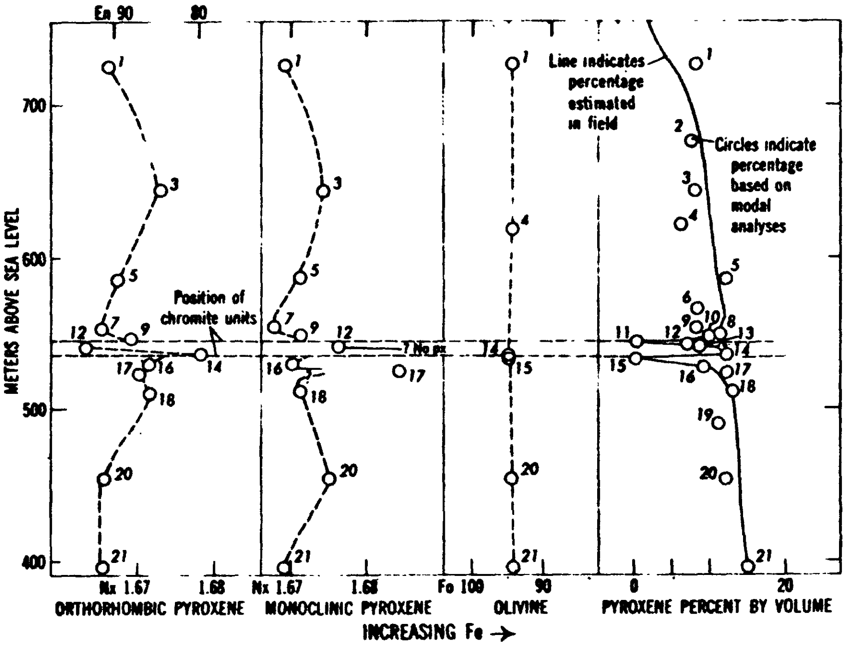


FIGURE 2.—Variation in the amount and composition of pyroxene and olivine in chromite-bearing saxonite east of Palauig. Location of samples shown on plate 12.

layers may extend several hundred meters into gabbro, the contact zone generally can be mapped within 20-30 m. Olivine in the dunite, as in all the major rock units, is uniformly Fo_{92-94} and occurs as rounded and euhedral grains 3-4 mm in diameter. Olivine grains in dunite at the gabbro contact typically are 1 to 2 mm in diameter, and may be poikilitically included in enstatite or embedded in chloritized plagioclase. In some places, particularly near chromite and gabbro contacts, olivine crystals may be 5 to 10 cm across.

In the central part of the map area shown in plates 1, 2, and 3, the rocks at the olivine gabbro-dunite contact are considerably brecciated, recrystallized, and mutually intrusive; the dunite contains rounded to angular gabbro fragments. In such contact zones olivine-plagioclase-pyroxene pegmatite commonly forms irregular masses. In some pegmatites euhedral or skeletal olivine crystals, several centimeters in diameter are embedded in plagioclase, and resemble pine trees or fish skeletons in outline.

Pyroxenite

Pyroxenite occurs only as layers in other rocks, and is most abundant in the vicinity of the Acoje mine near the norite-dunite contact. Most pyroxenite is composed of coarse granular mixtures of orthorhombic pyroxene and clinopyroxene; all gradations from pure enstatolite or bronzitite through websterite to clinopyroxenite exist. Generally light green clinopyroxene makes up the bulk of the rock, which also contains a sprinkling of light brown orthopyroxene crystals. The distinctive color, coarse grain size (1 mm-1 cm), and rough surfaces are in marked contrast to the smooth dun-colored surfaces of the dunite in adjacent layers. Some of the most evident layering observed is in pyroxenite-bearing sequences.

Clinopyroxene is composed of alternating lamellae of clino- and orthopyroxene with the larger part of any single crystal being composed of clinopyroxene. Orthopyroxene crystals have the reverse relation, with most lamellae in the crystal being composed of orthopyroxene. Monoclinic pyroxene has a refractive index (N_x) close to 1.685 and is probably augite; the associated orthopyroxene is about En_{80}. The texture is xenomorphic granular. Grains tend to lie along a line, generally but not always parallel to the plane of the layering.

Gabbroic rocks

The gabbroic rocks generally are composed of layers which contrast sharply in proportions of plagioclase, clinopyroxene, orthopyroxene, and olivine. Because of this, only a generalized rock name can be applicable over an area of any size. Norite (an orthopyroxene-bearing gabbro) is the most abundant rock type. Olivine gabbro is somewhat less abundant and is widespread as individual layers in the norite. The largest single mass of olivine gabbro lies in the base of Dalayap Hill immediately northeast of Coto in the Benguet Mine quadrangle.

Norite

Noritic rocks appear uniformly light gray in hand specimen, but commonly have light and dark layers in outcrop. Grain sizes range from 0.01 mm to 2 mm, with most grains being about 1 mm in diameter; feldspathic bands are coarser than mafic. At the contact with saxonite

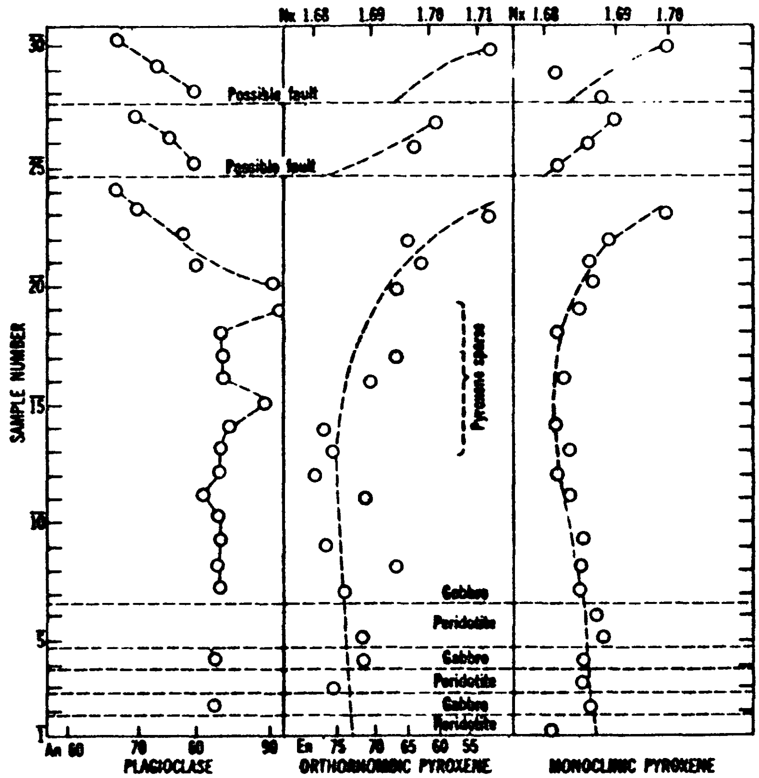
3 km west of Coto the average grain size of the gabbro is about 0.3 mm; westward the rocks are coarser. North of the Bugallon quadrangle (fig. 1) norite grades into fine-grained rock which terminates in a structurally complex assemblage of gabbroic dikes, diabase, and submarine basaltic flows.

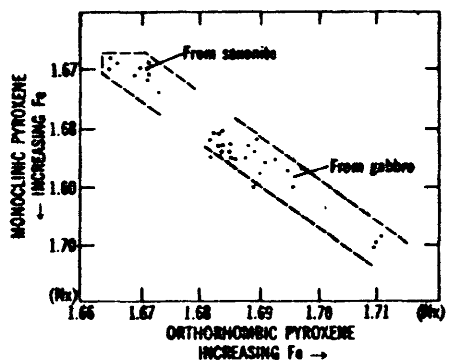
Norite is composed of plagioclase (An_{63-94}), orthopyroxene (En_{51-80}), augitic clinopyroxene, and commonly some olivine (Fo_{92-94}); the composition of all minerals except olivine varies with location. Figure 3 shows the composition of plagioclase, clinopyroxene, and orthopyroxene from norite northwest of Coto; discontinuities in the curves may be the result of duplication by faulting. The composition of the individual mineral species in the rocks in a given small area, varies little (no more than $\pm$ 1 percent An in the plagioclase, $\pm$ 2 percent En in the orthopyroxene, or $\pm$ 0.002 in Nx of clinopyroxene) regardless of their proportions in the rocks, but their composition varies widely from place to place. Thus it is believed that the composition of the minerals is independent of the bulk rock composition.

Rock texture is somewhat dependent upon proportions of component minerals. In feldspathic layers, feldspar grain boundaries mutually interfere, and the dark minerals are anhedral or subhedral against feldspar. In more mafic layers, pyroxenes are subhedral to euhedral and approximately equidimensional. Plagioclase is interstitial, and individual grains are rarely zoned.

Olivine gabbro

Most olivine gabbro is lighter in color than norite, but is somewhat darker and more mafic near peridotite contacts. Grain





Graph showing the compositional interrelationship between orthorhombic and monoclinic pyroxenes in gabbro and peridotite

FIGURE 3.—Plagioclase and pyroxene composition in layered gabbro and peridotite northwest of Coto. Location of samples shown on plate 2. Index determinations on plagioclase by Mauricio Marcello.

size ranges from 0.01 to 5 mm and averages about 2 mm. The largest known mass of olivine gabbro is in the lower part of Dalayap Hill immediately east of Coto; it grades upward into norite at an altitude of about 600 m.

Layered rocks vary widely in proportion of minerals, and rock composition can be determined only after considerable work. For this reason compositional differences between olivine gabbro and norite are not known exactly, but both contain clinopyroxene and orthopyroxene in about equal proportions. The only consistent differences between olivine gabbro and norite seem to be higher olivine content and more uniform composition of plagioclase in the olivine gabbro.

Plagioclase in the olivine gabbro ranges between An_{71-74}. The olivine averages Fo_{90-92}, and orthopyroxene En_{68-78}; the absolute composition of the clinopyroxene has not been determined but it is augitic. Compositional variation of these minerals from the dunite-gabbro contact in the South Lawis River (Benguet Mine quadrangle, pl. 2) to the top of Dalayap Hill is shown in figure 4.

The composition of the plagioclase from a layered succussion 300 m thick was measured by V. V. Gervasio (oral commun., 1961) on the universal stage. No significant variation in composition of the plagioclase (An 75) was found. The samples were collected along the Lawis River immediately east of Coto along a line parallel to the dunite-gabbro.

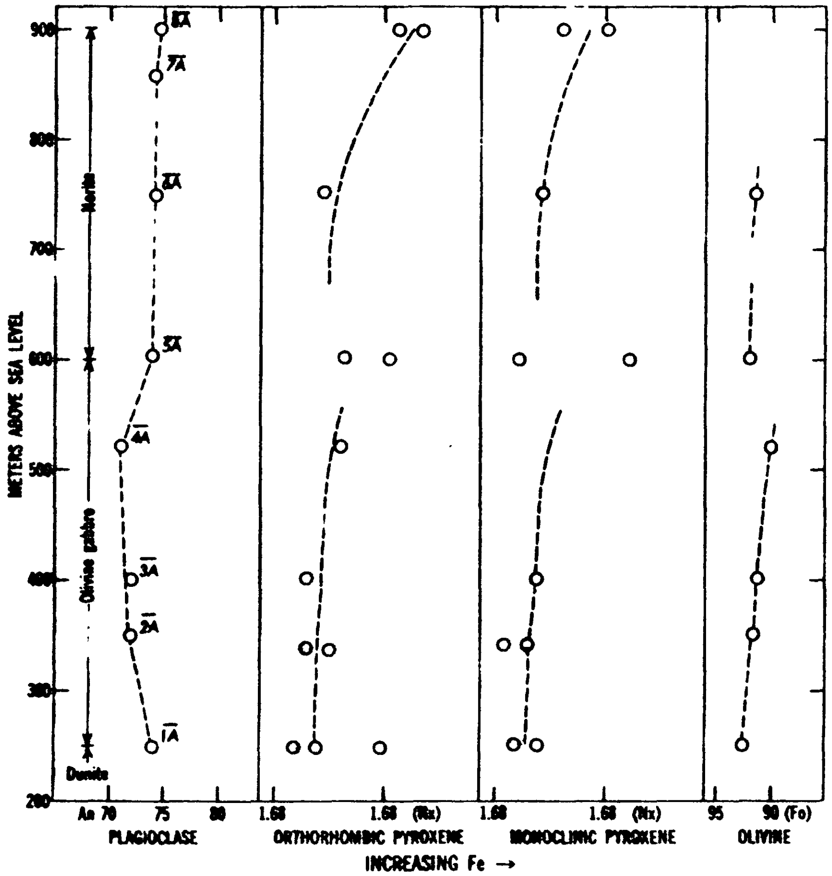


FIGURE 4.—Compositional variation in olivine gabbro and norite above dunite, Dalayap Hill. Location of samples shown on plate 2.

Diorite and related rocks

Diorite and quartz diorite are found in a few places in the Bugallon quadrangle, as well as further northwest. Several irregular masses occupy areas of a few square kilometers each, but most bodies are small. Diorite is most abundant in the eastern part of the Campbert quadrangle where it occurs in gabbro or peridotite near gabbroic dike swarms. Diorite is clearly younger than other rocks of the complex and in some places intrudes sedimentary rocks of middle and late Miocene age. It is possible that diorite of more than one age is present. At contacts with diorite, large hornblende and sodic plagioclase crystals in gabbro appear to be recrystallization products, but areas so influenced are small.

Dikes

Dikes of several kinds intrude the Zambales Complex. One of the most widespread and abundant was described as microdiorite by Stoll (1958), who also mentioned dikes of augite-hornblende and andesite which are similar to microdiorite. Dioritic dikes throughout the complex are most abundant near contacts with volcanic rocks and in contact zones between gabbro and peridotite, where they may make up 60 to 80 percent of the total rock volume. The reason for localization of dike swarms at gabbro-peridotite contacts is not known.

At Coto a uniformly coarse grained dike rock composed of olivine, enstatite, and labradorite-bytownite lies as irregular semitabular bodies in chromite. These dikes contain fragments of chromite and in places appear to have invaded or formed in the chromite without any definite contact. Another type of dike restricted to chromite is a pegmatite composed of enstatite and anorthite (An_{98}) crystals as much as 20 cm across which contain abundant needle-shaped apatite crystals. All known dikes of this type occur in chromite. The microdiorite dikes which cut the chromite at Coto commonly have chilled margins.

In a few places ultramafic dikes intrude gabbro. They contain olivine, as much as 16 percent enstatite, and small amounts of plagioclase. One such dike about 1 m thick crops out near kilometer 12 (from Masinloc) on the Coto mine road. These dikes commonly have some cataclastic texture and some certainly have undergone strong differential movement. Dikelike masses of dunite also occur in the saxonite.

STRUCTURE OF THE ZAMBALES COMPLEX

Layering, lineation, and foliation

At least parts of all major rock units in the complex are layered because of variations in the proportion of the included minerals or to variations in grain size or texture. Layers are most easily seen in rocks that contain minerals of marked color contrast or grain size. Plagioclase, being white, contrasts sharply with the other generally darker minerals: orthopyroxene, pale brown; clinopyroxene, light to dark green, and olivine, light to dark brown. Layering is commonly the most evident in gabbro, less evident in saxonite, and commonly indiscernible in dunite. Dunite is layered, however, as differences in grain size can be seen in thin section or in large polished rock slabs.

As a rule, boundaries between layers are not as well defined in olivine gabbro as they are in noritic gabbro, but they may be gradational or very sharp in both rocks. Grading in layers may resemble those in sedimentary rocks, even to being consistent in direction of grading across the strike through several layers. East of Mt. Lanat, grading was observed in each of a few tens of layers, but in general it is not common in the Zambales Complex.

Chromite layers have been observed along the Bugsit River in the Prensa quadrangle: on Reservation No. 1, in an area 7.5 km N. 80° E. of Coto, and at two other places in the quadrangle east of the Benguet Mine quadrangle, where tiny crystals of chromite coated by magnetite are interstitial to serpentinized olivine grains.

Before detailed study, the layers in the Zambales Complex were thought to be similar to those found in truly stratiform-type complexes (Thayer, 1960), which are believed to form from crystals of different sizes and densities settling differentially on the floor of the magma chamber. In stratiform complexes, as in sedimentary rocks, layering is parallel to and defines the major rock units. In the Zambales Complex, however, layered structures cross the boundaries of major rock units, including chromite deposits, at any angle. Because of this, layering obviously cannot be used in the Zambales area to determine the location of chromite along favored "stratigraphic" horizons. Layering is of no apparent value in predicting disposition of rock units, or the attitude of rock or chromite contacts as described in regular stratiform deposits

(Cameron and Emerson, 1959; Jackson, 1961). Relationships similar to Zambales-type layering have been described by R. A. M. Wilson (1959) on the island of Cyprus. Structures of this type are characteristic of peridotite-gabbro complexes found in island-arc belts, recently termed "alpine mafic complexes" by Thayer (1960).

Layers in norite range from 1 mm to several meters in thickness. Layers in olivine gabbroic rock are thicker, ranging from 5 cm to several meters; layers between 10 to 75 cm thick are most plentiful. Layering in saxonite ranges in thickness from a few centimeters to several meters averaging about 25 cm. In most exposures layers thin or pinch out within a few meters, but in some places individual layers only a centimeter or so thick may be traced as far as 100 m. Other layers pinch and swell in an extremely elongate boudinage-like structure. Some layers grade into gneissic layers which commonly have curved contacts; others have an internal wavy foliation. Sedimentary features such as crossbedding, trough, or slump features are not apparent. Layers rich in serpentinized olivine and pyroxene are common in olivine gabbro, especially near contacts with peridotite.

Pyroxenite layers in dunitic and noritic rocks characterize the norite-peridotite contact zone east of Acoje, which extends around the east and south sides of Mount Lanat. Some pyroxenite layers are 30 m thick and several hundred meters long. Pyroxenite may end abruptly against pyroxenite dikes although adjacent layers of different mineral composition may extend beyond the dike.

Chromite layers less than 5 mm thick in dunite are generally not more than a few meters long, but in some places chromite layers are sufficiently thick or abundant to be ore. These are described under the section on chromite deposits.

Foliation is marked by the planar orientation of minerals or groups of minerals. It differs in appearance from layering in that although the rock may appear banded or streaked, the streaks are thin and discontinuous and may lie along tight seams or fractures. Layered rocks commonly are foliated parallel to the layering, and the two features intergrade. Rarely foliation crosses layering (Thayer, 1963, p. 58).

Widespread lineation in rocks of the Zambales Complex results from a preferred parallel dimensional orientation of mineral grains or groups of grain. Ordinarily, lineation lies parallel to the layering, but in places it definitely cuts across layers such as in saxonite near the Palauig chromite deposits where it is prominently shown, and in the area near Coto and Reservation Number 1. In chromite deposits, lineation is indicated by elongated lenses of serpentite in chromite; at Coto such lineation is alined with the plane of layering in the surrounding peridotite. Both lineation and foliation are regarded as flowage phenomena.

Distribution and relationships of the major rock units

Plates 1, 2, and 3 show that the long dimensions of the major rocks units trend northeast approximately parallel to the regional trend of the layering.

Because nearly all boundaries between major rock units are gradational zones of interlayering, few single major contacts can be observed. Consequently, the dip of rock unit contacts cannot be determined by direct observation. Nevertheless, the transitional (interlayered) zone is commonly only 5 to 20 m thick except for individual isolated layers which may extend for several hundred meters from one unit, such as peridotite, into the other. Positions of rock boundaries can be determined within about 20 m, on the average. By tracing rock boundaries across areas of sharp relief some idea of rock disposition can be obtained. In some places the contacts are steep, and in others they dip at low angles. Where faulting or other deformation has taken place along contacts, original relationships are no longer observable. The writer believes that, with some local exceptions, gabbro overlies the peridotite with a mildly undulating subhorizontal contact. The Zambales Complex as a whole, therefore, appears to be a variety of an alpine complex classed by Thayer (1960 p. 256) as pseudostratiform. To the writer, it closely resembles the ultramafic complex described by Wilson on the island of Cyprus (Wilson 1959).

The relation of the peridotite containing the refractory-grade chromite to that containing the metallurgical grade chromite is not known, as the two are separated at the surface by intervening gabbro. Both peridotite masses have essentially identical compositions and textures. A few differences exist however: (1) Peridotite containing metallurgical chromite contains layers of pyroxenite near the gabbro contact, but pyroxenite is absent from peridotite associated with refractory chromite; (2) metallurgical chromite lies near norite, but refractory grade chromite lies near olivine gabbro; and (3) plagioclase is somewhat more calcic in norite than in olivine gabbro. Because of the general overall similarities, however, and the fact that no evidence of separate intrusions exists, the writer believes that the two masses crystallized from a single magma.

GEOLOGY OF THE CHROMITE DEPOSITS

General characteristics of the deposits

Most chromite in the ore deposits of the Zambales Complex is composed of either grain fragments or fractured massive chromite. Euhedral chromite crystals such as characterize stratiform deposits are uncommon. Nodular chromite is locally present but is not abundant. The refractory-grade chromite deposits generally contain a gangue of altered plagioclase and serpentine. The metallurgical chromite, on the other hand, contains little plagioclase, and the gangue consists of olivine or serpentine, and in a few places altered enstatite.

Table 2 shows the composition of chromite from various deposits in the complex.

The chromite deposits in the Zambales Complex range from the huge Coto body, which probably contained more than 12 million tons originally, to deposits too small to be mined economically. Shapes of the deposits vary between irregular masses and regular tabular units. The Coto deposit is an irregular lens-shaped mass 550 m long, 400 m wide, and 85 m thick. Other deposits, such as the Mother and Uncle lodes east of Palauig, and the deposits in the eastern part of Chromite Reservation No. 1, are flat-lying tabular units known to be as much as 200 m long, 20 m wide, and 7 m thick. Some of the Acoje ore bodies, as much as 300 m long by 120 m in vertical dimension and 30 m thick, are composed of thousands of tiny parallel chromite layers.

Table 2.--Analyses of chromite samples, Zambales District, Philippines

Prepared by Philippine Bureau of Mines.

Sample designation	Cr_2O_3	Al_2O_3	Fe_2O_3	FeO	Fe	MgO+CaO	MgO	SiO_2	Acct. percentage	Cr:Fe ratio
Res. #1, I 1/	37.2	29.5	2.1	11.6	--	17.9	--	0.45	98.89	
Res. #1, II 2/	35.3	29.7	4.7	11.5	--	17.1	--	.91	99.64	
Res. #1, III	38.2	30.0	2.2	11.8	--	17.9	--	--	100.1	
Res. #1, IV	36.5	30.3	4.9	11.5	--	16.8	--	--	100.0	
Res. #1, Refractory	37.20	29.5	2.1	11.6	--	17.9	--	.45	98.75	
Masinloc average	32.08	30.01	--	--	9.97	--	17.53	4.62	94.21	
Masinloc chromite										
average 1952 3/	32.33	29.38	--	--	10.59	--	17.93	5.06	95.83	
Coto ore body										
refractory.............	36.50	31.00	--	10.8	--	17.2	--	.85	96.35	
Acoje metallurgical ore	49.58	--	--	--	14.96	--	--	2.92	67.46	
Acoje (IC):										
Mill feed	25.01	--	--	13.7	--	--	--	19.56	58.27	1.6:1
Concentrate	50.03	--	--	18.81	--	--	--	2.86	71.70	2.3:1
Tails	18.57	--	--	11.51	--	--	--	22.99	53.07	1.4:1
Shipping ore	48.22	--	--	18.37	--	--	--	1.24	67.83	2.3:1
Metallurgical	52.80	13.4	5.6	13.3	--	13.7	--	.97	99.77	

Sample designation	Cr_2O_3	Al_2O_3	Fe_2O_3	FeO	Fe	MgO+CaO	MgO	SiO_2	Acct. percentage	Cr:Fe ratio
Zambales Chromite										
Mining Co.	48.22	--	--	--	16.43	--	--	--	64.65	2.6:1
Luzon Stevedoring										
Cagayan project	48.00	--	--	--	10.7	--	--	--	58.7	
Molenete refractory	40.30	27.6	4.2	10.6	--	16.7	--	.52	99.92	
Salor metallurgical	52.70	16.1	5.3	12.6	--	14.0	--	.07	100.77	
Filipinas Western										
refractory................	43.60	25.5	--	17.4	--	12.0	--	1.11	99.61	
Filipinas Eastern										
Part metallurgical........	48.60	15.1	--	23.5	--	10.1	--	1.60	98.9	
San Felipe, Zambales										
Abiog [4/]	32.06	28.92	--	16.95	--	--	--	3.48	84.14	
Absai Mining, Palauig										
Zambales I-Zepeda..........	24.27	22.91	--	--	11.72	--	23.74	12.61	95.25	
Palauig-Zambales										
II - Zepeda...............	34.27	31.98	--	--	13.43	--	16.71	1.65	98.04	
Zambales Mineral Chrom.										
Res. #2	46.83	21.87	--	16.84	--	--	13.61	.98	100.13	

Sample designation	Cr_2O_3	Al_2O_3	Fe_2O_3	FeO	Fe	MgO+CaO	MgO	SiO_2	Acct. percentage	Cr:Fe ratio
Zambales Res. #2 lens ..	37.37	29.61	--	14.70	--	--	16.0	1.98	99.66	
Zambales:										
Tubo-Tubo										
Sta. Cruz SR-1	48.05	13.81	--	--	15.45	--	13.61	1.29	92.21	
Sta. Cruz SR-2	44.74	14.88	--	--	12.69	--	17.07	4.66	94.04	
Sta. Cruz SR-6	38.52	12.47	--	--	11.90	--	19.92	9.87	92.68	
Sta. Cruz SR-7	34.59	11.68	--	--	13.87	--	20.49	11.74	92.37	
Candelaria sample 3	36.19	15.29	--	--	13.48	--	17.20	10.05	92.21	
Sample 4	34.88	15.73	--	--	14.28	--	16.86	10.05	91.80	
Sample 6	37.38	20.59	--	--	14.66	--	12.53	1.84	87.0	
Sample 9	40.07	27.74	--	--	12.30	--	13.56	1.77	95.44	
Sample 11	25.69	15.25	--	--	10.22	--	16.69	9.45	77.3	
Anungan, 16a										
Zambales	19.44	--	--	--	8.96	--	--	19.87	48.27	

1/ Contains 0.14 percent TiO_2

2/ Contains 0.43 percent TiO_2

3/ Contains 0.54 percent CaO

4/ Contains 2.73 percent CaO

Most chromite deposits show internal structure owing to changes in the chromite-to-gangue proportions. All show some deformational features. Some pencil-shaped, serpentine-rich bodies a few centimeters long lie parallel to the lineation in the enclosing peridotite. At places such as Acoje, chromite itself is lineated, which as far as observed, always lies in the plane of layering in the country rock.

Commonly a set of tension fractures, described as "pull apart" textures by Thayer (1960, p. 254; 1964), is oriented normal to lineation. The direction of elongation is parallel to the lineation. At Coto and on the western ore body of Reservation No 1, the chromite deposits are elonged in the direction of lineation; but the chromite deposits east of Palauig are subhorizontal flattened masses and although transected by lineation show little evidence of distortion as a result of flowage. At Acoje elongate fragments of dunite in chromite and fragments of massive chromite in disseminated chromite resemble a plastically deformed breccia.

Most chromite deposits show some internal layering. Where the chromite is massive, layering cannot be easily seen, but even the massive chromite at the Coto deposit contain visible traces of layering which are parallel to the projection of the layered structures in the enclosing rock. Layering has not been observed in the chromite at the deposits near Palauig, but at Acoje it is well developed.

Relations of chromite deposits to enclosing rocks

Distribution of deposits

Most chromite deposits in the Zambales Complex lie in a relatively narrow zone in the periodotite adjacent to the gabbro. Stoll (1958, p. 444) suggests that they may be concentrated there by large-scale flowage phenomena, but the layered structure as mapped does not bear this out. Many refractory-type chromite deposits lie along a northeast-trending line extending from the deposits southwest of Coto in the Benguet Mine quadrangle to the Soli deposit in the Campbert quadrangle.

Chromite deposits parallel to layering

Many of the chromite deposits of metallurgical grade at Acoje, and those farther south around the east and south flanks of Mount Lanat are composed of chromite layers which are parallel to the layering in the enclosing rock. In detail, however, many are en echelon structures in which chromite layers overlap so that the overall deposit lies at low angles to the layering. All deposits finger out in short distances along the strike, although the layered structure continues into the enclosing rock; in this respect the deposits differ basically from the stratiform chromite deposits.

Because some chromite is present in layers and some as irregular-shaped masses, the question may arise as to whether the chromite's position may be predicted by the shape, texture, or other observable characteristic. So far no valid criteria have been found that relate the composition to any observable structural or textural feature.

Chromite deposits across layering

Many chromite deposits in the Zambales Complex lie with their greatest dimension at an angle to the layering. Where such deposits are internally layered the layering clearly passes through the deposit without the slightest deviation from the normal local trend. As such deposits are composed of individual layers which lie en echelon, the layering governs the shape to some extent. But the form of the deposits east of Palauig seems not to have been modified at all by the layering in the enclosing rock. The Palauig deposits are made up of two, or in places three, tabular, nearly horizontal chromite bodies with knife-sharp contacts that are separated from each other by a meter or more of peridotite. These chromite bodies are known to be more than 150 m long. Layering in the enclosing peridotite clearly extends across the deposits at an angle of about 30° to 35° and is visible above, between, and below the chromite layers, but is not visible in the chromite itself. Lineation passes through both peridotite and chromite without discernably modifying the chromite's tabular shape.

Compositional relation of chromite deposits to nearby gabbroic rocks

The high-aluminum ores at Coto contain considerable interstitial plagioclase (altered), and those at Acoje do not. The Acoje deposits are associated with dunite, clinopyroxene-rich pyroxenite, and the nearby gabbro is norite. The high-aluminum ores (refractory grade) at and near Coto lie in either a narrow incasement of dunite which grades outward into saxonite or directly in saxonite. Pyroxenite is missing. The associated gabbro is olivine gabbro. The principal difference in composition between olivine gabbro at Coto and norite at Acoje is in the ratio of CaO to Al_2O_3, which in turn affects the ratio of Al_2O_3 to Cr_2O_3 in chromite. Addition of Al_2O_3 to the clinopyroxenite near the noritic gabbro at Acoje would convert it to olivine gabbro or troctolite, and an addition of Al_2O_3 to Acoje chromite (plus MgO) would convert it to Coto-type. The differences in composition of the rocks are therefore completely consistent with those in the chromite in the two areas. The plagioclase in norite near Acoje (pl. 1) is about An_{87}; farther south is An_{83}, whereas that in the olivine gabbro is about An_{75}. The problem is not simple, however, as attested by the wide range in composition of plagioclase in the norite-olivine gabbro south of the chromite deposits near Palauig.

Chromite reserves

High-alumina (refractory) ore

The Zambales Complex is the major free-world source of high-alumina chromite, which, as "Masinloc ore," has had a dominant role in the basic refractories industry of the United States, and in recent years has been used in increasing amounts in Europe. Reserves of the Complex are, therefore, of much more than local interest. By far the largest producers are the Acoje and Coto deposits which also contain most of the known chromite reserves.

Geologically, it is likely that deposits comparable in size to those now exposed in the area lie not far below the present surface; to hope to find another Coto deposit, however, would be rather optimistic. Systematic exploration of known ore zones, therefore, should find more ore. The Coto mine and deposits in Chromite Reservation No. 1 quite obviously are alined in a zone about 500 m wide that strikes N. 50°-60°E., and plunges 10°-20° northeastward under dunite and gabbro. The Coral deposit, of about 150,000 tons, and others are along the same contact zone 5 km farther northeast. Well-planned underground exploration northward along this zone from Reservation No. 1 might locate substantial tonnages of ore. Development of the other known deposits in the Complex should result in further discovery. On the premise that other deposits comparable in size to those on Reservation No. 1 lie not far below the present surface, discovery of another 2 to 3 million tons of high-alumina ore in the Zambales region should be possible.

More thorough exploration of smaller deposits along the belt that extends from the vicinity of the Zambales mine, including the Acoje mine, and extending southward past Mt. Lanat should find some deposits that are minable. The prospects for metallurgical-grade chromite elsewhere in the Zambales Complex do not seem encouraging.

Reserves of chromite in the Coto and Acoje mines

Ore reserve figures published in the annual reports of the two major companies as of December 31, 1966, were as follows:

Consolidated Mining Company, Incorporated, Annual Report of January 1, 1966, gives 4,914,075 m.t. run of mine ore; also there are 1,403,945 m.t. of minus ¼-inch chromite fines from the mill in stockpiles. Disseminated ore in place and in dumps contains 3,302,274 m.t. The Acoje Mining Company's annual report of January 1, 1966, states that their reserves total 2,279,750 m.t. of metallurgical-type chromite ore. The above constitutes most of the known reserves in the Philippines.

Description of chromite deposits

In the following paragraphs, the principal deposits of chromite in Zambales Complex are described. Table 3 contains a list of these principal deposits.

Table 3. List of chromite properties

Name	Number on map	Plate No.
Sansar Mining Co.	1	1
Filipinas Mining Co.	2	1
Zambales Chromite Mining Co.	3	1
Acoje Mining Co.	4	1
Dawn Mining Co.	5	1
Aurora	6	2
Libmed	7	2
Camote	8	2
Olga Mining Co.	9	2
Manga	10	1
Carunuan	11	1
Barumor Mines	12	1
Abbot	13	1
Malawang	14	1
Soli	15	2
Tampalao	16	2
Coral	17	2
Taltal	18	2
Takipan-Bubuan	19	2
Tupalao-Balacoc	20	2
Coto	21	2
Consolidated Mines Inc.	22	2
Zambales Development Co.	23	2
Igba	24	3
High Peak	25	3
Candelaria	26	3
Palauig	27	3
Unnamed	28	3
Unnamed	29	3
Unnamed	30	3
Roxal	31	3
Calet Deposit	32	2

Reservation No. 1

The chromite deposit on Reservation No. 1, which has been described in an earlier report (Rossman and others, 1959), will not be discussed here.

Acoje mine

Location, access, and local geography.--The Acoje mine lies in the northern end of the Zambales Range in the Campbert quadrangle (pl. 1). A gravel-surfaced all-weather road 27 km long connects the mine to the National Highway. Chromite is hauled 35 km by truck to a company-owned pier about 4 km south of Santa Cruz. The Acoje community has a population of more than 3,000, approximately 900 of whom are mine employees.

History, production, and reserves.--The Acoje chromite deposit is reported to have been discovered in 1933. The Luzon Consolidated Co., which owned an adjoining property, built the initial access road to within 2 km of the Acoje property, and this road, by agreement between the two companies, was used by the Acoje Mining Co. The first ore was mined in 1937, mostly from laterite in the northern part of the property. From 1941 to 1944 the mine was operated by the Japanese, who mined only massive, direct-shipping ore. The mine buildings were burned in 1945. In 1947 operations were resumed by the original company, but the main activities were shifted to the easternmost deposits. The camp was harassed by the Hukbalahap from 1948 to 1954; at one time about 20 persons were ambushed and killed along the road leading to the mine, and in 1951 most of the buildings again burned. A mill was completed in 1952 to concentrate lower grade ore.

Acoje mine is the Republic's major source of metallurgical grade chromite at present (1965). Its reserves total 2,279,750 m.t. (Acoje Mining Co., Ann. Rept., 1965), and the company has consistently discovered more chromite than it has mined. The Acoje mill has the capacity to mill 130,000 m.t. annually, and since 1954 it has averaged more than 100,000 m.t. The mine will probably remain an important chromite producer for many years to come.

All mining is underground, and in 1960 six separate deposits were operated simultaneously. All the ore is milled and sold as concentrates which average about 49 percent Cr_2O_3, are low in SiO_2, and have a Cr:Fe ratio of about 2.4:1.

Geologic setting.--The chromite deposits lie in or near a dunitic zone adjacent to the norite (pl. 5). This zone extends from north of Acoje to the southwest side of Mount Lanat, a distance of more than 20 km (pl. 1). Chromite deposits are scattered throughout its length. Layering consistently transects the major rock unit contacts, and is generally evident in outcrops. The general structure is shown on plates 4 and 5. A complex system of faults cuts the rocks in the mine area. The Acoje fault strikes northwest across the northern part of the area shown on plate 7 and dips about 60° NE. South of the fault, layers in the peridotite strike northeast, and north of the fault they strike northwest; it is likely, therefore, that the Acoje fault lies along the axial plane of a broken fold. South of the Acoje fault, a system of faults trends northwest and dips northeast, but most of these can only be seen underground and are not shown on the geologic map. On the northwest faults, like the main fault, the northeast side has been moved relatively northwestward over distances that range from a meter to several hundred meters. A fault, or faults, trending northeast lies near the south-central portion of the area shown on plate 4. These appear to have a maximum right-lateral displacement of about 60 m, but displacement seems to be less along the trace to the northeast; this is attributed to splitting. Apparently these northeast faults cut the northwest-trending set. North of the Acoje fault, a system of northeast-trending right-lateral faults may have displacements of as much as 100 meters. Splitting is common on all, and parallel faults are commonly connected by S-shaped faults.

Chromite deposits.--Internal layering of chromite in the Acoje deposits is essentially continuous with that in the enclosing rocks. Most ore bodies lie parallel to the layering, but in several the long dimensions are oblique to the layered structure; for convenience, these are referred to as parallel or crosswise, respectively (Thayer, 1964, p. 1512). Chromite deposits do not lie along any particular "horizon" within the layered succession, but rather appear to be distributed along a zone approximately parallel to the gabbro-peridotite contact.

Deposits parallel to layering.--Ore bodies J-101, KO-86, J4-73, H5-86, and several others northwest of the area included in plate 8 lie parallel or nearly parallel to layering in the enclosing peridotite. Within the area of plate 4 the deposits strike northeasterly and dip steeply to the southeast. The largest, H5-86, is 250 m long, as much as 20 m thick, and in places probably extends more than 100 m below the surface. The others are similar but smaller; their strike length is shown on plate 4, but none are known to extend as much as 100 m below the surface. The deposits north of the Acoje fault strike northwest and dip steeply southwest, apparently parallel to the layering. These deposits individually extend at least 300 m along the strike and are as much as 20 m thick; their vertical extent is unknown. A. Cerkel, Acoje mine geologist (oral commun., 1959), pointed out that J4-86 and H7-95 probably lie at a low angle to the layering.

Chromite deposits parallel to layering either do not crop out or have been mined out at the surface, so only a few surface remnants can be seen. Underground the ore occurs as a system of parallel layers a few centimeters to half a meter thick which are separated by chromite-poor layers or by serpentinized dunite. Where the chromite is highly concentrated, layering is correspondingly difficult to recognize, but traces of layering can be seen in all except massive ore.

The deposits grade along the strike and the end of the mine workings is determined by grade of the ore. Disseminated chromite may extend 10 to 100 m beyond the end of the mineable material.

Deposits across layering.--Ore bodies H3-112 and F5-94 lie across layering in the country rocks, as shown in plates 4, 6, and 7. Both deposits are about 200 m long and range from 3 to 30 m wide. The long axis of H3-112 lies at about 30° to the layering, and F5-94 at about 60°. In each, the layering is apparent in the ore as well as in the enclosing saxonite and clearly crosses the long axes of the deposits.

Generally, in ore body H3-112 (pl. 6) disseminated chromite clearly shows internal structures. In parts of the ore body chromite is concentrated into massive, irregular masses, lenticles, or knots. Many chromite layers vary in the proportion of chromite to serpentinite along their length. Lenticular masses of barren dunite commonly lie with their long axes parallel to layering and enclose chromite stringers. Knotty, massive chromite is most abundant around the ends of these dunite lenses, which may be boudin-like remnants of dunite layers that have been deformed plastically. In places, massive chromite is encased in disseminated ore. Such masses have many shapes: some are lenticular and appear undeformed, but in others plastic flowage features are obvious.

At most places ore contains some evidence of flowage parallel to the layering. Pull-apart fractures in massive ore are filled with serpentine. Lineation is marked by chromite-rich streaks in H3-112 and is probably present also in F5-94, although it was not observed there. The lineation in ore body H3-112 plunges 30° to 40° NE.

Ore bodies H3-112 and F5-94 are in saxonite but are surrounded by a dunite aureole as much as 6 m thick, but the amount and average grain size of the pyroxene in the saxonite gradually become less with nearness to the chromite deposits. The disappearance of pyroxene with proximity to chromite, leaving a pyroxene-free dunite zone, is characteristic of the Zambales chromite deposits. The dimensional orientation and distribution of chromite grains in the dunite shows that the layering passes through this dunite aureole. At one place in ore body F5-94, a rather irregular chromite stringer half a meter long and approximately 5 cm wide extends from the main chromite across the layering in the saxonite. This stringer is surrounded by a dunite aureole about 4 cm wide containing vestiges of the layered structure which crosses the dunitic aureole without deviation. This feature is not unique but was observed in other deposits in the Zambales Complex.

Ore body K1-65, now mined out (see pl. 8), appears to be unique in the Acoje mine area. This deposit consisted of massive chromite and was approximately 79 m long and 27 m wide; it lay within 30 m of another ore deposit to the east which is nearly parallel to layering in the enclosing rocks. Structural relationships and habit of K1-65 are similar to those at the Coto deposit. Contacts of ore against enclosing rock are sharp, and mining left an exact replica of the undersurface. This undersurface is V- or boat-shaped, with a keel or trough making an angle of about 25° with the strike of the layering. Like the Coto deposit, the underside of K1-65 contains branching, steeply plunging troughs which converge downward toward the central trough. Because this deposit has been mined out, the original internal structure and texture can only be surmised from the few chromite slabs left along the contact. There, the ore is nodular, with individual spherical masses about 6 mm in diameter which show little evidence of deformation. No evidence of layering in the remaining chromite was found, but may have been present in the original mass. Although lineation can no longer be seen in this deposit, it is very well shown in the adjacent deposit to the east where it lies within the plane of the layering and plunges 0° to 20° S.

A well-layered pyroxenite band about 20 m wide lies south of the chromite deposit K1-65, but is separated from it by a dunitic zone 50 cm to 5 m wide. Chromite layers only one to a few crystals thick extending from the deposit about 1 m into the pyroxenite; each stringer is surrounded by a 2-mm to 2-cm dunite aureole. The pyroxenite layers interfinger with and grade into the dunite which surrounds the chromite. There was no evidence that one rock intruded the other.

Composition and physical characteristics of ore.--Most of the chromite in the deposits at Acoje is disseminated and composed of both euhedral and fragmental grains of 1 mm and less in diameter. In thickly disseminated ore some chromite grains are octahedrons, though most have mutual boundaries. In general, they are slightly larger than grains in lower-grade ore. Rarely, the chromite lies in a plagioclase matrix, and in a few places the ore is nodular. Dunite in immediate contact with the chromite is bleached to a lighter color than that farther away.

Chromite composition varies from place to place, but the Cr_2O_3 generally is about 49.5 percent, and total iron is about 14 to 14.5 percent, giving a Cr:Fe ratio of about 2.4:1. Some of the iron is present as magnetite attached to the chromite grains.

Coto mine

Location, access, and local geography.--The Coto mine is by far the largest single source of high-alumina chromite in the free world, and shipped about 470,000 m.t. of high-quality refractory lump ore annually during the period 1959 through 1964. The mine is located in the north-central part of the Zambales Range in the Benguet Mine quadrangle (pl. 2). A gravel all-weather road 25 km long connects the mine to National Highway No. 7 at Kilometer 247 from Manila. Chromite is hauled 24 km over a 36-inch gauge railway to a company-owned pier at Masinloc. The mine employs about 700 persons and the mining community has a population of about 2,5000.

The ore is mined by open pit. At the mill, coarse ore is sorted on a picking belt; finer material is screened, then separated from the gangue by heavy-media separation machines. Since 1959 the company has been developing a market for chromite as fine as 28 mesh.

History, production, and reserves.--The Coto deposit became known to the outside world about 1921, and was staked in 1933 by L. H. Wilson, and exploration began that year (Wilson, L. H., 1956). Development and mining continued until the beginning of World War II, with estimated production of 350,000 tons during this period. Mining was resumed in 1945 and has continued since by contract arrangement between Consolidated Mines, Inc., owner, and Benguet Consolidated Mines, Inc., the operator. Production from 1945 through 1964 totaled approximately 7 million metric tons of lump ore, by far the largest recorded from a single ore body of the podiform type.

When discovered, the deposit probably contained more than 12 million metric tons of chromite. Reserves including Reservation No. 1, in 1966 were estimated at 4,914,075 metric tons of run-of-the-mine lump ore containing less than 6 percent silica, together with 3,302,274 tons of disseminated chromite, and 1,403,945 tons of minus ¼-inch chromite in stock piles and dumps. (Consolidated Mining Co., Annual Report, January 1, 1966).

Geologic setting.--The Coto deposit originally capped a hill and extended down its northeast side. The area was tree and brush covered, but now it is bare or grass covered. Laterite as much as 7 meters deep covers the lower flanks of the hill. Chromite float was scattered in thick concentrated deposits below the ore body and extends as far north as the Lawis River.

The deposit consists mainly of massive chromite, is 550 m long, 400 m wide, and had an original thickness of at least 100 m. The long dimension trends northeast and plunges about 21°N. (See pls. 9 and 10). The ore body is cut by many parallel, steeply dipping dioritic dikes that strike northeast.

The lower contact is characterized by a series of rounded troughs and ridges as much as 30 m in height which strike roughly parallel to the long axis of the deposit. The troughs tend to converge down the plunge so as to form a dendriform pattern. Generally the upper contact of ore and dunite is gradational; chromite is thickest, or highest, directly over the troughs of the lower contact.

Parallel faults that strike northwest and dip southward cut off the deposit at the north and south ends. Originally the southern fault was believed to have right-lateral horizontal displacement of about 50 m, but later work by the mining company has cast some doubt on this. The amount and direction of movement on the northern fault is not known, but efforts to find offset ore north of it by deep drilling have been unsuccessful. Other faults within the deposit and at the contacts have small displacements, and have not materially modified the original position or shape of the deposit.

The Coto deposit is partly enclosed by dunite which grades outward into saxonite. Pyroxene in the saxonite increased in grain size and amount, from traces at the contact with dunite to 16-20 percent at 20 m from the contact. The dunite seems to be thickest above the high points on the upper surface of the chromite, and also below the trough-like structures at the lower contact, where it is as much as 5 m thick. The dunite sheath is thin or absent along parts of the southwestern side. Another dunitic zone, shown by drilling to also contain chromite, lies beneath the main deposit but separated from it by 50 m or more of saxonite.

Layering, generally visible in saxonite near the Coto deposit, strikes uniformly northeast and dips steeply west, except in one area at the southwest corner of the deposit where there is an anticline. The layering in the saxonite can be projected across the chromite, seemingly without the slightest deviation. Even such features as folds in the layering can be so projected. Evidence of layering is generally lacking in massive ore and in the adjoining dunite, but is shown by tabular streaks of chromite along the contact. Attitudes of such streaks along the southwest corner of the ore body show that the fold in nearby saxonite extends through the chromite.

Small-scale tensional fractures which are normal to the deposit's long dimensions are abundant in the chromite. Elongated and flattened lenses of dunite (Thayer, 1964, figs. 8, 9) and disseminated ore within more massive ore plunge parallel to lineation in the enclosing saxonite and to the deposit's long dimension. Deformation of the chromite probably increased the length of the deposit at least 1½ to 3 times. Other deposits examined in the complex have similar features, but elongation is not everywhere as evident as at Coto. Good descriptions of many textural and structural features of the Coto deposit are given by Stoll (1958) and need not be repeated here.

Composition and physical characteristics of ore.--A considerable amount of careful work has been done by Stoll (1958) on the composition of the chromite--his reported results agree with the analyses made for this investigation. He indicates that the chromite formula for most of the chromite is $Cr_{41}Al_{54}Fe_5(Mg_{74}Fe_{26})$. The ore meets requirements for good refractory-grade chromite.

Palauig deposits

Location, access, and local geography.--The Palauig deposits (No. 27, pl. 3) are in the Prensa quadrangle, 16 km due east of Palauig. They are reached from National Highway No. 7 at Kilometer 234 from Manila by a 17-km graded road. The chromite crops out at an altitude of 650 m on the steep, north slope of an east-trending ridge between the Bancal and Bugsit Rivers. The area is drained by Kinamaligan Creek which flows north to join the Bugsit River. Dense bamboo, brush, and scattered hardwood grow near the deposit and the surrounding countryside is heavily wooded.

History, production and reserves.--The chromite deposits were discovered in 1936 by a hunting party headed by Mr. Simeon Pamplona. Some surface exploration was done that same year, but little more was done until 1953 when further work was undertaken by Mr. Jose Robles, and exploration has continued intermittently to date (1961).

The Philippine Bureau of Mines drilled this deposit. Nearly all the chromite contains considerable silica and probably cannot be mined economically at present.

Geology.--The rocks at and near the Palauig chromite deposits appear to have undergone relatively little movement, and to have retained many of their original features. The rock and chromite disposition and structure is consistent with that at the other chromite deposits of refractory grade in the complex. But at no other place examined have the relations been so clear and understandable; the deposits and inclosing rocks at the Palauig deposits are regarded as coming close to being type exemplifications of the rock-chromite relations present in the Zambales Complex.

The general rock distribution is shown on plates 11 and 12. The gabbro covers the ridge south of the chromite deposits and is surrounded or underlain by a dunitic zone a few tens of meters thick. This grades downward into saxonite, owing to the gradual increase in size and number of included pyroxene grains. The chromite deposits, with one exception, which is believed to be the result of faulting, are parallel, sub-horizontal, thinly lenticular masses, that lie in saxonite approximately 200 meters below the gabbro contact.

Layering in the area is likewise straight forward and uncomplicated. It strikes uniformly northward and dips 30°-50°W. The layering crosses the gabbro, dunite, and saxonite contacts without deviation. Dunitic layers may extend into the gabbro for 100 to 200 meters, but most of the interlayering takes place in the first few meters. Normally the dunite-gabbro contact can be located within one 20-meter contour interval, but the common boundary is a zone of interlayering and no actual contact is visible. For this reason the dip of the contact cannot be seen or measured directly. The writer believes, from consideration of the mapped contact, that it is nearly horizontal near chromite deposits, and that this same structural relation attains, with some exceptions, throughout the Zambales Complex.

The chromite deposits (pl. 12) consist of several separate masses. The Father Lode is irregular in shape and lies in fault contact with the gabbro; it is believed to be an upthrown fault block. All the other chromite deposits lie in a narrow vertical zone, no more than 50 meters thick, which can be traced southward for over one kilometer, along the contour, from the Mother Lode to Kinamaligan Creek and thence northwest to the Sister Lode (pl. 12). These deposits are all tabular or thinly lenticular, subhorizontal masses which consist of as many as three parallel units. They are separated from each other by peridotite which commonly is composed of a narrow aureole of dunite lying next to the chromite that grades, with increasing size and number of pyroxene grains, into saxonite. The distribution, composition, and amount of pyroxene found in the interval between the gabbro to a point below the chromite deposits is shown in figure 2.

Layering is visible in the saxonite above, between, and below the parallel chromite deposits and clearly transects their common plane at an angle of 20° to 50°.

Lineation, shown by the elongation of enstatite in the saxonite and by elongate streaks of dessiminated chromite in more massive ore is clearly evident in the field and is shown on the geologic map (pl. 11).

The general disposition of the Palauig chromite deposits as parallel subhorizontal units is similar to that found in chromite deposits in stratiform complexes, but differs in that the Zambales deposits are less extensive laterally and occur in peridotite near the top of the peridotite rather than near the base of the ultramafic complex, as is the case in stratiform complexes.

Father Lode.--The Father Lode, an irregular mass of chromite 2 to 7 m thick extends over a known horizontal distance of 90 m. A steeply dipping northwest fault cuts off chromite on the east, and a parallel fault cuts through the center of the deposit. Another easterly trending fault is present near the south end of the deposit.

In places, contacts of the deposit appear to be parallel to the layering, but the footwall contact of the eastern part clearly transects the layering. Some chromite stringers, each jacketed by dunite, extend below the deposit as a delicate interwoven network. Most stringers are parallel to the layering but some cross it; however, even the crosswise stringers show internal layering parallel to that in the enclosing rock. At places, especially near the north end of the deposit, chromite near the base contains flattened, elongated, serpentine-rich zones which plunge 10° to 20° northward, parallel to lineation in the enclosing saxonite.

The Father Lode has been delineated by diamond drilling on all sides except the south. Probably the deposit does not extend much farther than shown on the sections in Plate 13.

Mother Lode.--The Mother Lode appears to be nearly as large as the Father Lode, and consists of two or more parallel subhorizontal chromite units. The upper ranges from 14 cm to about one meter in thickness. The lower unit is one to 4.5 m thick and is exposed over a distance of about 20 m. The shape and disposition is shown on the cross sections in Plate 13.

Uncle Lode.--The Uncle Lode is tabular and connects with the Mother Lode to the north. The chromite ranges from 0.3 to nearly 3 m in thickness and is about 1 m thick where exposed. In places, particularly north of the main outcrop, drilling shows the chromite as two parallel units which dip gently eastward in contrast to the westerly dipping layers in the enclosing saxonite.

Brother and Son Lodes.--The Brother and Son Lodes probably are parts of the same deposit and crop out at an altitude of 545 and 525 m respectively. The Brother Lode has an exposed thickness of 2.5 m and a length of 6 m. The lower contact is similar to that in the Father Lode. The Son Lode crops out over 4.5 m and is half a meter thick or less. Both deposits lie at an angle to the layering in the enclosing saxonite, and along the projection of the common plane of the Mother, Uncle, Daughter, and Sister Lodes.

Daughter and Sister Lodes.--The Daughter and Sister Lodes are on the west side of Kinamaligan Creek at approximately the same altitude as the

Mother and related lodes on the east. Drilling of the poorly exposed Daughter Lode shows it to be a thinly lenticular mass composed of disseminated chromite. The Sister Lode is intermittently exposed over 27 m; it has a maximum exposed thickness of slightly more than one meter. It is not certain that the Daughter and Sister Lodes lie along the same horizon, because the Sister Lode crops out about 30 meters lower than the Daughter Lode. Moderate faulting, or other slight movement or change in attitude may account for this difference. Drilling indicates that the Daughter and Sister Lodes are not actually connected.

Soli, Abbot, and Malawang chromite deposits

The Soli (No. 15 on pl. 2), Malawang (No. 14 on pl. 1), and Abbot (No. 13 on pl. 1) chromite deposits are near the Zambales-Pangasinan provincial border; they are 20, 14, and 15 km, respectively, airline distance from Mangatarem, Pangasinan. The easiest access is by trail from Mangatarem up the valley of the Olo River, a stream with moderate gradient and no waterfalls in the lower portions, although the topography adjacent to the river is sharp.

Soli chromite deposit.--The Soli chromite deposit is exposed for a distance of about 66.5 m on a cliff face along the west side of Natay Creek; it consists of tabular layers 1 cm to 1.5 m thick in three separate bodies. At locality "A" in figure 5 the upper chromite layer is about 14 m long and has an average thickness of 1½ m, strikes N.20°-30°E. and dips 15°-20°NW. It is cut by a troctolitic dike, and a fault in the center has a displacement of approximately 30 cm. Below this ore body

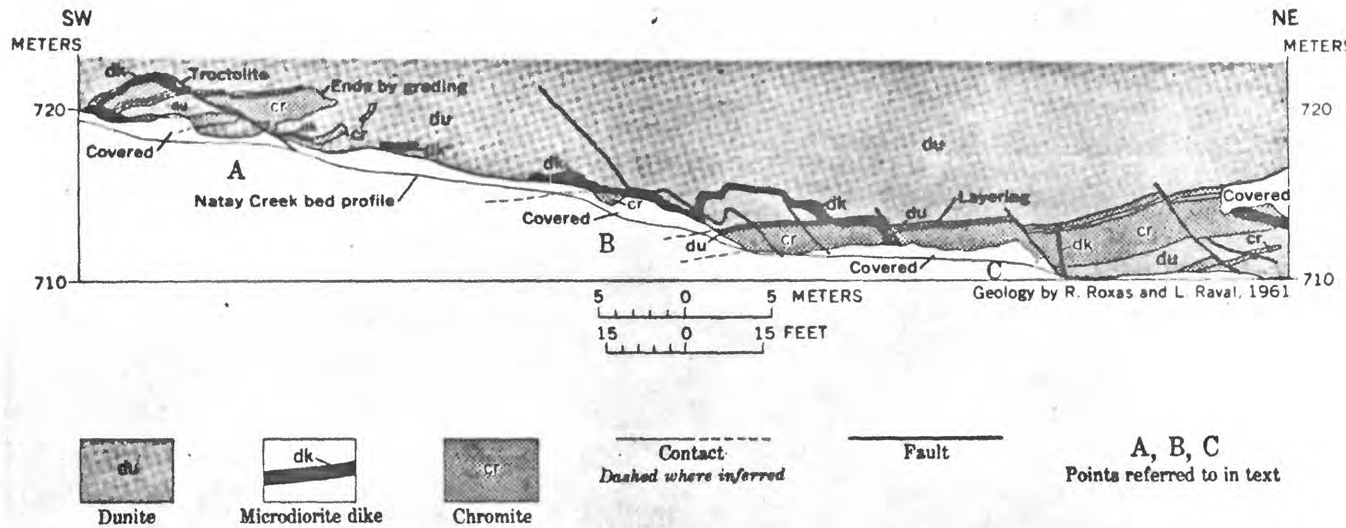


FIGURE 5.—Sketch of cliff face at the Soli chromite deposit.

are small chromite pods parallel to the main deposit, which range from 1 to 6 m in length and have an average thickness of half a meter.

Part of a chromite layer 2 m long and about 60 cm thick crops out at locality "B." Exposed chromite at locality "C" is 30 m long, is 1 to 3 m thick, trends N.20°-50°E., and dips 15°-20°NW. It is cut by normal faults which have an average displacement of 70 cm. A microgabbroic dike that strikes N.50°-70°E. and dips 75°-85°NW. cuts parts of the deposit.

Layering in dunite which encloses the chromite, and also layering in saxonite in this vicinity, trends northeast and dips at low angles to the northwest parallel to the chromite layers. This parallelism of the ore body and country rocks probably indicates the shape of the deposit and may assist in the search for possible ore extensions.

Probably the chromite in all three localities is part of one horizon which is displaced by normal faults so that in each the northeast side is downthrown with respect to the southwest. Chromite probably extends beyond the exposures.

The extent of the deposit is unknown, but blocks of massive and layered chromite measuring as much as one meter in diameter are found near shallow pits 200 m N.56°E. of the main deposit on the east side of Natay Creek. It is probable that this is an extension of the same chromite-bearing zone just described. Because the chromite is flat lying, extensions may exist at any direction from the exposures. Drilling to the south (upstream) and to the east as well as to the west seems warrented.

A pile of about 1.5 tons of chromite has been collected at the northernmost outcrop mentioned above. Analysis indicates that the chromite is of refractory grade, and if representative the chromite is of acceptable grade.

Malawang chromite deposit.--Chromite deposit No. 14, on plate 1, known as the Malawang deposit, is at an altitude of 480 m and about 200 m from the peridotite-gabbro fault contact. Chromite in the cross section exposed along a near-vertical surface is triangular-shaped, about 4 m across the base and 4.5 m high.

Chromite deposit No. 30

An unnamed chromite deposit east of Botolan, Zambales, No. 30 on plate 3, is near the southern edge of the Prensa quadrangle at an altitude of 975 m. The deposit, described in an unpublished report by D. P. Cruz (1958) of the Philippine Bureau of Mines can be reached by a 14-km trail from San Juan, a small barrio 5 km east of Botolan.

Bedrock at the deposit is peridotite, but little else is known of the geology. Regional layering in saxonite strikes north or northeast and dips easterly at moderate angles.

The chromite deposit consists of a single east-trending lens which dips 40°N. The central part of the body is concealed by rock debris in a creek bed but chromite crops out on each bank. At the western outcrop, the lens of disseminated and nodular ore is 12 feet in width and has an irregular lower contact with dunite. The eastern outcrop contains chromite in two (parallel?) zones, an upper zone of nodular chromite, and a lower zone of massive ore. It has an exposed length of 37 ft.

Chromite deposits Nos. 28 and 29

Chromite deposits Nos. 28 and 29 are shown on plate 3, they are about 15 km northeast of Iba, Zambales, and can be reached on foot across rugged terrain. The deposits were discovered by Delfin Oballes in Jan., 1961, and are described in an unpublished report by N. Biscocho of the Philippine Bureau of Mines. The topography is rugged; immediate areas of the deposits are grass and bamboo covered.

The area was initially mapped by D. Abiog of the Philippine Bureau of Mines. Rocks at the deposits are peridotitic. Ridges to the south and northeast have not been examined, but from the general rock distribution pattern of the complex and because the ridges are wooded, it is suspected that they are either of gabbro or dunite. Layered saxonite near the deposits strike 5^{o}W. of N. and dips about 45^{o}E.

Chromite deposit No. 28 crops out at an altitude of 340 m near a Bancal River tributary. The chromite is massive, fine grained, and forms a tabular lens with an average exposed thickness of 25 cm, an exposed strike length of 3 m and a dip length of 5.5 m. Chromite ore strikes N.25^{o}W. and dips 50^{o}S. It pinches out at the top, but the west (down dip) side is covered. A channel sample taken across the lens is reported to contain 14.76 percent SiO_2, 10.71 percent Fe, and 25.86 percent Cr_2O_3[2/].

Chromite deposit No. 29, 1,700 m east-northeast of deposit No. 28, crops out at an altitude of 400 m. The chromite in the deposit is both

[2/] Analyzed by the Philippine Bureau of Mines.

nodular and disseminated and forms a lenticular body 2.3 m thick, 2.5 m wide, and it has a dip length of approximately 20 m. Chromite layers were not observed, but the chromite-peridotite contact strikes northwest and dips southwest. The chromite is highly disseminated but is somewhat more massive near the center. The ore body appears to pinch out upward. A sample assayed 19.87 percent SiO_2, 8.96 percent Fe, and 19.44 percent Cr_2O_3 3/.

EXPLORATION AND PROSPECTING

Exploration for chromite

General.--Most of the local hunters and natives in the Zambales area are now fully capable of recognizing chromite and are well aware of its value; because of this and because other prospectors have searched widely in the Zambales Range for chromite, it seems likely that no large exposed chromite deposits remain undiscovered. In the future, therefore, prospecting must depend upon something other than simple search for chromite exposures.

To successfully find new unexposed deposits and to systematically determine extensions of known masses, a knowledge of the rocks and general habit of the chromite disposition in the complex is worthwhile. This is particularly so because the relationships present have a high order of consistency, and thus one can plan and concentrate his efforts to optimum advantage once the pattern is understood.

Gabbro is believed to be the uppermost rock and is underlain by a dunite zone a few meters to several hundred meters thick; this grades downward into saxonite which is of great but unknown thickness. At

3/ All figures are from U. S. Bureau of Mines, Minerals Yearbook and Mineral Trade Notes.

least 95 percent of the chromite deposits occur no more than 100 or 200 meters below the gabbro in either dunite, or preferentially in saxonite. Most of the chromite deposits found in the saxonite are separated from it by a narrow dunite aureole similar to but narrower than that found between the gabbro and the saxonite.

The writer believes that the gabbro originally lay as a rolling subhorizontal unit over the peridotite. On some places, such as at the top of Mt. Lanat in the northwestern part of the Benguet Mine quadrangle, it is believed that the gabbro has been removed by erosion, and the chromite deposits found there actually were originally only a few hundred meters below the gabbro. Thus even these deposits, which appear on the map to be far removed from the gabbro, actually are in a position which was originally only a short distance from it. It is also believed that the type of chromite (i.e., refractory versus metallurgical grade) reflects the type of overlying gabbro. The refractory-grade chromite is believed to underlie olivine gabbro and the metallurgical type to underlie norite. The two rock types generally can be recognized in the field because the olivine gabbro commonly is coarser than the norite, and the latter contains orthorhombic pyroxene which can be recognized with a hand lens as pale reddish brown grains. The norite is present over the northwestern two-thirds of the Campbert quadrangle and the northwestern one third of the Benguet Mine quadrangle whereas the olivine gabbro crops out in the southeastern two-thirds of the Benguet Mine quadrangle and the southeastern one-third of the Campbert quadrangle.

Plates 1, 2, and 3 show the location of the gabbro and hence the favorable chromite-bearing areas can be inferred.

This investigation has shown quite conclusively that the chromite deposits in the Zambales Complex differ fundamentally from those of the stratiform type in which chromite concentrations occur in tabular layers parallel to the layering of the enclosing rocks (Jackson, 1964, p. 114). Hence the search for chromite along some favored layered horizon in the Zambales Complex is fruitless. For example, the distribution of chromite and the known layered structure from Acoje southward around Mount Lanat shows that the chromite is concentrated in a zone parallel to the gabbro-peridotite contact, but at large angles to the layering.

Some of the chromite deposits, particularly those in the Acoje area, have their largest dimension along the layering, but this knowledge must be used with caution when planning exploration, because even at Acoje, the parallel deposits may be only a few meters away from other deposits which are at an angle to the layering. (See, for example, ore deposit K1-65 pl. 8). In other areas such as the Palauig deposits, the chromite forms tabular parallel bodies which clearly lie at an angle to the layering in the enclosing rocks.

A typical chromite prospect in the Zambales area consists of a series of isolated bodies all cropping out at about the same altitude or perhaps in two or three parallel zones lying a few meters one above the other. These lie near gabbro in either dunite or saxonite. In the past some investigators believed that such isolated bodies were connected, and in a few places this has proved to be true. However, this investigation has shown that many deposits, although lying along the same zone, are truly discontinuous.

A prerequisite for chromite prospecting in this area is careful geological mapping in order to determine the general distribution of the chromite and its relationships to gabbro, dunite, and saxonite. Trenching to determine position and possible extensions of exposed ore may be followed by diamond drilling where indicated. Ore extensions between outcrops should not be assumed to exist until proven.

Chromite for refractory purposes must have a relatively low silica content (below 6 percent SiO_2). The mineral chromite does not contain silica, so all the silica found in chromite ore occurs as other minerals between and in chromite grains. The common silicate minerals are feldspar (white), serpentine (white to brown), and olivine (olive drab). With experience, one can visually estimate the silica content with reasonable accuracy by noting the amount of these other minerals. Because weathering may remove the silicates for as much as 3 meters beneath the surface, surface samples are likely to give an impression that the silica content is less than will actually be found in fresh material. All deposits vary in silica content from place to place, and the minable grade can only be determined by careful sampling and analysis.

Geophysical methods.--The detection of any buried mass by gravity measurements depends upon there being differences in densities such that the gravitational attraction caused by the searched-for mass is large enough to be measurable. Thus all masses effecting the gravity measurements must be corrected for before a hidden body can be detected. Any factors influencing the assumed rock densities such as serpentization, position and shape of rock units, faults, and dikes must be at least fairly well known before minimum adequate corrections can be made. In other words, everything influencing the gravity must be known, except for the ore itself. If adequate knowledge of all factors cannot be obtained, and in areas of complex geology this may not be feasible, a gravity survey will have little chance of success.

A magnetic survey was made with an Askania magnetometer over the deposits on Reservation No. 1 in the hope that the magnetite resulting from serpentization of peridotite surrounding the chromite might produce diagnostic magnetic anomalies. The magnetic variations measured, however, could not be correlated with the known chromite deposits. The anomalies were so large that they could easily have been mapped with a less sensitive instrument. Magnetic surveys for chromite in general have proven to be of little value (Hawkes, 1951).

Exploration for minerals other than chromite

Sulfides and platinum minerals

During this chromite investigations some information was obtained on sulfides in the ultramafic rocks. Pyrite, chalcopyrite, pentlandite, other sulfides, platinoids, and native copper are widely disseminated in the peridotite. In one area at Acoje, sulfides are sufficiently concentrated to allow economic exploitation.

In general sulfides are difficult to recognize in peridotite outcrops and can be found only by careful observation. The highest concentrations of sulfides were found in the dunitic zone near the gabbro contact, but no evidence was found to indicate that sulfides and chromite are closely related. Many sulfides crystallized fairly early, probably magmatically, and are not obviously related to later fracturing; these are typically disseminated through the rock.

Some later sulfide mineralization can be distinguished from the disseminated type by its morphology. Because disseminated sulfides are difficult to see in the field it is believed that the Zambales area has not been adequately prospected especially for copper and nickel. Possibly, there are large areas containing disseminated sulfides of economic importance, and a systematic prospecting and sampling program may be justified. Geochemical prospecting might prove to be a valuable tool in the search for copper and nickel. Judging from limited observations, the most potential zone for sulfides is in the dunite near the gabbro.

Nickel occurs both in sulfide form and as an ionic substitution for magnesium in olivine. Fire or chemical assay cannot differentiate between the two. This is important because nickel incorporated in the olivine structure cannot be recovered economically by any presently known process. For economic mining it is therefore necessary to determine the amount of nickel present which can be removed by ore dressing.

Asbestos

Chrysotile asbestos was noted in some places in the Complex although no large concentrations of long fiber asbestos were found.

However, some asbestos probably approaches consideration, as ore. Most asbestos-bearing rock appears ash-colored in outcrops, and the asbestos forms parallel, discontinuous dark-colored veinlets. On fresh surfaces peridotite containing asbestos veinlets is generally light green and highly altered. Where fresh, asbestos-bearing peridotite may be dark brownish green, and the asbestos veinlets are a pale yellow green typical of chrysotile.

Little is known about the most favorable areas for asbestos. Where peridotite has been sheared near gabbro contacts, it contains in places a multitude of tiny asbestos-filled fractures. Perhaps contact areas may be favorable for the occurence of asbestos deposits. However, some of the largest asbestos zones are found in saxonite well away from the gabbro contact.

Most fault zones contain a little chrysotile but in a few it is abundant. On the other hand asbestos-bearing zones are found which are unrelated to any definite fracturing. Insufficient knowledge about controls governing the location of chrysotile asbestos makes it necessary to explore virtually all peridotite areas.

One asbestos-bearing zone on the southwest slope of Mt. Lanat appears to extend for about 500 m. Few actual outcrops were observed but abundant float suggests that two to three parallel asbestos-bearing zones may be present. These are as much as 3 m wide and consist of a series of closely spaced chrysotile-filled veinlets constituting about 15 percent of the rock by volume. Samples showed no fibers longer than a quarter of an inch, with most being between one thirty-second and three-sixteenths of an inch. Other asbestos-bearing outcrops were found for over 1 km northwestward along the same line of strike, but all these isolated outcrops may not be parts of a single deposit.

Another asbestos-bearing area was noted on the Olo River in the Campbert quadrangle. Limited time for examination did not permit the determination of size, continuity, or grade. Where observed in the bed of the Olo River, the asbestos appeared to make up about 10-30 percent of the rock by volume and was fairly continuous over a distance of perhaps 70 m, this being apparently a diagonal distance across a wide fault zone.

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