Serpentinite and Rodingite in the Hunting Hill Quarry, Montgomery County, Maryland

GEOLOGICAL SURVEY BULLETIN 1283

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By DAVID M. LARRABEE

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Description of rocks exposed in the quarry near the center of the Hunting Hill ultramafite

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SERPENTINITE AND RODINGITE IN THE HUNTING HILL QUARRY, MONTGOMERY COUNTY, MARYLAND

By David M. Larrabee

ABSTRACT

The Hunting Hill pluton is about 1 mile wide and 4 miles long and consists of serpentinized dunite cut by gabbro dikes which have been altered to rodingite. It is best exposed in the active quarry of Rockville Crushed Stone, Inc., 4 miles west of Rockville, Montgomery County, Md. This quarry, when mapped in 1966, was about 2,600 feet long, 850 feet wide, and 210 feet deep; it is centered within the pluton and trends about N. 45° E. Forty-seven minerals have been identified from the quarry.

The pluton is of probable Ordovician age and was intruded into the Wissahickon Formation of late Precambrian (?) age. The pluton trends about N. 22° E. and probably dips vertically or steeply southeast. The serpentinite ranges from dull green through gray to black and is largely antigorite; subordinate magnetite affects the color. Minute, nearly parallel gash veins of chrysotile occur in the serpentinite.

The rodingite ranges in shape and size from lenslike bodies a few feet long to highly irregular, branching dikelike masses as much as 1,500 feet long and 100 feet wide. Neither the rodingite of this deposit nor any other rodingite between Alabama and New Jersey seems to have been described previously, though the rock is not necessarily as uncommon as this circumstance might imply. Dikes of pegmatitic hornblende quartz diorite cut the serpentinite northeast and southwest of the quarry.

The rodingite is composed of bright-green chromian diopside, cinnamon-colored to pink grossularite, white diopside, zoisite, and small amounts of other minerals, including prehnite and hydrogrossularite. The dikelike intrusive rocks provide striking contrast to the host ultramafite and are approximately parallel to each other—strike N. 50°–65° E.; most of them dip steeply or vertically. The diopside generally is brighter green and the grossularite content is higher in the northeast end of the open pit than in the active benches of the southwest end. Well-defined compositional layering marks some of the smaller rodingites, the layers paralleling the walls of the dikes. Most rodingite-serpentinite contacts are sheared and have chlorite, tremolite, picrolite, or calcite and dolomite along the shear planes. The presence of tremolite in adjacent serpentinite indicates that calcium escaped from the gabbro during its metasomatism to rodingite. Strong narrow shear zones alternate with hard fresh rock in the southeast part of the quarry. In places, the dikes have been offset a few feet by faulting.

Small veins include chrysotile and clinochrysotile, tremolite, talc, chlorite, calcite-dolomite, aragonite, deweylite, magnesite, and rarely, hydromagnesite, penninite, coalingite "films", grossularite, prehnite, hyalite, and chalcedony.

The major geologic factors affecting the use and economics of the crushed stone are the fibrous nature of the antigorite, the minute but heavier particles of attached magnetite, the presence of very hard and heavier rodingite, and the shear planes and joints. The interlocking fibers add toughness to the crushed rock and have a felting effect when used as asphalt binder. The minute attached magnetite particles accelerate settling of fibers from the air and thus reduce the loss of fines by wind. The rodingite improves the overall hardness of the various aggregates but adds considerably to the drilling, breaking, crushing, and screening costs. Shear planes contribute to backbreak, rockfalls, and slides, and may increase costs in places. Where shear zones are present, as along the southeast side, the rock is more deeply weathered and is wasted. Close jointing, where present, reduces breaking and crushing costs. The quarry serves a large market area centered principally on the northwest side of Washington, D.C.

INTRODUCTION

The Hunting Hill serpentinite quarry is 4 miles west of Rockville, Montgomery County, Md., and about 17 miles N. 41° W. of the Capitol in Washington, D.C. By road, the quarry is 1.5 miles southwest of Maryland Route 28 at its junction with Travilah Road and 0.3 mile west of Piney Meetinghouse Road, south of its junction with Travilah Road (fig. 1). The quarry is near the center of a serpentinite mass 4 miles long and 1 mile wide, which trends N. 22° E. and is named for the settlement of Hunting Hill near its northeast end. The serpentinite is surrounded by the Wissahickon Formation, the foliation of which generally strikes about N. 20° E. and dips steeply to vertically (pl. 1).

The quarry was opened in 1955 after a modest core-drilling program by Rockville Crushed Stone, Inc., and when mapped in 1966 it had a maximum length of 2,600 feet, an average width of 850 feet, and a maximum depth of approximately 210 feet (pl. 2). The quarry originally was developed and operated in benches on all sides; recent work, however, has been by benching in a southwesterly direction only (fig. 2).

The Hunting Hill quarry was studied because it affords the best exposures of serpentinite in the Washington area, and it also provides a unique opportunity to study the relations of the gabbroic rocks in three dimensions as quarrying progresses. The topographic and geologic map was prepared between April 21 and June 23, 1966, by planetable methods (Larrabee, 1966b). Geologic studies continued intermittently thereafter, and a brief summary has been published (Larrabee, 1968).

The purpose of this report is to describe the major structural and petrological relations of the rocks and their alteration; a more detailed investigation of the complex mineralogy and geochemistry is continuing.

PREVIOUS GEOLOGIC WORK

The Hunting Hill pluton was first outlined by Cloos and Cooke (1953). In 1956, several minerals from the quarry were described by Griesbach who also called attention to "two dikes of unusual pyroxene garnetite rock" (p. 351). Additional minerals were described by Sinkankas in 1958 and 1959. The quarry location was first shown on a map and briefly noted by Pearre and Heyl (1960, p. 724) as "Large; in serpentinized gabbro." Griscom and Peterson (1961), in a short

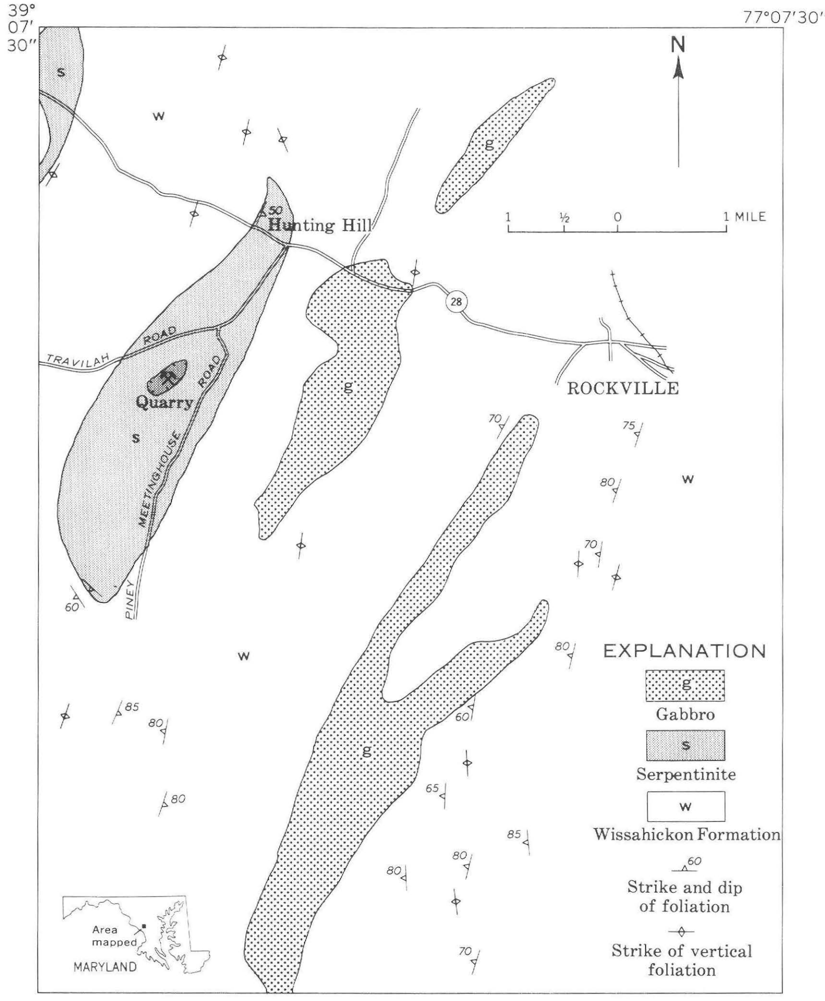

FIGURE 1.—Index map showing location of the Hunting Hill serpentinite pluton, Montgomery County, Md., and its relation to nearby serpentinite and gabbro masses. Compiled from Cloos and Cooke (1953) and from Griscom and Peterson (1961).

geophysical paper, indicated high magnetic and low radioactive anomalies over the pluton; however, a long narrow negative anomaly is within the western edge of the pluton. Blanchett, Tyson, and McGowan (1963) published a map showing the aeromagnetic features of the Rockville quadrangle. Hopson (1964, p. 151–153), after a short reconnaissance, described the exposed serpentinite briefly and stated that the contained "metagabbro is in large streaky masses enclosed in the serpentinite. These look like gabbroic schlieren, not later intrusive bodies" (p. 153). A natural gamma aeroradioactivity map of the Rockville quadrangle by Blanchett, Griscom, and Vargo (1966) showed low radioactivity above the pluton. The serpentinite body was shown in relation to other known serpentinites on the regional map of ultramafites from New Jersey to Alabama by Larrabee (1966a). After a visit to the quarry with the author in 1966, Thayer (1967, p. 236), in a list of alpine features of the Baltimore Gabbro Complex and related gabbro and periodotite masses in Montgomery County, stated that the gabbroic rocks in the Hunting Hill quarry "are not schlieren * * * but form two or more sets of dikes and irregular [intrusive] masses." Sasajima, Sun, and Scharon (1968) reported studies of the magnetic properties of the serpentinite and rodingite, on the basis of 187 specimens from 55 drill cores.

Prof. Charles Milton, of George Washington University, formerly of the U.S. Geological Survey, and Mary E. Mrose, of the U.S. Geological Survey, have also identified specimens from the quarry for collectors during the past few years.

ACKNOWLEDGMENTS

The generous cooperation of officials of Rockville Crushed Stone, Inc., especially of W. K. Shewbridge, Vice President, and William H. Schrock, Superintendent, made the study possible. Other employees of that organization, especially R. D. Moreland and J. K. Bise, assisted in many ways. J. W. Allen, of Chevy Chase, Md., ably assisted in the planetable work.

I am also indebted to geologists and a chemist of the U.S. Geological Survey, especially to T. P. Thayer for being the first to identify the altered gabbro as rodingite and for giving much helpful guidance and petrographic assistance throughout the project and to J. J. Fahey for many chemical analyses and mineral determinations. J. J. Norton was helpful in the review of the report. Malcolm Ross, G. T. Faust, R. G. Coleman, D. B. Stewart, M. E. Mrose, and Eleanora Iberall made X-ray identifications. Norman Page furnished a description of chromite. Harvey Belkin and Paul Broughton told me of minerals they and others had collected during the history of the quarry and pointed out

FIGURE 2.—View of Hunting Hill quarry, 1966, looking east from southwest corner of second bench. Two major dikes are shown.

two references that otherwise would have been overlooked. My first specimens of grossularite crystals occurring in vugs of open veins were a gift from Paul Broughton. A. J. Bodenlos was most helpful in discussions of the magnesite veins, and C. E. Brown assisted one day in the field. In 1967, M. E. Mrose identified certain minerals by X-ray at the request of the U.S. National Museum and kindly permitted me to use her unpublished data. In 1969, she identified brochantite for John Gruger, a collector, who permitted its inclusion in this report.

K. N. Weaver, State Geologist of Maryland, provided enthusiastic encouragement and offered helpful suggestions when he visited the quarry in July 1966; he found the only specimens of hydromagnesite that I have seen. These specimens were identified chemically and optically by J. J. Fahey and checked by X-ray methods by Malcolm Ross in 1966. Black-and-white photographs of specimens were taken by J. A. Denson of the U.S. Geological Survey, and the color photograph was taken by Norman Prime, who is at the U.S. Geological Survey laboratory in Menlo Park, Calif.

GEOLOGIC SETTING

Although it stands at the same general altitude, 200 to 500 feet above sea level, as the surrounding area underlain by the Wissahickon Formation, the area underlain by serpentinite is much less dissected and is marked by broad gentle slopes. Around the quarry, the bedrock surface is nearly flat—a plane sloping southwest about 1 foot per 100 feet. This bedrock is covered by a saprolitic soil that ranges from 2 to 12 inches in thickness on flat areas and to as much as 24 inches in

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shallow valleys to the southwest. Possibly because of the gabbroic rocks present, the soil over this serpentinite body seems to support a heavier forest, with pines and hardwoods 12 to 14 inches in diameter, than is common on other serpentinites in the Appalachian region. Marshall (in Bell and others, 1911, p. 30) observed similar unusual forest conditions in areas of ultramafic rocks and rodingite in New Zealand. Exposures of bedrock are few and far between, although float fragments of serpentinite are common. Rodingite is exposed in only a few places, and rodingite float is less than 5 percent of the rock observed on traverses across the pluton.

The Hunting Hill pluton is one of many masses of serpentinite and gabbro, separately or together, that extend in a broad discontinuous belt northeastward from northern Virginia across Maryland into Pennsylvania; these are in the Piedmont of the east-central part of the Appalachian region (Larrabee, 1966a). The pluton is near the southwestern end of the Maryland-Pennsylvania concentration of ultramafic rocks. On the regional scale, the pluton is petrologically related to the Baltimore Gabbro Complex (as used by Hopson, 1964; Thayer, 1967; and Southwick, D. L., unpub. data), which is 65 miles long and comprises peridotite and gabbro. Bodies of gabbro, ranging in size from 1.25 by 0.25 miles to 5 by 1.5 miles, have been reported east of the pluton by Griscom and Peterson (1961) (fig. 1). Other intrusive bodies in Montgomery County similar to it in size and form consist of serpentinite and gabbro (Cloos and Cooke, 1953). The pluton is rudely elliptical and bluntly rounded at the ends; it trends N. 22° E., is about 4 miles long, and ranges from 0.4 to 1 miles in width (pl. 1). The contacts with country rock, a muscovite-chlorite-biotite-quartz schist of the Wissahickon Formation, are not well exposed but appear to dip vertically or steeply southeastward, parallel to the foliation in the schist. Talc and tremolite schists occur at the pluton boundaries.

Surficial float and exposures in trenches and along roads indicate that the composition of the pluton as a whole is not very different from the exposures in the quarry. Rodingite seems to be more common in the center of the pluton, however, than in the ends. Most of the serpentinite is massive, free of pyroxene or pyroxene pseudomorphs, and is believed to have been dunite. Near the southwestern contact, 1- by 2-inch knobs or knots that weather in relief are believed to have been pyroxene, but they now are tremolite. Rodingite float in a few places seems to have been derived from small dikes.

Coarse-grained hornblende quartz diorite was found in two small areas—as outcrops and float in the northeastern end of the pluton and as float about 3,000 feet south of the quarry. The mineralogy of this diorite is so completely different from that of the rodingite-gabbro dikes that the two are not believed to be related at all closely.

SERPENTINITE

MINERALOGY AND PETROGRAPHY

Serpentinite constitutes 80 to 90 percent of the rock exposed in the quarry, the remainder being chiefly rodingite. On fresh fractures, the serpentinite ranges from dark gray or dark green to black; it is tough and medium hard. Interlocked fibers and plates of antigorite in a felted pattern make up the bulk of the rock, as determined by X-ray and differential thermal analysis (Faust, G. T., written commun., 1967). On weathered surfaces the serpentinite is orange-brown to a depth of one-fourth to one-half of an inch; along joints within 15 feet of the surface, some is soft and light gray.

The serpentinite generally is of two types: (1) Fine-grained, sooty gray to black rock, characterized by dusty magnetite and a few coarser aggregates of opaque altered chromite and magnetite, and (2) coarser, medium-gray or greenish-gray rock with magnetite aggregates. The chromite-magnetite relations are the same in both.

The prevailing dark color is caused by secondary magnetite, which occurs chiefly in two forms: (1) Fine dust scattered through the rock around the margins of original olivine crystals and along cleavage planes of possible olivine pseudomorphs (Hawkes, 1946), and (2) larger plates and highly irregular masses of magnetite and altered chromite generally between coarser antigorite blades. Some chromite in these masses is rimmed with magnetite and hematite (Page, Norman, written commun., 1968). Crystals of magnetite as much as one-fourth of an inch across and partly altered to hematite occur with chlorite in some shear zones near the southwestern corner of the quarry. Chlorite also replaces some of the coarser antigorite. Bastite pseudomorphs are rare.

Much serpentinite is mottled light gray or greenish gray and dark gray. Although the mottling is accentuated by weathering, it is well shown in fresh rock to depths of at least 200 feet (figs. 3 and 4). Concentrations of magnetite dust in fine-grained antigorite form roughly circular ¼-inch ovoids or irregular spots, 0.25 inch by 1 inch long, of dark-gray or black dust-rich areas separated by areas of light-green antigorite relatively free from such dust. Rarely, magnetite-rich concentrations form ¼- to ½-inch bands separated by antigorite-rich layers. In some places the dark bands are related to fractures.

The dark spots or bands are composed of fine-grained antigorite in fibers having a gray to yellow birefringence and ranging from 0.02 to 0.05 mm (millimeter) in length or in aggregates this size; many fine dustlike (0.001–0.005 mm in diam) and larger (0.03–0.04 mm in diam) magnetite particles are scattered throughout the spots, but in

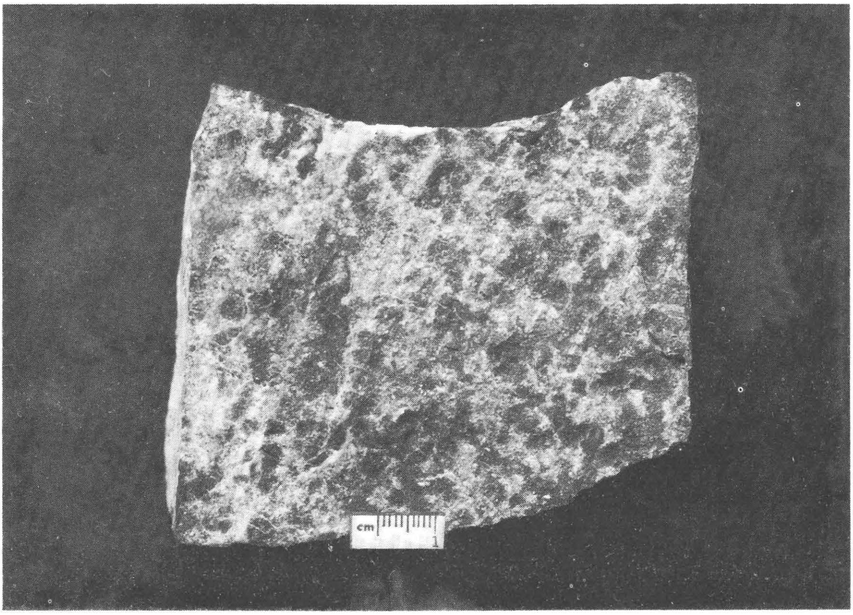

FIGURE 3.—Specimen of serpentinite showing irregular spots and patches of fine-grained dark phase in a matrix of coarser grained gray-green phase. See figure 4.

places they are well-alined. Rarely, small remnants of olivine are centered within the spots. Some of the spots contain minor chlorite with magnetite and chromite surrounded by magnetite. Magnetite is reoriented along fibers of the chrysotile in gash veins or in irregular veins cutting chrysotile veins, but not in the center of chrysotile veins and rarely at the margins. Chrysotile has a lower index of refraction than antigorite and is the latest mineral in some specimens.

The light-green areas between magnetite-rich spots and elsewhere are made up of coarser antigorite plates, fibers, and aggregates of fibers 0.02 to 0.12 mm long; birefringence is gray, and the index of refraction seems to be slightly lower than the serpentine of the dark spots. Some antigorite follows a reticulate pattern, suggesting replacement along partings in olivine. Areas of the spotted serpentinite were shown on the map (pl. 2) where observed; however, this feature is noticeable only where conditions of light striking the rock surface provide contrast, and doubtless many other such areas are present.

Tremolite occurs chiefly in serpentinite in a zone at the contact of each rodingite dike; it is less common as scattered prisms or blades and as distinct white veins. Tremolite at the contacts with rodingite extends 10 to 30 cm (centimeters) (4–12 in.) into serpentinite (table 1), where it lightens the color of otherwise dusky-gray rock. The

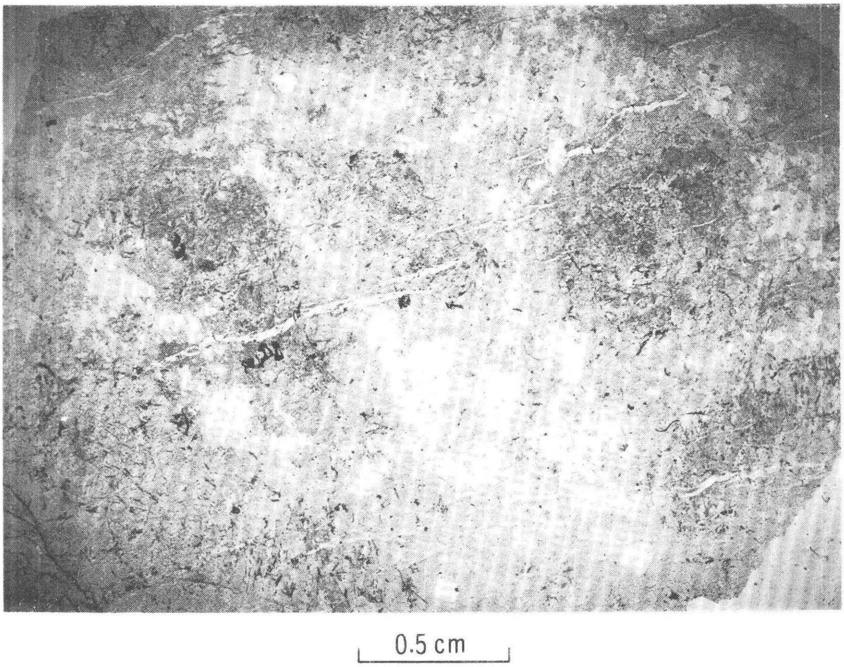

FIGURE 4.—Photomicrograph of spotted serpentinite showing concentration of magnetite in fine-grained antigorite and clear patches of coarse antigorite. Thin gash veins are cross-fiber chrysotile. Plane light. Same specimen as in figure 3.

crystals are fine white needles, blades, or prisms, as much as 1 cm (0.5 in.) long, and are of apparent random orientation. In serpentinite, large irregular white masses, 2.5 to 5 cm (1–2 in.) in diameter, are composed of randomly oriented tremolite blades, each less than 3 mm (1/8 in.) long. These blotches are in the southwest end of the quarry, where tremolite veins also irregularly cut the serpentinite, inclusions of serpentinite remaining as dark-gray patches. Scattered prisms of tremolite occur throughout the serpentinite and in rodingite. Veins of tremolite are more common in the shear zones than elsewhere.

In thin section, tremolite replaces antigorite, and in places, it is in turn replaced by a later antigorite. Elsewhere, some tremolite blades cut chrysotile veins. Tremolite also occurs with magnetite in veins at the margins of and crossing chrysotile veins. The tremolitized spotted serpentinite is composed of well-formed tremolite blades 5 to 13 mm (3/16–1/2 in.) long, replacing fine-grained antigorite associated with magnetite dust. Generally these blades are fresh and have sharp boundaries. Some tremolite crystal boundaries are fuzzy and corroded, however, at the border of original coarser light-green antigorite-rich and magnetite-poor areas, now largely replaced by fine-grained

TABLE 1.—*Chemical analyses and norms of serpentinite and rodingite*

[Analyses 2, 3, 5, 6, and 7 are rapid rock analyses as described by Shapiro and Brannock (1962) and are supplemented by atomic-absorption analyses by Paul Elmore, S. D. Botts, L. T. Artis, H. Smith, G. W. Chloe, James Kelsey, J. L. Glenn, and Leonard Shapiro, U.S. Geol. Survey. Analysis 8 is a standard chemical analysis by J. J. Fahey, U.S. Geol. Survey, and is made from part of the same hand specimen used in making analysis 7, showing variation in rodingite. Analysis 4 is a standard chemical analysis by J. J. Fahey. Nd, not determined. CIPW norms recalculated to 100 percent]

	Serpentine	Serpentinite			Rodingite			
	1	2	3	4	5	6	7	8
Lab. No.		W167341 (R)	W167342 (R)		W167343 (R)	W167856	W167855	
Field No.		186–RM–66–L	187–RM–66–L	129–RM–66–L	188–RM–66–L	205–RM–66–L	12–RM–66–L	12–RM–66–L
Chemical analyses								
SiO_2	40.65	39.40	40.00	51.58	42.50	46.40	46.00	48.96
Al_2O_3	1.60	1.20	1.50	2.70	17.00	17.80	10.80	6.62
Fe_2O_3	2.80	5.10	4.90	0.56	1.60	.74	1.70	1.53
FeO	1.34	2.50	2.50	2.63	2.30	3.60	1.70	2.11
MgO	38.71	37.70	37.60	25.33	13.10	13.90	12.50	13.93
CaO	.02	.35	.31	11.42	19.00	12.70	24.30	24.60
Na_2O		.09	.10	0.16	.16	1.70	.00	.14
K_2O		.11	.00	0.03	.00	.00	.00	.02
H_2O-		.50	.47	0.01	.16	.15	.11	.04
H_2O+	13.31	12.40	12.20	4.38	3.70	2.30	1.90	1.46
TiO_2		.04	.06	0.01	.13	.11	.09	.10
P_2O_5		.03	.02	0.00	.02	.02	.03	Nd
MnO		.12	.12	0.04	.13	.13	.21	.15
CO_2		.24	.11	0.88	.26	.05	.41	.10
Cr_2O_3		Nd	Nd	0.11	Nd	Nd	Nd	.42
Sum	98.43	99.78	99.89	99.84	100.06	99.60	99.75	100.18
Bulk density			2.58			2.99	3.17	3.230
Powder density		2.642	2.649	2.926	3.146	3.00	3.25	3.304
CIPW norms recalculated to 100 percent								
C	1.9	1.1	1.2					
Or		.7		0.2				
Lc								0.1
Ab		.9	1.0	1.4		14.6		
Ne					.8			.6
An			.8	6.9	47.5	42.2	30.1	17.6
Wo				19.5	14.0	9.3	27.6	37.3
En	45.5	39.2	41.6	60.5	11.3	7.4	22.8	30.6
Fs		.2	.3	4.2	1.0	1.3	1.4	2.1
Cs					4.7		7.5	5.1
Fo	47.7	48.3	46.1	3.8	15.8	19.9	6.4	3.2
Fa		.3	.4	.3	1.6	3.8	.4	.2
Mt	4.9	8.5	8.1	.9	2.4	1.1	2.5	2.2
Cm				.2				.6
Il		.1	.1		.3	.2	.2	.2
Ap		.1	.1			.1	.1	
Cc		.6	.3	2.1	.6	.1	1.0	.2
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Average composition of 15 serpentine minerals calculated by Thayer (1966, p. 687), from analyses by Faust and Fahey (1962, p. 18).
2. Serpentinite sample taken from 104 locations, exclusive of shear zones and contact effects of rodingite.
3. Serpentinite bulk sample from one location at base of first bench, active southwest end of quarry; color, black; uniform rock.
4. Tremolitized serpentinite from northeast end of quarry.
5. Rodingite sample taken from 41 locations, exclusive of shear zones; only rock having ½-inch or smaller crystals was sampled.
6. Rodingite specimen from southwest end of quarry; gray green, no visible grossularite.
7. Rodingite specimen from northeast end of quarry; bright green, containing cinnamon grossularite.
8. Rodingite specimen from northeast end of quarry; bright green, containing cinnamon grossularite; part of same hand specimen as 7, showing variations.

tremolite crystals or sheaves of crystals ranging from 0.05 to 0.4 mm in length. The varied relations of tremolite to antigorite of at least two stages indicate two or more stages of tremolitization. In parts of shear zones along the southeast wall of the quarry, green actinolite substitutes for later tremolite.

Talc flakes occur randomly in the serpentinite but are most common in the sheared areas of the southeast wall. These flakes range from white to pale green and rarely are as much as 3 mm long. Coarse (8-mm diam) talc flakes occur in veins of the sheared areas. In some thin sections, talc pseudomorphs after antigorite were noted, whereas in others, antigorite replaces talc. Talc-carbonate rock is rare in the quarry and is found only in sheared rock near the northeast end of the southeast face. This rock is a mixture of equal parts of soft limonite-stained carbonate and gray-green talc. Magnetite grains and dust remain in both talc and carbonate veins cutting the talc, some of which replaces chlorite. Here the talc occurs as minute rosettes and as small fibers pseudomorphic after antigorite.

Chlorite is common in serpentinite, especially in the shear zones, where it occurs in fist-sized twisted intergrowths. It is common along shear surfaces and elsewhere, as a replacement of antigorite.

CHEMICAL COMPOSITION

Although the chemical composition of the serpentinite superficially seems inconsistent with the petrographic evidence that it was derived from dunite, there is no contradiction. Page and Coleman (1967) provide some serpentine-mineral analyses for reference. The average composition of 15 serpentine minerals analyzed by Faust and Fahey (1962, p. 18) is strikingly similar to the analyses of the two tremolite-free serpentinites from the quarry (table 1). The ratios of normative olivine to pyroxene in the three analyses (recalculated to 100 percent) are about 51:49, 55:45, and 53:47, respectively. Recalculation of the analyses to allow for modal magnetite in the serpentinites and of the norms to correct for feldspar because the alkali determinations in serpentinite probably are too high (Thayer, 1966, p. 688) would bring the ratios of normative olivine to pyroxene even closer. The change of dunite to a rock of this composition is wholly consistent with conversion of olivine to antigorite and magnetite (Thayer, 1966). The CaO and SiO_2 contents of the tremolitic serpentinite indicate that in places tremolite constitutes about three-fourths of the rock. Any brucite present is negligible. Part of the high normative magnetite content of the serpentinite is primary; the balance—chiefly the dustlike particles—has been derived from alteration of the olivine to antigorite.

As might be expected, the spectographic analyses (table 2) of the serpentinite show high contents of chromium and nickel, along with unusual amounts of cobalt and scandium (Faust, 1963). Tremolitized serpentinite contains additional elements indicated at the top of table 2.

Analyses of the composite split sample of serpentinite by fire assay and quantitative spectrography by L. B. Riley, W. D. Goss, and Joseph Haffty of the Geological Survey gave the following results (in parts per million): platinum, 0.005 to 0.010; palladium, 0.016; and rhenium, 0.005. Although platinum and palladium are present in amounts near the lower limits of determination, palladium clearly exceeds platinum.

RODINGITE

The term "rodingite" was first used by Marshall (in Bell, Clarke, and Marshall, 1911) and later by Grange (1927) to describe unusual dense white calc-silicate rocks within the serpentinized ultramafites in the upper part of the Roding River valley at Dun Mountain, New Zealand. Coleman (1966, p. 12) stated, "These rocks are altered gabbros that consist predominantly of hydrated calcium silicates and relict pyroxene * * * rodingites are restricted to serpentinites." The original definition has been broadened by various writers to include

TABLE 2.—*Semiquantitative spectrographic analyses of serpentinite and rodingite*

[Only those elements found are reported below. Analyses by J. L. Harris, W. B. Crandell, and A. W. Helz (project leader), U.S. Geol. Survey. Results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, and so on, which represent approximate midpoints of interval data on a geometric scale. The assigned interval for semiquantitative results will include the quantitative value about 30 percent of the time. <, less than number shown, usual detectabilities do not apply. 0, looked for but not detected]

	Serpentinite			Rodingite		
	1	2	3	4	5	6
Lab No.	W167341	W167342	--------	W167343	W167856	W167855
Field No.	186-RM-66-L	187-RM-66-L	129-RM-66-L	188-RM-66-L	205-RM-66-L	12-RM-66-L
Al			1.5			
Fe			2.			
Ca			10.			
Na			.05			
Ti			.005			
Mn			.05			
Ag	0	0	0	0	<0.0001	<0.0001
Ba	0	0	<.0003	0	.003	<.0003
Co	.003	.005	.05	.0015	.005	.002
Cr	.2	.2	.05	.15	.2	.7
Cu	.003	.01	.02	.003	.015	.02
Ga	0	0	0	.003	.0005	0
Ni	.15	.2	.15	.03	.05	.05
Pb	0	0	0	0	.002	0
Sc	.0003	.003	.0003	.002	.003	.003
Sr	0	0	.0003	.01	.02	.0007
V	.001	.001	.002	.005	.007	.007

1. Serpentinite sample (104 locations).
2. Serpentinite specimen from southwest end of quarry.
3. Tremolitized serpentinite specimen from northeast end of quarry.
4. Rodingite sample (41 locations).
5. Rodingite specimen from southwest end of quarry.
6. Rodingite specimen from northeast end of quarry.

altered rocks other than gabbro. Thayer (1966, p. 701) wrote, "Rodingite consists essentially of the Ca-rich minerals hydrogarnet, prehnite, idocrase, zoisite and clinozoisite, diopside, edenite and xonotlite, with chlorite as the principal magnesium mineral * * *. [It] is an alteration product of many kinds of rock ranging from keratophyre to dolerite and quartz-sericite-albite-chloritic schist." An extensive bibliography on rodingite was listed by Coleman (1967). Rodingitic rocks were described by Graham (1917) and De (1967) in the Thetford-Black Lake area of Quebec and by Cady, Albee, and Chidester (1963) in Vermont. I could find no reference to such rocks elsewhere in the Atlantic Coast region and no reference to such brightly colored rodingites anywhere in the United States. Dike rocks of rodingitic composition that cut the serpentinite in the Hunting Hill pluton all appear to have been originally medium to coarse-grained gabbro. The term here, then, applies only to calcium-rich metasomatised gabbro.

STRUCTURAL RELATIONS AND DISTRIBUTION

Dikes and irregular masses of light-colored rodingite-gabbro as much as 1,500 feet long and 100 feet wide are the most conspicuous geologic features of the Hunting Hill quarry (pl. 2). Because of its light color, the rodingite stands out against the background of dark serpentinite (figs. 5 and 6). Although the serpentinite is closely jointed and highly sheared in places along the southeast face, many gabbro dikes are completely intact for distances of several tens of feet. This fact is shown best in the steep faces. In the northeast half of the quarry floor, some rodingite intrusions are either small and lenslike or possible parts of larger bodies broken apart during tectonism, although this latter feature never was observed in vertical sections.

With one exception, the gabbro bodies are roughly parallel and have strikes of N. 50° to 65° E. and vertical or steep dips. One dike of fine-grained light-gray rodingite 20 feet thick, in the southwestern part of the quarry, was unexposed when the map was prepared but was exposed in recent (1968) development. This dike, bordered by a discontinuous 24-inch-thick tremolite vein on the hanging wall, strikes N. 70° W. and dips 53° SW. The crests and keels of most dikes and irregularities mapped in the southwest part of the quarry plunge northeastward; elsewhere a plunge to the southwest was noted. Most contacts or apparent contacts of gabbro with serpentinite are sheared and slickensided and have lineations in as many as four directions. Most unsheared contacts, although rare, are sharp and definite, even where tremolite is unusually abundant in the adjacent serpentinite.

Gabbro appears to be distributed very irregularly in the pluton, and the forms of the masses vary considerably from place to place. When

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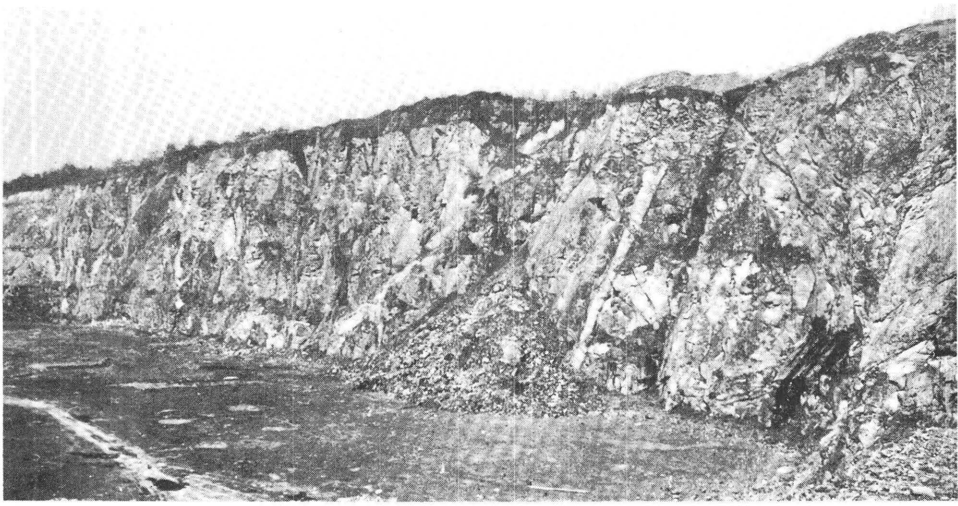
mapped, the amount of gabbro in the southwestern part of the quarry was double that in the northeastern part (approx. 20 percent as opposed to 10 percent, averaging about 13 percent, pl. 2). Quarry development after the mapping, however, revealed a marked decrease of gabbro, thus indicating an erratic distribution. The bodies of gabbro exposed in most places in the northeastern end are narrower and more dikelike than those in the southwestern part, which are larger and more irregular. Gabbro is more common in the quarry area than elsewhere in the pluton (pls. 1 and 2).

MINERALOGY AND PETROGRAPHY

In hand specimen the rodingite ranges from uniform light-gray fine-grained rock to a more common coarse-grained mixture of bright-green or gray-green relict diopside in a pale-gray aphanitic groundmass cut by irregular masses or veins of massive cinnamon to pink grossularite (fig. 7). In parts of the quarry the intrusive bodies are pegmatitic and have diopside crystals as much as 20 cm (8 in.) in diameter. The diopside grain size generally exceeds 1 cm (½ in.). The rock is hard, tough, and poorly jointed. The specimen shown in figure 7 illustrates unusually well the textures that result from metasomatic replacement of coarse-grained gabbro by the massive reddish garnet and fine-grained light-gray mixture of white diopside, hydrogrossularite, zoisite, and prehnite. Rocks similar to this have been misidentified as altered pyroxenite.

The grain size is not related to thickness of the dike or to distance from the dike margin, even where the dike is compositionally layered (fig. 8). This layering is shown by variation in diopside content in proportion to other minerals and is parallel to the walls, except where sheared. The layering is highly sporadic and is best developed in dikes as narrow as 36 inches (about 1 m); most larger gabbro masses, 25 to 100 feet wide, show no layering. This layering fades out along strike after being present for only a few tens of feet. In places, well-formed pyroxene crystals an inch or more long are oriented with their long axes normal to the layers. Gneissic structure of the kind described and figured by Thayer (1963) in flow-layered gabbro and peridotite was not seen in the quarry.

The green relict diopside is in a fine-grained matrix of white prismatic diopside, zoisite, and brownish-red grossularite; the grossularite is commonly massive and in veins cutting the white to gray groundmass. Hydrogrossularite and prehnite occur sparingly, but the latter is more common than the former. Tremolite occurs as isolated blades or in veins. Chlorite and clinochlore are common near the margins of the dikes. White diopside replaces margins of the green diopside. The green diopside in places is twinned and striated, and most of it



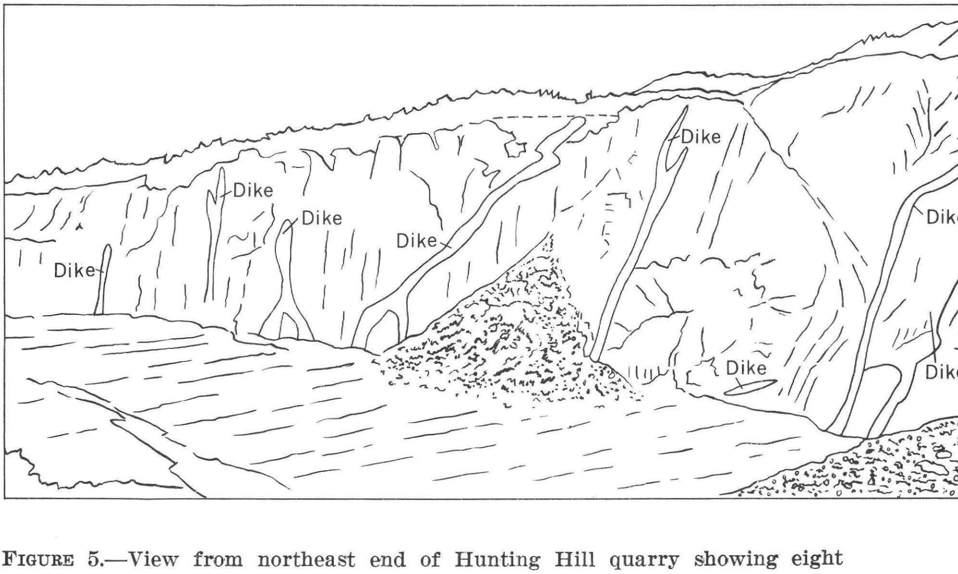


FIGURE 5.—View from northeast end of Hunting Hill quarry showing eight steeply dipping rodingite dikes in northwest wall. Height of face at talus slope is 185 feet.

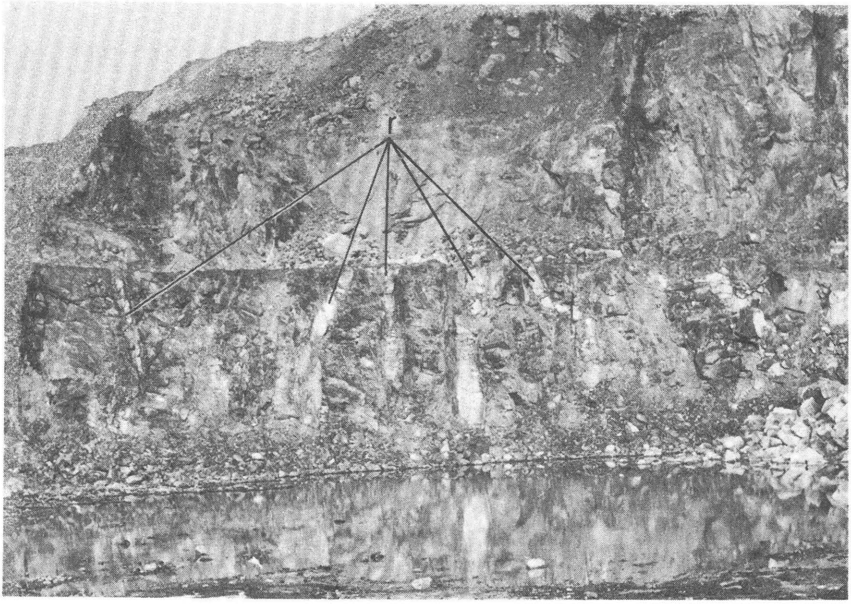


FIGURE 6.—Five small rodingite bodies (r) in southwest end of pit. Note uninterrupted continuity of the rodingite masses despite closeness and irregularity of fracturing in serpentinite. Height of bench is 30 feet.

has been severely deformed by bending and fracturing. Crush zones within green diopside contain white unsheared prismatic diopside, much of which shows comb texture normal to banding, as in vein fillings. Prehnite was the last to form in some thin sections and encloses coarse clear white secondary diopside; the prehnite also encloses clinozoisite and has not been deformed. Clinochlore surrounds remnants of white and green diopside and grossularite.

Chloritization along the borders of some rodingite dikes obscures their contact relations with serpentinite. This kind of alteration is especially well shown in the Y-shaped dike in the northwest wall of the quarry above the talus (fig. 5) and to a lesser degree, in the dike above and northeast of the primary crusher. As shown in figure 9, a dark mixture of clinochlore and garnet mainly replaces the secondary matrix minerals between the primary chromian diopside crystals but also attacks white diopside. In thin sections, relict prisms of secondary vein diopside are preserved in both garnet and clinochlore, and clinochlore replaces primary chromian diopside along the cleavages. The width of the chloritized zones is obscured by minor shears parallel to the walls of the dikes and by the gradational nature of replacement, but probably ranges from 4 to 6 inches (10–15 cm).

FIGURE 7.—Typical rodingite from northeastern part of quarry. Green chromian relict diopside and massive cinnamon grossularite in a groundmass of light-gray and white diopside, zoisite, and clinozoisite. Specimen is 3.5 inches long. Photograph by Norman Prime.

CHEMICAL COMPOSITION

The chemical analysis of a bright-green diopside specimen (table 3) indicates that the color results from the presence of chromium. Rodingite from the northeastern part of the quarry contains diopside with a higher chromium content than that from the southwestern part (table 2), where the diopside generally is grayish green. Analyses were made of two specimens of grossularite—the massive type (hessonite) from unsheared rodingite in the northeast end of the quarry and a well-formed crystal from a vuggy vein in the sheared southeast wall near the southwest end of the quarry. These show a notable range in composition. The grossularite specimens vary chiefly in the content of TiO_2 and Fe_2O_3 substituting for Al_2O_3. The massive specimen has a higher index of refraction. The cinnamon to pink massive grossularite, so characteristic of rock in the northeast end of the pit, generally is lacking in the opposite end; this difference is reflected in the specific gravities of the specimens (table 1).

FIGURE 8.—Compositional layering in central part of 6-foot-thick rodingite dike in northeast end of quarry floor.

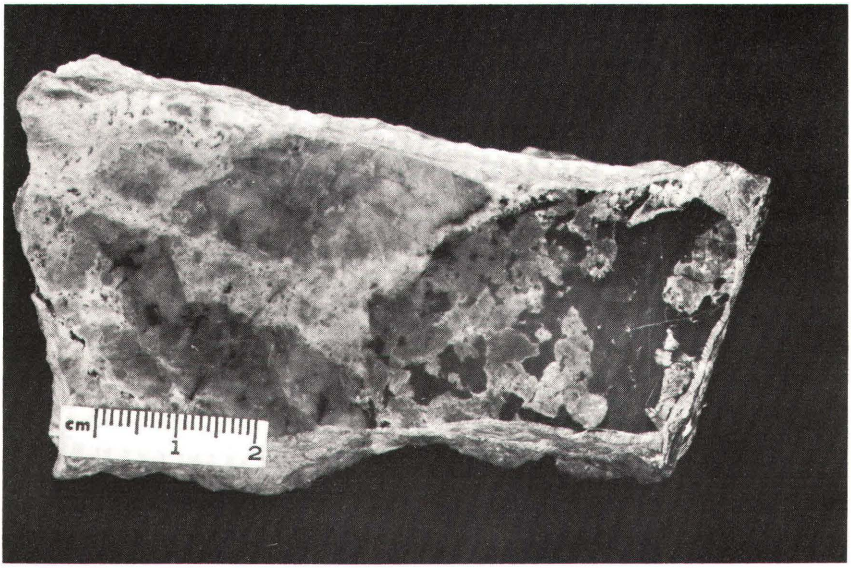


FIGURE 9.—Border zone of rodingite dike showing green relict diopside in matrix of dark-gray clinochlore and garnet, which have replaced secondary minerals after original feldspar. In left part of specimen, fine-grained white prismatic diopside veins cut a mixture of chiefly green diopside and clinozoisite.

TABLE 3.—*Chemical composition and refractive indices of several minerals from the Hunting Hill quarry*

[Standard chemical analyses by J. J. Fahey, U.S. Geol. Survey]

	Diopside (bright green)	Grossularite (massive, hessonite)	Grossularite (crystal)	Hydromagnesite
Field No	12-RM-66-L	176-RM-66-L	244-RM-66-L	160-RM-66-L
SiO_2	48. 87	38. 66	39. 04	
Al_2O_3	5. 53	16. 53	20. 43	
Fe_2O_3	. 78	6. 08	3. 29	
FeO	2. 26	1. 35	1. 81	0. 16
MnO	. 05	. 34	. 34	
Cr_2O_3	1. 15			
TiO_2	. 16	1. 16	. 12	
NiO	. 00			
MgO	15. 93	1. 66	. 73	43. 29
CaO	23. 33	33. 75	34. 29	
Na_2O	. 18			
K_2O	. 02			
$H_2O-110°C$	. 04		. 00	20. 25
$H_2O+110°C$	1. 43	. 34	. 36	
CO_2	. 15	. 20		36. 10
Insolubles				. 04
Total	99. 88	100. 07	100. 41	99. 84
Bulk density	3. 267	3. 612		
Powder density			3. 635	2. 171
Refractive index (n)		1. 772	1. 753	
Refractive index (α)	1. 672			1. 527
Refractive index (β)	1. 689			1. 537
Refractive index (γ)	1. 703			1. 550

QUARTZ DIORITE

Coarse-grained dark-gray hornblende quartz metadiorite crops out in the serpentinite northeast of the quarry, and float was found southwest of the quarry (pl. 1). The original diorite appears to have been a mixture of hornblende (0.5 in.–1.0 in.) and calcic plagioclase feldspar. Most plagioclase is replaced by aggregates of epidote-clinozoisite which also forms corroded, approximately square or prismatic crystals; sodic plagioclase (refractive indices less than balsam) and considerable quartz also are present. Granular aggregates of quartz and albite(?) replaced some original feldspar units.

The contacts of the diorite were not observed, but the bodies are believed to be dikes or small plugs.

VEINS

SILICATE VEINS

Veins or lenslike bodies of silicate minerals, in approximate order of their abundance, are: chrysotile, tremolite, deweylite, grossularite, talc, clinochrysotile, anthophyllite, tourmaline, clinozoisite-epidote, and penninite. The relative ages of many veins could not be determined.

Nearly parallel en echelon gash veins of green cross-fiber chrysotile, mostly of hairline thickness but some as thick as 0.1 inch, are common in the serpentinite (fig. 4). Most veins strike about N. 25° E. and dip vertically or nearly so. Where present at all, associated with chrysotile, magnetite occurs marginal to or crosscutting the veins; it never is present as the common central parting. The veins are estimated to be only a small fraction of 1 percent of the serpentinite.

Clinochrysotile forms veins 1/8 to 2 inches thick in serpentinite; the largest vein strikes N. 50° W. and dips 25° NE. The mineral is extremely fine grained, pale grayish green to bluish green, massive, waxy, and has an unctuous feel; it is hard and breaks with a conchoidal fracture. The outer surfaces or contacts of the thickest vein are mammillary or botryoidal; the clinochrysotile is bordered with calcite and dolomite. According to Norman Page (oral commun., 1967), the clinochrysotile probably formed well below 100° C., perhaps below 50° C. It appears to be the last serpentine mineral formed. Hostetler and Christ (1968) indicated that chrysotile and other serpentine minerals probably are formed at temperatures below 100° C.

Deweylite, as shown by Faust and Fahey (1962), and as identified from this quarry by Faust, using X-ray, is a mixture of stevensite and a chrysotile-group mineral. Here it forms veins in serpentinite as much as 4 inches thick, but they commonly range from 0.5 to 1 inch in thickness. The veins are laminar, with layers of pale-chocolate brown and lighter brown sandwiched between calcite and dolomite sheets at the boundaries. Deweylite is friable and waxy in appearance. Most veins strike about northwest and dip 20° to 40° SW.

Creamy-gray anthophyllite veinlets less than one-fourth of an inch thick were found in serpentinite float; rosettes or whorls of the mineral were noted on fracture planes. Both occurrences are in the sheared rock in the southeast benches.

Small veins and films of penninite occur in serpentinite float of the highest southeast bench.

Talc occurs as cream to pale-green crystalline flakes in veins averaging 0.5 inch but as much as 2 inches thick; the occurrences are in the strongly sheared serpentinite at the top of the southeast bench.

Veins containing vugs of cinnamon-brown to pink crystalline grossularite were found in the southeastern part of the quarry. Clinozoisite-epidote and minute plates of chlorite occur with the garnet. The veins range from 0.5 to 2 inches in thickness, six or more veins occurring across a 20-foot-wide exposed zone of sheared rodingite. The veins range in strike from N. 10° E. to N. 40° W. and dip from 45° SE. to 65° SW. The garnet is friable, having been shattered.

White to cream tremolite veins as much as 2 feet thick, but in most places less than 0.5 inch thick, cut the serpentinite, chiefly in the southeast and southwest parts of the quarry. Small crenulations normal to lineation were noted; other minor distortion included folding and slipping. The veins range from strike N. 35° E. and dip 80° SE. to strike N. 55° W. and dip 65° SW. The large 2-foot vein south of the mapped quarry crosscuts the others; it strikes N. 70° W. and dips 53° SW.

A lenslike 2.5-inch vein of bluish-black striated tourmaline crystals was found in sheared rodingite float on the top southeast bench. The prisms are small, as much as one-fourth of an inch long and very fragile. On one side of the vein the tourmaline is intergrown with clinozoisite-epidote crystals as much as one-fourth of an inch in diameter and 1 inch long; these crystals range in color from dirty light grayish green to creamy gray, are striated or fluted, are very fragile, and extend inward from the wallrock of sheared rodingite. Some epidote crystals have formed around long thin prisms of tourmaline.

QUARTZ VEINS

Small veins of chalcedony, hyalite, and quartz are rare. A hard green chalcedony vein in the northeast end of the quarry pinches and swells from 0.5 to 6 inches thick. Brown chalcedony from veins at least 2 inches thick was found as float near the base of the large talus slope on the northwest wall of the quarry. Some pale-gray hyalite in veins 0.25 inch thick was noted in the upper faces at the northeast end. Minute quartz crystals are attached to massive quartz "plates," forming a hollow boxwork vein filling, also in the northeast end of the quarry. Most of the few silica veins trend generally about N. 35° W. and dip 40° NE.

CARBONATE VEINS

Thin veins of calcite and dolomite are common throughout the quarry; frequently the two minerals occur together in a single vein. One vein of aragonite and one of hydromagnesite also were seen. Many veins of magnesite occur in the southwest end.

Veins of calcite and dolomite ranging in thickness from a thin film to 1 inch are along joints and some shear planes in serpentinite and rodingite in all parts of the quarry. Most crystals are white and well-formed; crystals of calcite as much as half an inch in diameter were found. In places calcite was deposited on a layer of dolomite; elsewhere the reverse was noted. Tiny beads of pale-yellow to white dolomite are grouped to form mammillary structures on some joint planes. Most veins seem to trend about N. 30° E. and dip from 16° to 80° NW., but the trend is highly variable

Coalingite, huntite, and brucite have been identified in the serpentinite. John White, of the U.S National Museum, and later M. E. Mrose (written commun., 1967) identified golden-brown to bronze micaceous plates as coalingite, $Mg_{10}Fe_2CO_3(OH)_{24}.2H_2O$. The coalingite occurs as thin veins and films on shear planes in the quarry floor. It is pale yellow when fresh and darkens to bronze in a few months, when exposed. This quarry is the second reported occurrence of coalingite, which was first identified (Mumpton and others, 1965) in the New Idria serpentinite mass in Fresno and San Benito Counties, Calif. Mrose also found huntite, $Mg_3Ca(CO_3)_4$, associated with brucite and an unknown white lathlike hydrated magnesium-iron carbonate.

Water-clear plates of aragonite (fig. 10) extend into openings in

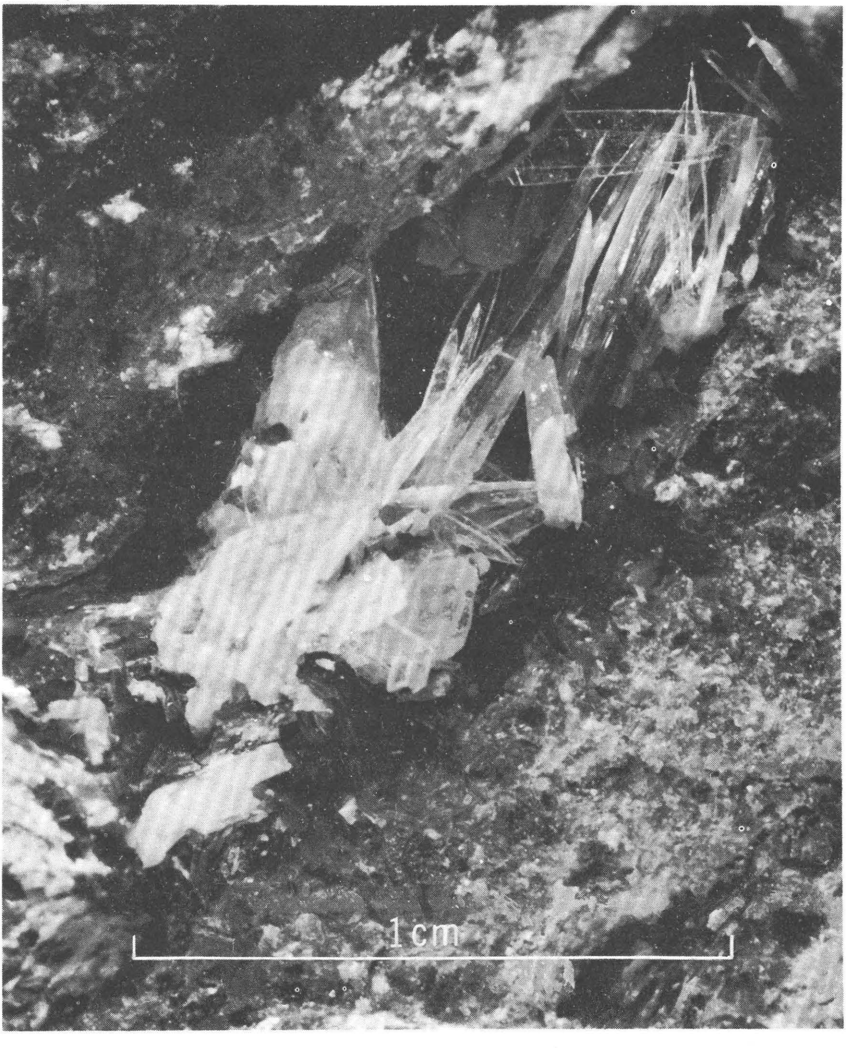


FIGURE. 10—Water-clear platy crystals of aragonite at top of a small vug within a narrow shear zone in northwest face of Hunting Hill quarry.

the center of a vein as much as 2 inches thick; this vein is lined with fine-grained banded calcite. The vein, in a shear plane in serpentinite at the base of the northwest wall, strikes N. 31° W. and dips 35° SW. Elsewhere, aragonite commonly forms whorls, fans, and low conical rosettes as much as 4 inches in diameter on fracture surfaces.

Magnesite veins 0.5 to 2 inches thick cut the serpentinite; the veins commonly strike N. 45° W. and dip 50° SW., although they are of many trends. The magnesite is cream to white, hard, porcelaneous, has a conchoidal fracture and in places a rough, highly irregular to botryoidal or mammillary central parting. The veins generally are bordered with thin layers of dolomite and calcite The veins were observed only in the actively worked southwest benches of the quarry.

Hydromagnesite in a $\frac{1}{4}$-inch-thick vein was found only as a late fracture filling in black serpentinite blasted from the face below the lowest active southwest bench The delicate, brilliant white needle crystals about 1 inch long are arranged in whorls, rosettes, or circular fans. The crystals have an uneven fracture. Found by Kenneth Weaver, they were identified by J. J. Fahey and Malcolm Ross, as the optical properties are unusual (table 3).

Table 4 lists the minerals reported to date.

TABLE 4.—*List of minerals identified from the Hunting Hill quarry*

[Name of person who first identified the mineral indicated for those identifications made by X-ray, microprobe, or other special means]

Actinolite.
Anthophyllite.
Antigorite, of at least two stages (G. T. Faust, 1967).
Aragonite.
Azurite.
Brochantite (M. E. Mrose for John Gruger, collector, 1969).
Brucite (M. E. Mrose, 1967).
Calcite.
Chalcedony, green, brown.
Chalcocite.
Chalcopyrite.
Chlorite.
Chrysotile.
Clinochlore (Eleanora Iberall, 1968).
Clinochrysotile (R. G. Coleman, 1966; G. T. Faust, 1967).
Clinozoisite-epidote (J. J. Fahey and G. T. Faust, 1967) and brown clinozoisite (J. J. Fahey, 1969).
Chromite (Norman Page, 1968).
Coalingite (John White, 1967; M. E. Mrose, 1967).
Deweylite (stevensite and chrysotile) (G. T. Faust, 1967).
Diopside, both green and white varieties (J. J. Fahey, 1966; Eleanora Iberall, 1967).
Dolomite.
Grossularite, of two stages (J. J. Fahey, 1966, 1967).
Hematite.
Huntite (M. E. Mrose, 1967).
Hyalite, gray to white.
Hydrogrossularite (G. T. Faust, 1967).
Hydromagnesite (J. J. Fahey and Malcolm Ross, 1966).
Idocrase (John Sinkankas, 1958).
Limonite.
Lizardite (G. T. Faust, 1967).
Magnesite.
Magnetite.
Olivine.
Penninite.
Picrolite.
Platinum, trace; plus palladium, trace (L. B. Riley, W. D. Goss, and Joseph Haffty, 1967).
Prehnite (J. J. Fahey, 1966).
Pyrolusite.
Pyrite.
Pyrrhotite.
Quartz.
Talc.
Thulite (J. J. Fahey, 1969).
Tourmaline.
Tremolite.
Zoisite.

MINOR STRUCTURES

JOINTS

Joints of all attitudes characterize the serpentinite; they are most numerous and closely spaced in the northeast end of the quarry. Although a comprehensive study was not attempted, the plot of the first 100 prominent joints to be observed (fig. 11) suggests a predominance of north-northwest and west-northwest strikes and steep dips. Most of the joints in serpentinite are extremely tight. For example, 5-inch blast holes drilled dry to depths of 65 feet collect only 50 to 60 gallons of water during dry periods of 3 to 4 days, and there is very little leakage along joints in the quarry faces.

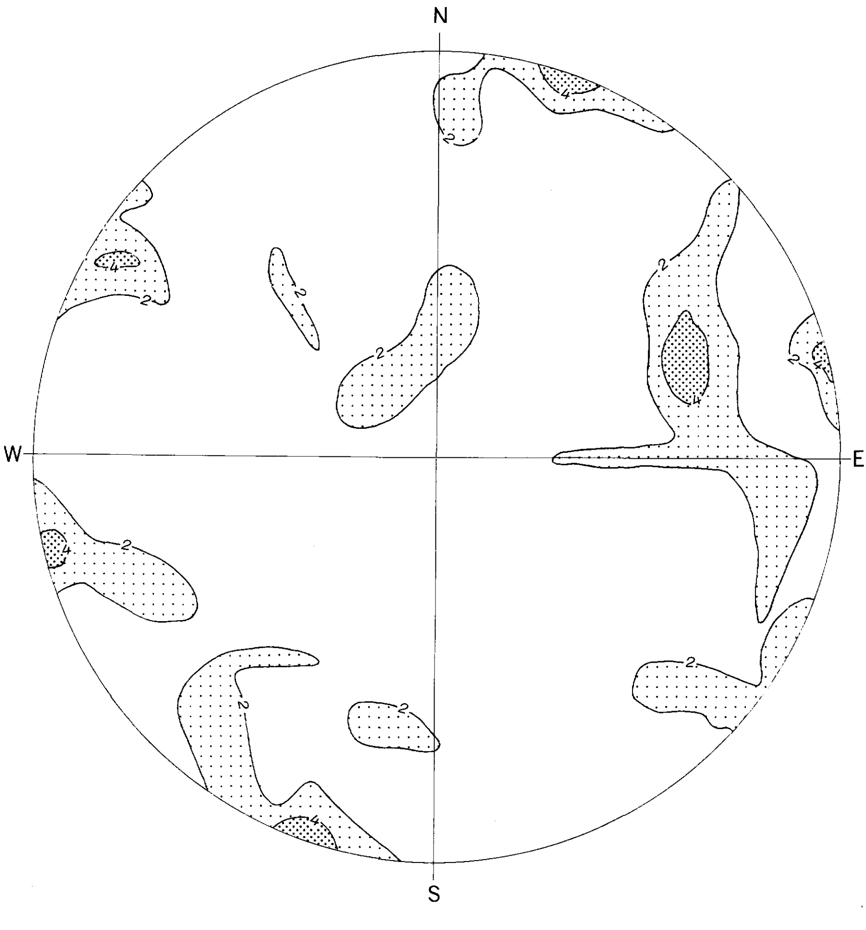


FIGURE 11.—Schmidt net showing poles of 100 joints in serpentinite and rodingite plotted on lower hemisphere. Contours at 2 and 4 percent per 1-percent area.

SHEAR STRUCTURES AND FAULTS

Two hundred shear planes ("slips") of various trends, believed to be representative, are indicated in figure 12. Most are curved rather than plane surfaces, strike about N. 25° E., and dip steeply to the northwest or southeast. Generally, the shear surfaces are much more widely spaced than joints, are more prominent, and are coated with one or more of the following minerals: brittle green picrolite, chlorite, calcite, dolomite, tremolite, talc, and coalingite. Most are slickensided, and as many as four intersecting sets of slickensides have been noted on a single shear plane. In some places, the movement was updip or downdip; in others, along the strike. Some shear surfaces are marked by open cavities containing calcite, dolomite, and aragonite.

Minor faulting has occurred throughout the quarry. The maximum

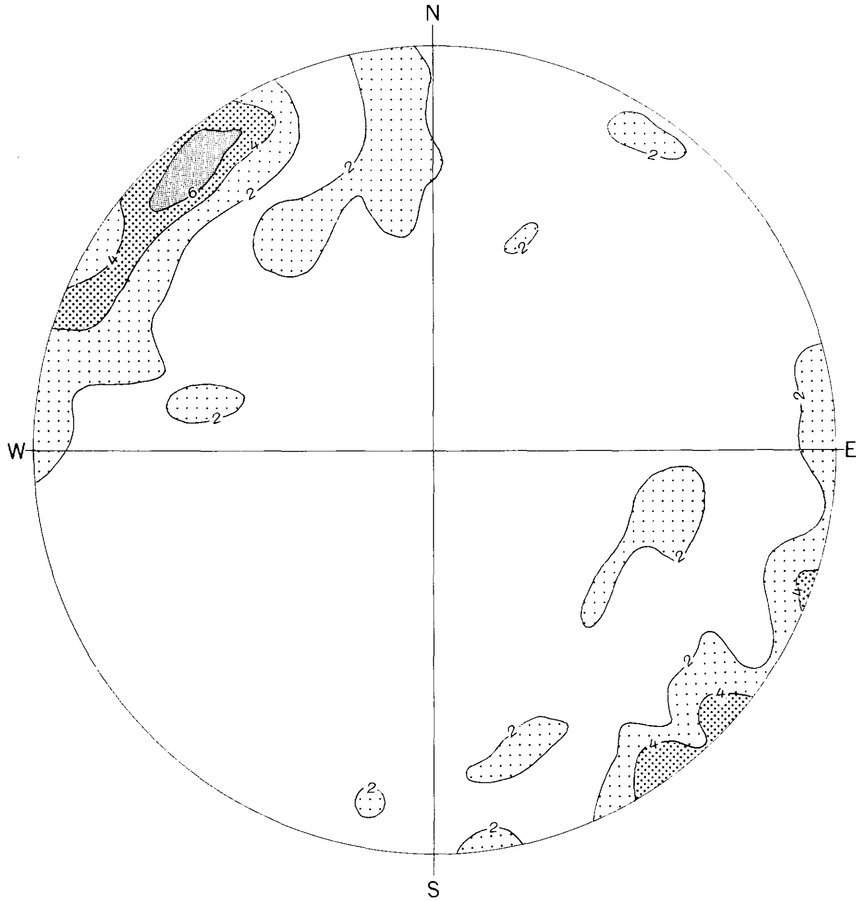


FIGURE 12.—Schmidt net showing poles of 200 shear planes in serpentinite and rodingite plotted on lower hemisphere. Contours at 2, 4, and 6 percent per 1-percent area.

displacement was 15 feet and was observed in the highest active bench in the southwest end of the pit, where a rodingite dike was offset normally. Most displacements are a few inches, and few exceed 3 feet.

Several shear zones, each containing several closely spaced shear planes which strike approximately N. 46° E. and dip vertically, are exposed along the southeast face of the quarry (pl. 2). Within the shear zones, chlorite occurs as fist-sized knots and probably is the most abundant mineral formed from serpentinite. Magnetite crystals as much as one-fourth of an inch across and partly altered to hematite are prominent, and there are flakes and veinlets of talc and veins of tremolite. Hyalite with pyrolusite dendrites, and malachite, azurite, and penninite are rare.

Table 5 and figure 13 give the most common trends of various structures at the quarry and the trend of the quarry itself.

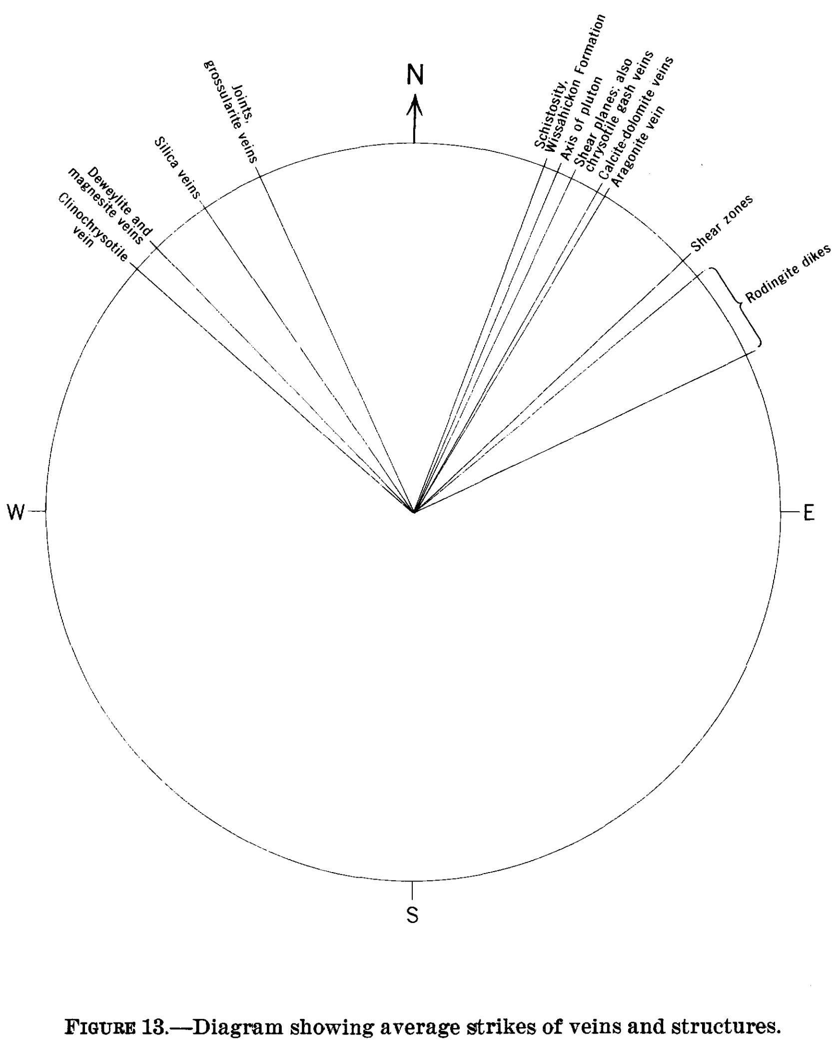


FIGURE 13.—Diagram showing average strikes of veins and structures.

TABLE 5—*Structural trends*

[Axis of quarry, N. 45° E.]

Feature	Strike	Dip
Average schistosity, Wissahickon Formation	N. 20° E	Vertical.
Axis of serpentinite pluton (4 by 1 mile)	N. 22° E	
Average trend, rodingite dikes	N. 50°-65° E	Steep.
Average trend, chrysotile veins	N. 25° E	Vertical.
Average trend, clinochrysotile veins	N. 50° W	25° NE.
Average trend, deweylite veins	N. 45° W	30° SW.
Average trend, magnesite veins	N. 45° W	50° SW.
Average trend, tremolite veins	(1)	(1).
Average trend, grossularite (crystal) veins	N. 25° W	55° SW.
Average trend, quartz (all forms) veins	N. 35° W	40° NE.
Average trend, calcite-dolomite veins	N. 30° E	(1).
Average trend, aragonite vein	N. 31° E	35° SW.
Average trend, shear planes	N. 25° E	(1).
Average trend, shear zones	N. 46° E	Steep.
Average trend, joints (only those measured)	N. 25° W	(1).

[1] Highly variable.

PETROLOGY AND GEOCHEMISTRY

PRIMARY IGNEOUS FEATURES

The pluton is believed to have been intruded as a dunitic crystal mush during a tectonic disturbance, probably the Taconic orogeny in Ordovician time. The intrusion probably was guided by preexisting structure of the Wissahickon Formation. The gabbro was intruded after the dunite had cooled sufficiently to sustain a fracture system but before it had cooled enough to chill the fluid gabbro magma. The original composition of the gabbro is unknown, but the rock appears to have been a simple augite-bearing variety. The pegmatitic texture in parts of some gabbro masses implies rather slow cooling at temperatures of 1,000°C. or more. The difference of at least 500°C., between the temperature of crystallization of gabbro magma and the upper thermal limit of stability of serpentine minerals, and the lack of any recognizable thermal metamorphism of serpentinite along contacts of the gabbro dikes are evidence that the dunite was fresh at the time of gabbro intrusion, as in other alpine peridotite-gabbro complexes (Thayer, 1966).

METAMORPHISM AND ALTERATION

By analogy with the Baltimore Gabbro Complex (as used by Hopson, 1964; Thayer, 1967; and D. L. Southwick, unpub. data, 1967), the Hunting Hill pluton has undergone one or more episodes of regional metamorphism and related hydrothermal alteration. The principal local metamorphism of the Wissahickon Formation to muscovite-biotite facies is thought to have followed emplacement of the pluton. Variations in local temperatures and pressures and the chemical composition of solutions moving through the rocks during metamorphism should be reflected in the mineral paragenesis in the serpentinite and rodingite. Until a great deal more is known about both problems, however, even tentative correlations are speculative.

Serpentinization and rodingitization are two aspects of one principal alteration process that has affected the rocks. Because the details of this process have been discussed elsewhere (Coleman, 1966, 1967; Thayer, 1966, 1967) and because mineralogical studies in the Hunting Hill quarry are continuing, only some major relationships can now be considered briefly.

The compositions of the analyzed rodingite samples (table 1) are characteristic of such rocks from all parts of the world (Coleman, 1967). The variations in proportions of CaO, Al_2O_3, and SiO_2, reflect differences principally in the ratio of diopside to garnet and clinozoisite. The very low contents of Na_2O and K_2O, except in one sample, confirm the observed absence of feldspar in thin sections. Variations in the chromium content of rodingite from the northeastern and southwestern parts of the quarry (table 2, samples 5 and 6) are in accord with the conspicuous variation in color of pyroxene from brilliant green to grayish green.

Contemporaneous alteration of the peridotite to serpentinite and the gabbro to rodingite, although seemingly paradoxical because of the compositional contrast of the resulting rocks (Thayer, 1966, p. 701), is widely accepted; the rock relationships in this quarry seem to permit no obvious reasonable alternative. The distribution of tremolite in serpentinite along the walls of dikes and chloritization of the borders of some dikes are believed to result from diffusion of calcium and magnesium in opposite directions across the gabbro-peridotite contact (Coleman, 1966, p. 85). Replacement of the calcium and sodium originally in plagioclase by magnesium would produce the clinochlore shown in figure 9. Formation of tremolite in serpentinite would require only the introduction of calcium, because silicon is available from the serpentinization of olivine (Thayer, 1966, p. 698). The chlorite-rich margins on the rodingite-gabbro dikes suggest a chemical parallel to the chloritic "blackwall" along contacts of serpentinite in Vermont (Chidester, 1962).

The physical changes accompanying serpentinization and rodingitization might seem as contradictory as the chemical changes. At the same time that the specific gravity of the ultramafite was reduced from about 3.2 (dunite) to about 2.65, the specific gravity of the gabbroic rock was increased from about 2.8 to about 3.2. If the changes in density were caused by proportionate changes in volume, serpentinization would entail a volume increase of 35 to 40 percent (Hostetler and others, 1966, p. 96) and formation of rodingite would cause a volume decrease of about 15 percent. It seems to me that volume changes of the order indicated for serpentinization probably would pull the dikes apart, if not completely disrupt them. This has not occurred, however, except for possible disruption of some rodingites mapped on the quarry floor. The unbroken continuity of many dikes, despite presence in the serpentinite of the intricate jointing that characterizes alpine-type serpentinites everywhere, is impressive. The field and petrologic relationships of the rodingite and serpentinite seem to me to be best explained by alteration at constant volume.

The petrography of the rocks shows that serpentinization and related alteration were discontinuous; they probably took place over a long time. Replacement of antigorite by tremolite and talc, and then replacement of both of them by antigorite is evidence of changing geochemical conditions. The present of partially serpentinized tremolite, which appears to have replaced antigorite, not olivine, in the same thin section with relict olivine, is evidence that the serpentinization took place at two or more different times. Although most tremolite is believed to be related to local diffusion of calcium from gabbro, the large discontinuous crosscutting tremolite vein in the southwestern part of the present quarry requires a different explanation.

The time and method of emplacement of the pluton are uncertain. Although no direct evidence is known, comparison with exposed contacts of similar plutons suggests that serpentinite probably formed along the borders at the time of intrusion, and these borders became zones of major movement. The continuity of the rodingite-gabbro dikes is interpreted as evidence that movement of the pluton as a solid diapir, during or after serpentinization, probably was not large. It seems unlikely that the incompetent serpentinite could move very far without more internal shearing and adjustment along fractures than the continuity of most dikes would permit.

In conclusion, the principal serpentinization of the dunite and contemporaneous alteration of gabbro dikes to rodingite in the Hunting Hill pluton are believed to have progressed intermittently over a long time and to have occurred chiefly in place without significant changes in volume.

ECONOMIC GEOLOGY

Crushed stone from the Hunting Hill serpentinite quarry is used as binder-filler for asphalt in black-top paving, as base course for all types of highways, road metal for parking lots and driveways, and concrete aggregate. It was used as concrete aggregate in the Little Falls Interceptor Dam across the Potomac River in 1956–57, and later, in 1960, in runways at Andrews Air Force Base, Md. Most of the rock is sold in sizes ranging from fines (dust) to 3½ inches, although some large jetty stone is produced. Most of the jetty stone is rodingite. A "hot mix" plant for asphalt road surfacing is operated on the quarry property by the Contee Bituminous Co. Haulage from the property is by independent truckers.

The crushed, equidimensional stone or fines must pass tests for (1) soundness by Los Angeles or Deval abrasion tests, or the magnesium or sodium sulphate test, (2) proper screen sizes of particles, (3) plastic index, (4) liquid limit, (5) specific gravity, and (6) chemical composition. For some uses, other tests may be required.

Before quarrying for production, the top 15 feet is blasted and stripped as waste, although much sound rock is included. Truck-mounted pneumatic percussion-type rigs drill 5-inch vertical blastholes to a few feet below the level of the next lower bench. The burden on holes normally ranges from 5 to 8 feet, and holes are spaced about 15 feet apart. Ammonium nitrate and dynamite are used as explosives, and only a few holes are blasted at a time. Fragmentation is highly variable and is affected by joints, shear zones, and the angles at which these intersect the face. The degree of backbreak developed during any shot of several holes is largely a matter of natural rock-fracture spacing, relation of shear and joint directions (strike and dip, table 5 and fig. 13) to face of bench, and proper depth of hole below the floor of the next lower bench. The benches averaged 40 to 60 feet in height at the time of mapping. During the period of my close association with the operation, no earth shock or airblast was noticed.

Most of the rodingite is much harder than the serpentinite, and can be drilled at only about one-half of the speed. Rodingite also is much less jointed and sheared than the adjacent serpentinite and more expensive to break. The frequency of jointing makes drop ball cheaper than blasting for secondary breaking, especially as this does not interfere with other phases of quarrying. Most blocks are reduced to about 2 feet in diameter before delivery to the primary crusher, although larger blocks can be handled. Because of the differences in specific gravity of the rodingite and serpentinite, constant blending of the two types of rock is required when a certain specific gravity is specified. The broken rock is trucked to a primary crusher on a bench at the northeast end of the pit and raised about 100 feet by belt conveyor to the secondary crushing and screening facilities on the surface.

A special arrangement for detection of tramp iron is required because of the large amount of magnetite in the serpentinite in addition to nonmagnetic manganese steel used in shovel-bucket teeth; an ordinary magnetic head pulley soon would become fouled with the magnetite.

After crushing and screening to the desired sizes or blend of sizes, the rock is either stockpiled or put into bins for direct loading. Special crushing equipment is needed to produce fine particle sizes, which are in great demand for black-top binder. Consequently, no large unsightly piles of fines—the common headstone for an abandoned crushed-stone operation—will be left as a permanent reminder of the operation when the reserves have been depleted to the economic limit. Waste rock is deposited in benches and graded to a level fill west of Piney Meetinghouse Road, where it may be recovered for future use.

The fines produced by drilling and blasting consist largely of fibrous antigorite. When wet, they form a light-gray thick slurry which dries to a relatively hard and tough mixture. This fibrous nature is one of the desirable properties of this material when it is used as a filler in asphalt. The minute particles of heavy magnetite attached to many fibers reduce their loss by wind.

Very little water flows into the quarry through joints or shear zones; some drainage near the southwest end is from a swamp beyond the northwest face or high wall. Water from the quarry is pumped into settling ponds and then used for washing the crushed rock, for sprinkling roads, and for spraying loaded trucks before they enter the public highway.

The influence of shear planes and zones, especially, is shown in this pit, as they are important in the development of backbreak, landslides, and rockfalls. Backbreak can result in the formation of a toe, which interferes with removal of broken rock from above the toe and causes problems in subsequent blasting and shoveling. The nonvertical shears and joints increase the difficulty of maintaining vertical faces in the curved benches.

Only scientific interest can be attached to further platinum studies at the deposit, and no industrial minerals as such can be economically recovered (table 4).

The loss of fines by wind is minimized by sprinkling the roads frequently and by shutting down the plant when the wind is excessive. The amount of wind-carried fines is determined by systematic sampling at a number of places around the plant. Small recording seismographs on the property measure any vibrations from blasting.

The contribution of the quarry to the local economy far exceeds the maintenance of a payroll, which (including truckers) at times is almost 200 employees. This quarry operation is the only producer of tough crushed stone near the northwest Washington area. This means that, in addition to being physically closest to the major highways, industrial complexes, private residences, and public buildings that are under construction or being planned, it offers purchasers in this area the advantage of sound material at lower costs than more distant quarries, which would have higher haulage prices. It is also clear that the quarry will remain important in the foreseeable future as the population expansion continues to promote new building and major highway construction.

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