ART. XIX.—*The Palisade Diabase of New Jersey*; by J.
VOLNEY LEWIS.*

THE intrusive trap that forms the Palisades of the Hudson extends, with outcrops several hundred feet thick, from west of Haverstraw, N. Y., southward to Staten Island and, somewhat intermittently, westward across New Jersey to the Delaware River, an aggregate length of about 100 miles.† It is everywhere a medium- to fine-grained dark gray heavy rock, with dense aphanitic contact facies.

The typical coarser rock contains, in the order of abundance, augite, plagioclase feldspars, quartz, orthoclase, magnetite, and apatite. The first two occur in ophitic to equant granular texture, and the next two in graphic intergrowths which sometimes constitute one-third of the rock; in the contact facies this micropegmatite disappears and scattering crystals of olivine occur.

A highly olivinic ledge, 10 to 20 feet thick and about 50 feet from the base of the sill, is exposed in the outcrops northward from Jersey City for about twenty miles. The olivine crystals, which constitute 15 to 20 per cent of this rock, occur as poikilitic inclusions in the augite and feldspar.

Chemically the diabase ranges from less than 50 to more than 60 per cent of silica, with corresponding variation in alumina, ferric oxide, and the alkalis, while ferrous iron, lime, and magnesia vary inversely. The augite is rich in these latter constituents and poor in alumina, giving a great preponderance of the hypersthene and diopside molecules. The feldspars range from orthoclase and albite to basic labradorite. Doubtless there is some anorthoclase since all feldspar analyses show potash.

While there is considerable range in the proportions of the minerals, augite usually comprises about 50 per cent of the rock, the feldspars about 40 per cent, quartz 5 per cent, and the ores 5 per cent, constituting a quartz-diabase, with normal and olivine-diabase facies. Basic concentration at the contacts, followed by differentiation by gravity during crystallization of the body of the sill, especially by the settling of olivine and the ores and the rising of the lighter feldspars in the earlier and more liquid stages of the magma, are hypotheses that seem to account for the facies observed and their present relations.

Microscopic characters.—In thin sections the texture of the rock is usually diabasic, or ophitic; that is, the augite fills the

* Read before the New York Academy of Sciences April 6, 1908. Published by permission of the State Geologist of New Jersey.

† J. Volney Lewis, *Structure and Correlation of the Newark Trap Rocks of New Jersey*, Bull. Geol. Soc. of America, vol. xviii, pp. 195-210; also *Origin and Relations of the Newark Rocks*, Ann. Rept. State Geologist of N. J. for 1906, pp. 97-129.

interstices between the interlacing lath-shaped feldspars, or when greatly in excess it forms the groundmass in which the feldspars are imbedded. In the coarser-grained portions of the rock there is often developed a granitoid texture, in which the two chief minerals occur in grains of approximately equal size and of nearly equal dimensions in every direction.

Augite, the most abundant constituent, is pale green to colorless and sometimes exhibits distinct pleochroism—pale green to light yellow.* It occurs in plates up to 3 or 4 millimeters in diameter, and in irregular grains whose forms are determined by the accompanying feldspars. Crystal outlines are rarely observed. In the denser contact facies augite of two generations appears, the earlier as large plates scattered through the denser groundmass in which the augite of later crystallization forms a fine granular filling between the feldspars. Two forms of twinning often appear, both separately and in combination. That parallel to the orthopinacoid (100) usually produces paired halves, while the basal twinning (parallel to 001) is more commonly repeated in thin lamellæ, which are sometimes exceedingly minute.

Plagioclase, the chief feldspar and the second constituent in abundance, occurs in characteristic lathlike forms, ranging up to 2 millimeters in length with a breadth one-fifth to one-third as great. In the coarse textures of the granitoid facies these dimensions become more nearly equal, and diameters of 3 to 4 millimeters are often observed. Often the plagioclase presents complete crystal outlines, but very commonly the terminal planes are lacking, the elongated crystals abutting irregularly against each other. They are made up of thin twinning lamellæ, chiefly according to the albite law, but pericline and Carlsbad twinning also occur. Zonal structure is quite commonly developed, and fringing the extreme acid borders a graphic intergrowth of quartz and orthoclase is often found.

Maximum extinction angles in sections normal to the albite twinning plane range a little under 30 degrees, corresponding to acid labradorite. Analyses of feldspars separated by heavy solution have shown that labradorite containing the soda and lime molecules in about equal proportions is the most abundant plagioclase; but other members of the series, present in considerable amount, range to almost pure albite.

Orthoclase and quartz in graphic intergrowth, as noted above, frequently form a fringe about the plagioclases, and fill many of the triangular and irregular interstices. These

* In the examination of several hundred sections of Newark diabase from New Jersey and neighboring states only monoclinic pyroxenes have been observed. It seems highly probable that the hypersthene that has been occasionally reported in these rocks is simply pleochroic augite.

areas are sometimes as much as 3 or 4 millimeters across, and are then distinctly visible in the hand specimen, as in the western portion of the Pennsylvania railroad tunnels at Homestead. Frequently individual grains of quartz, and less commonly of orthoclase, are also observed, attaining in some instances a diameter of 1 millimeter.

Magnetite is always present but in greatly varying amount. Crystals are sometimes observed, but most of it, like the augite, is irregularly clustered between the plagioclases, and sometimes partly incloses both the plagioclase and the augite. The frequent presence of magnetite secondary from the alteration of augite renders it impossible in many cases to distinguish with certainty that of primary origin. It is probable that masses molded about the other constituents are largely composed of secondary accretions.

Biotite is also often present in small amount, and is usually clustered about the magnetite in relatively large irregular flakes. It is strongly pleochroic—deep reddish brown and light yellow. Some secondary biotite, after augite, occurs, but in most cases this is readily distinguished from the primary mineral.

Olivine is absent from the great bulk of the rock. It occurs in small amounts, however, near the contacts with the inclosing strata, and is exceptionally abundant in the olivine-diabase ledge of the Palisades, constituting as much as one-fifth of the whole. In the fine-grained border facies of the rock it occurs in scattering porphyritic crystals, which sometimes exhibit resorption phenomena in rounded and embayed outlines. Corrosion mantles or "reaction rims" of radial enstatite occasionally surround the larger crystals, and nest-like aggregates of it entirely replace some of the smaller ones. In this part of the rock mass the olivine is usually more or less altered into yellowish or brownish serpentine; but in the olivine-diabase ledge it occurs in numerous perfectly fresh crystals and irregular grains. Most of it forms poikilitic inclusions in the feldspars and less abundantly in the augites, and it retains a striking freshness and transparency even in the presence of considerable alteration of the augite.

Apatite is always in well-formed prismatic crystals, ranging from very minute up to 1 millimeter in length and 0.06 millimeter in diameter. It is always abundant in the feldspars and quartz, sometimes in plagioclase, sometimes in the quartz-orthoclase intergrowth, and is rarely seen in the other constituents.

Chemical composition.—From a number of analyses that have been made the following are selected to show the range of composition of typical facies of the rock:

Analyses of Palisade Diabase.

	I	II	III	IV
SiO ₂	60.05	56.78	51.34	49.02
Al ₂ O ₃	11.88	14.33	12.71	10.14
Fe ₂ O ₃	3.22	5.76	2.65	1.54
FeO	10.21	9.27	14.14	10.46
MgO	0.85	1.58	3.66	17.25
CaO	4.76	5.26	7.44	8.29
Na ₂ O	4.04	3.43	2.43	1.59
K ₂ O	2.10	1.75	1.44	0.40
H ₂ O+	0.66	0.10	0.69	0.59
H ₂ O—	0.21	0.33	0.18	0.16
TiO ₂	1.74	1.44	3.47	0.99
P ₂ O ₅	0.52	0.36	0.20	0.11
MnO	0.28	0.25	0.36	0.16
	100.52	100.64	100.71	100.70

I. Pennsylvania R. R. tunnel, Homestead, 400 feet from the west end.

II. Old quarry near R. R. station, Rocky Hill, 420 feet from upper surface of the trap.

III. Pennsylvania R. R. cut 420 feet east of Marion station (Tonnele Ave.), Jersey City.

IV. Englewood Cliffs, on the Palisades, 11 miles north of Jersey City. From the olivine diabase ledge.

I, II, and IV by R. B. Gage, chemist of the Geological Survey of New Jersey; II by A. H. Phillips of Princeton University (this Journal, vol. viii, 1899, p. 267).

In general, alumina, ferric iron, and the alkalis vary with the silica, while ferrous iron, lime, and magnesia vary inversely. Chemically these rocks overlap the andesite-diorite series on the one hand and the most basic olivine-gabbros on the other, and the extremes are characterized by abundant quartz and olivine, respectively.

Classification.—In the older terminology the prominent facies of the Palisade sill would be known as *quartz-diabase*, *diabase*, and *olivine-diabase*, the prefixes quartz and olivine denoting special richness in these minerals. As indicated above, most of the coarse-grained rock, which constitutes by far the greater bulk of the Palisade sill from the Hudson to the Delaware, is decidedly quartzose, this mineral being quite generally present in graphic intergrowth with orthoclase. In the most acid facies micropegmatite constitutes about one-third of the bulk of the rock, but the average is probably somewhat less than one-tenth. On the other hand, the most basic facies contain 15 to 20 per cent of olivine, but this is confined to the relatively small mass of the olivine-diabase ledge. Normal diabase, without quartz or olivine, is much less abundant than

quartz-dabase, and this becomes slightly olivinic near the contacts.

In the quantitative system of Messrs. Cross, Iddings, Pirsson, and Washington the analyses given above would be classified as follows:

- I. Class II. Dosalané
 - Order 4. Quarhofelic, Austrare
 - Rang 2. Domalkalic, Dacase
 - Subrang 4. Dosodic, *Dacose*
- II. Class II. Dosalané
 - Order 4. Quarhofelic, Austrare
 - Rang 3. Alkalicalcic, Tonalase
 - Subrang 4. Dosodic, *Tonalose*
- III. Class III. Salfemane
 - Order 5. Perfelic, Gallare
 - Rang 3. Alkalicalcic, Camptonase
 - Subrang 4. Dosodic, *Camptonose*
- IV. Class IV. Dofemane
 - Order 1. Perpollic, Hungarare
 - Section 2. Dopyric
 - Rang 1. Permirlie
 - Section 2. Domiric
 - Subrang 2. Domagnestic, *Palisadose*

The great bulk of the rock, judging from about a dozen analyses and a large number of thin sections, appears to be of the type represented by the third of the analyses given above, and might be termed a *graphi-ophito- to graphi-grano-camptonose* (III. 5. 3. 4). Notable amounts of the rock, however, belong to the more salic *dacose* (II. 4. 2. 4) and *tonalose* (II. 4. 3. 4) and to the more calcic *auvergnose* (III. 5. 4. 4, 5).

The highly basic ferromagnesian olivine-dabase, of which the fourth analysis above is typical, is a sharply defined facies that may be designated as a *poikili-ophito- to poikili-grano-palisadose*. From the typical development of this rock along the Palisades northward from Jersey City it is proposed that the subrang into which it falls (IV. 1². 1². 2), hitherto unnamed, be designated as *palisadose*.

The relations of these various facies to each other and the problem of their origin are discussed in the report on the petrography of the Newark igneous rocks of New Jersey.* It has already been remarked that the hypothesis of gravitational differentiation seems to account satisfactorily for all the conditions observed.

Composition of the Augite.—Analyses of the augite from this sill at Rocky Hill† and from the very similar intrusive at West Rock, New Haven, Conn.,‡ yielded the following results:

* Annual Report of the State Geologist of New Jersey for 1907.

† A. H. Phillips, loc. cit.

‡ G. H. Hawes, this Journal, vol. ix, p. 185, 1875.

Analyses of Augite from the Palisade Diabase.

	I.	II.	III.	IV.
SiO ₂	47.72	48.54	50.71	47.10
Al ₂ O ₃	3.44	5.50	3.55	4.55
Fe ₂ O ₃	5.93	2.77	n. d.	n. d.
FeO	18.34	21.25	15.30	15.20
MgO	12.89	7.67	13.63	18.65
CaO	11.40	10.97	13.35	11.33
Na ₂ O	0.86			
		3.10	1.48 ¹	n. d.
K ₂ O	0.37			
MnO	n. d.	n. d.	0.81	0.17
Ign.	0.00	0.82	1.17	1.33
Insol.	---	---	---	0.34
	<hr/>	<hr/>	<hr/>	<hr/>
	100.95	100.62	100.00	98.67

¹ By difference.

I. Rocky Hill, N. J. Quarry near the middle of the trap sheet. A. H. Phillips, analyst.

II. Rocky Hill, N. J. Old quarry near the railroad station, about 420 feet from the upper contact. A. H. Phillips, analyst.

III. West Rock, New Haven, Conn. G. W. Hawes, analyst.

IV. Aakeroe, Sweden. Partial analysis of diallage by H. von Post.*

With the exception of small deficiencies in silica in I, II, and IV, these analyses correspond to the following pyroxene molecules in the proportions indicated:

Acmite, $\text{NaFe}(\text{SiO}_3)_2 = \text{ac.}$

Hypersthene, $(\text{Mg,Fe})\text{SiO}_3 = \text{hy.}$

Diopside, $\text{Ca}(\text{Mg,Fe})(\text{SiO}_3)_2 = \text{di.}$

Aluminous molecule, $(\text{Mg,Fe})(\text{Al,Fe})_2\text{SiO}_6 = \text{alm.}$

	ac.	hy.	di.	alm.	
I.	108	: 640	: 816	: 159	=
	1	: 5.93	: 7.56	: 1.47	=
	2	: 12	: 15	: 3	(approx.)
II.	270	: 530	: 784	: 81	=
	3.33	: 6.54	: 9.68	: 1	=
	7	: 13	: 19	: 2	(approx.)
III.	126	: 522	: 956	: 69	=
	1.83	: 7.72	: 13.86	: 1	=
	2	: 8	: 15	: 1	(approx.)
IV.	?†	: 864	: 808	: 135	=
		6.40	: 5.99	: 1	=
		13	: 12	: 2	(approx.)

These formulas indicate a quite exceptional composition for augite in the great excess of ferrous iron and magnesia over lime, alumina, and ferric iron.

* Dana's System of Mineralogy, 6th ed., p. 360.

† Ferric iron and alkalis not determined.

Composition of the Feldspars.—Feldspars were also separated and analyzed from the Rocky Hill material by Phillips and from the West Rock locality by Hawes. Omitting non-feldspathic constituents and assigning the potash to orthoclase, and the soda and lime to albite and anorthite, respectively, the analyses show the following constitution :

<i>Mineral Constitution of the Feldspars.</i>							
	I.	II.	III.	IV.	V.	VI.	VII. VIII.
Sp. gr.	>2.69	<2.69	>2.69	<2.69	<2.60	=2.577	>2.69 <2.69
Orthoclase	7.5	7.7	13.2	12.6	27.4	31.7	6.0 7.2
Albite	47.1	71.3	60.6	70.3	68.9	64.2	24.4 40.9
Anorthite	45.4	21.0	26.2	17.1	3.7	4.1	69.6 51.9
	ab ₁ an ₁	ab ₂ an ₂	ab ₃ an ₂	ab ₆ an ₂	ab ₂₀ an ₁	ab ₁₇ an ₁	ab ₃ an ₈ ab ₅ an ₆

I, II. Rocky Hill. Quarry near the middle of the trap sheet.

III, IV, V, VI. Rocky Hill, N. J. Old quarry near upper contact.

VII, VIII. New Haven, Conn. West Rock.

The plagioclase molecules as calculated range from nearly pure albite to labradorite. It is probable, however, that some of the soda is combined with the potash in orthoclase and anorthoclase. On the other hand, it is also quite possible that small amounts of more basic plagioclases would have been found if the heaviest portions had been further separated before analysis. The frequent occurrence of zonal structure in the plagioclases, however, seems to indicate that these minerals do not occur in individualized grains of uniform composition, but have been built up into composite crystals of successively more acidic and more sodic character. In the instances determined the portion with the highest specific gravity constituted more than half the total feldspars, so that the labradorite molecule undoubtedly predominates.

Metamorphic effects.—Contact metamorphism has produced an elaborate series of hornfels, rocks characterized by various combinations of feldspar, biotite, quartz, augite, hornblende, tremolite, garnet, spinel, magnetite, muscovite, cordierite, scapolite, vesuvianite, sillimanite, andalusite, chlorite, calcite, analcite, titanite, tourmaline, zircon, apatite, and possibly leucite. The various types within the zone of metamorphism seem to vary with the original composition of the shales, and not to depend on relative distances from the contact nor degree of metamorphism.

Metamorphic arkose, both in the inclusions and at the contacts, contains besides the usual plagioclase, orthoclase, and some quartz, also augite, biotite, epidote, cordierite, chlorite, calcite, tourmaline, and apatite.

The contact metamorphic effects of the sill at Hoboken, New Jersey, have been described by Andreae and Osann,* who show that it is of exomorphic pneumatolytic character. To the four types of hornfels which they describe, J. D. Irving† has added five others, and the present studies, in which no attempt has been made to present a complete series of alteration products, have brought out eight additional types of hornfels and four of metamorphic arkose. These might be extended almost indefinitely, since they do not occur as sharply defined types, but present various degrees of gradation from one to another. Furthermore, they do not form zones or belts in any systematic order with relation to the intrusive rock, but alternate irregularly throughout all parts of the zone of metamorphism. It is evident, therefore, that the types observed are not the results of varying degrees of metamorphism, but are dependent only on original variations in the composition of the shales and sandstones themselves.‡

* Andreae and Osann, *Tiefen contacte an intrusiven Diabasen von New Jersey*; Verh. d. Naturh. Med. Ver. zu Heidelberg. N. F. V., Bd. I, 1892.

† *School of Mines Quarterly*, vol. xx, pp. 213-223, 1899.

‡ For descriptions of these rocks, and of other igneous rocks besides the great intrusive sill, see "Petrography of the Newark Igneous Rocks of New Jersey," Ann. Report of the State Geologist of New Jersey for 1907, pp. 98-169.