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THE SPILITE AND MANGANESE PROBLEMS OF THE OLYMPIC PENINSULA, WASHINGTON.[1]

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ABSTRACT. The broad zone of volcanic rocks that borders the northern, eastern, and southern parts of the Olympic Peninsula, Washington, contains numerous spilitic flows, thin layers of associated limy red rocks, manganese deposits, and jasper.

Agitation of the sea water during submarine extrusion caused a precipitation of calcium carbonate. The resulting limestones, mixed with fine-grained volcanic debris, are the present-day "red rocks."

Evidence is advanced to show that during periods of rapid extrusion in deep water, the sea water in the underlying sedimentary beds was trapped and heated. The fragmental volcanics chilled quickly and permitted rapid escape of the fluids, but the thicker flows tended to retain the heat, and were subjected to a continuous stream of escaping gases. The original constituents of the lavas were decomposed, albite and later zeolites were deposited in their place, and silica, lime, iron, magnesium, and manganese were carried upward. On reaching the limy accumulations near the tops of the flows, the materials in the fluids were left as replacement deposits, or, where the conduits broke through to the sea floor, they were deposited as part of the accumulating sediments.

Introduction

THE Olympic Peninsula, in the northwestern part of the State of Washington, is a rugged and difficult terrain, on the lower slopes of which is a dense growth of vegetation. Timber line is generally at about 5,000 feet elevation or lower, and the bare high peaks offer ideal exposures.

Published geologic work in the area has been based on reconnaissance mapping, mostly around the borders of the mountains and in the valleys of the larger streams.[2] In 1938

[1] Published with the permission of the Director, Geological Survey, U. S. Dept. of Interior.

[2] Weaver, C. E. 1922, Tertiary stratigraphy of Western Washington and Northwestern Oregon: Univ. of Washington publications in Geology, **4**.

————: 1944, Correlation of the marine Cenozoic formations of North America: Geol. Soc. Amer. Bull. 55, 595-596.

the Geological Survey began an investigation of the manganese deposits previously described by Pardee and others.[3] Field work was carried on for three seasons and this paper is a by-product of the study. Many geologists have helped in the work, and suggestions offered by Harold L. James, John A. Straczek, Wallace M. Cady, James R. Balsley, Jr., Robert G. Yates, John M. Nelson, Ralph J. Roberts, Earl Ingerson, and D. F. Hewett have been particularly helpful. S. L. Glover, who has spent several seasons mapping the west coast of the Peninsula and is thoroughly familiar with the area, has discussed parts of the problem, and has particularly called attention to isolated patches of basalt.[4] W. S. Burbank, R. S. Cannon, Jr., Aaron Waters, the late Stephen St. John, and Michael Fleischer have read the manuscript and have offered helpful ideas, particularly relating to the mechanism by which albitization could be accomplished by sea water.

General Geology.

STRATIGRAPHY.

The oldest rocks of the Olympic Peninsula are closely folded and partly crystallized argillites, graywackes, schists, and quartzites. No diagnostic fossils have been found in them, but from their position below known Eocene beds the rocks are considered to be basal Tertiary or Cretaceous in age.[5] Walter Warren has recently reported the finding of fossils of Eocene or possibly Oligocene age on Mt. Appleton, in the interior of the Peninsula.[6] Around the northern, eastern, and southern

[3] Pardee, J. T.: 1927, Manganese-bearing deposits near Lake Crescent and Humptulips, Washington: U. S. Geol. Survey Bull. 795A, 16-20.

———: 1922, Deposits of manganese ore in Montana, Utah, Oregon, and Washington: U. S. Geol. Survey Bull. 725C, 236.

———, Larsen, E. S., and Steiger, George: 1921, Bementite and neotocite from western Washington, with conclusions as to the identity of bementite and caryopilite: Jour. Wash. Acad. Sci., **11**, 25-32.

Arnold, Ralph: 1909, Notes on some rocks from the Sawtooth Range of the Olympic Mountains, Washington: Amer. Jour. Sci., 4th Ser., **28**, 9-14.

Hodge, E. T.: 1938, Preliminary report on some northwest manganese deposits: U. S. Army, Corps of Engineers, Portland, Oregon, 28-68.

[4] Glover, S. L.: 1940, New data on the distribution of igneous rocks in the Olympic Peninsula, Washington: abstract, Geol. Soc. Amer., joint program with Amer. Assoc. Adv. Sci., p. 15.

[5] Weaver, C. E.: 1937, Tertiary stratigraphy of Western Washington and Northwestern Oregon: Univ. of Washington publications in Geology, **4**, 22.

[6] Warren, Walter: 1940, personal communication.

borders of the Peninsula, and apparently conformable with the older rocks are at least 30,000 feet of argillites, graywackes, volcanic rocks, and limestones of early-middle Eocene age

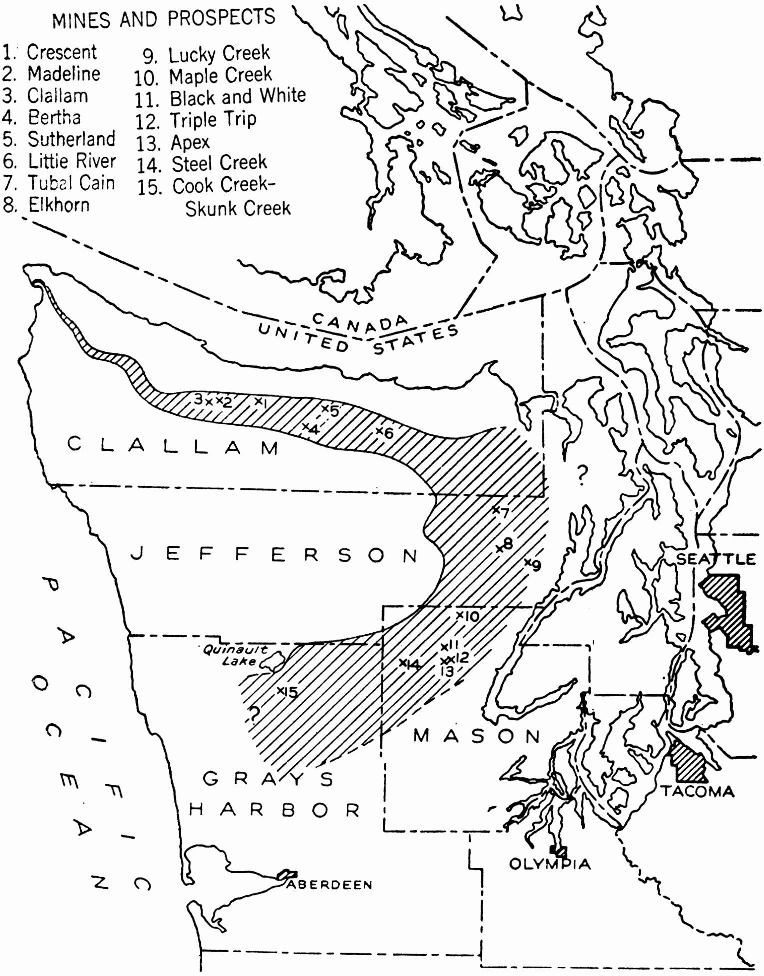

Figure 1.— Index map of the Olympic Peninsula, Washington. Ruled area shows belt of volcanic rocks and associated sedimentary beds in which the spilites and the manganese deposits are known.

(Fig. 1). Above these are the shales, sandstones, conglomerates, and volcanics of younger Tertiary age. This paper is primarily concerned with the early-middle Eocene volcanic rocks and associated sediments.

VOLCANIC ROCKS OF EARLY-MIDDLE EOCENE AGE.

The volcanic materials are chiefly very resistant lavas (Fig. 2), and agglomerates interlayered with softer tuffs, agglomerates, and sedimentary beds. Many of the flows are properly designated as spilites. They are albite-rich amygdaloids in which pillow structures are abundantly developed. Pillows are found throughout the flows, but are particularly well formed in the lower parts of the section. At places, such as Mt. Constance, the pillow lavas have accumulated in tremendous piles, where they stand nearly vertical, and are measurable across the strike in thousands of feet (Fig. 3). Many flows, particularly in the upper parts of the section, are massive and locally contain unaltered labradorite feldspar. Agglomerates and tuffs are also abundant and form the intermediate members in the gradational series argillites-tuffs-agglomerates-flows. Diabase is found locally, either in the interior of thick flows or as sills.

Pillow lavas are considered generally to be of submarine origin,[7] though in places they may be subaerial.[8] In the Olympic Mountains many of the pillow flows are interlayered and interfingered with water-sorted argillites and graywackes. Siliceous red limestones and argillites also accompany the spilites. Globigerina are commonly found in the so-called red rocks, and sharks' teeth have been found at three widely separated localities in glassy seams in the lava or in volcanic debris near the flows. The pillow lavas are of submarine origin, and, judged by the fossils found in associated tuffs, were probably extruded under a considerable depth of water. The massive basalts may or may not be submarine flows. They are generally emplaced in such a way that their origin is obscure, but at least in part they are probably submarine.

The volcanic rocks form essentially a steeply dipping or overturned monocline that extends around the northern, eastern, and southern side of the Peninsula. On the western slope, where the geology is poorly known, the Eocene and older materials may possibly be overlain unconformably by younger rocks.[9]

[7] Anderson, Tempest: 1910, The volcano of Matavanu in Savaii: Quart. Jour. Geol. Soc., 66, 631-633.

Fuller, R. E.: 1940, personal communication.

[8] Lewis, J. V.: 1914, Origin of pillow lavas: Geol. Soc. Amer., Bull. 25, 591-654.

[9] Warren, Walter: 1941, personal communication.

In the upper parts of the volcanic rocks, the dips flatten, and in few places are the dips of the Oligocene and younger beds greater than 30°. Strike faulting in the volcanics is common, though the amount of movement is unknown. This type of faulting is best developed along the contacts of massive rigid flows with the less competent, complexly distorted sedimentary beds. Faulting transverse to the bedding is generally minor, though at least a few breaks that have displacements of several hundred feet or more are present. Transverse faults are difficult to follow as they swing into the bedding and are lost in the incompetent layers. The rocks become increasingly more deformed and crystalline towards the center of the Peninsula.

Red Rocks.

Limestones and argillites, which are associated only with the spilites, agglomerates, and tuffs, form a very small part of the thick accumulation of volcanic materials, but they are of special interest because they are the usual host rocks for the manganiferous bodies. They are dominantly red, and for that reason are referred to as "red rocks," though locally they are chocolate-colored or light greenish. The red color may be bleached to a grayish or greenish at lava contacts, though elsewhere the red color is confined to thin borders next to the lava. The red rocks are principally siliceous limestones which are intimately associated with and grade into limy argillites and tuffs. In many places they contain irregularly shaped pockets and masses of jasper. They are usually in irregular and disconnected bodies from the size of small fragments up to 25 or more feet across. Some of the red rocks are in fairly persistent beds, generally 10 feet thick or less (Fig. 4), although a few layers are 50 feet thick and one as much as 300 feet thick is known.

The red rocks appear to be most abundant at the tops of flows. In places they are within flows, in part filling the interspaces between pillows, and in places they are around the borders of flows and below flows. The red rocks form the matrix of the agglomerates in places, and fragments of them are found in the agglomerates, and locally even form cores in pillows. Many fragments of red rocks, ranging in size from small chips to blocks 30 feet or more across, are engulfed in the lavas. The contacts between the fragments and the lavas are tight and the bedding in the fragments is molded somewhat to the borders of the block.

The tops of normal basalt flows are commonly red, a character caused by the presence of finely divided hematite.[10] The red color is also a feature of many argillaceous and limy rocks accompanying spilites,[11] and in places the spilitic lavas themselves are dull reddish or purplish. In the spilitic flows of the Olympic Peninsula the borders of many of the pillows are red to a depth of about 3 inches, and the centers of the pillows are green. Sundius[12] has called attention to the abundance of the oxides hematite and magnetite in spilites, and, in the Olympic Peninsula, hausmannite is in a few places intimately associated with the other oxides.

The red rocks contain poorly preserved globigerina tests,[13] but no other fossils have been found in them. Globigerina are floating forms and are not diagnostic of temperature or other conditions of deposition; the tests sink wherever the organism happens to die. Radiolarian cherts are reported to occur with spilites in many areas. To quote Dewey and Flett, "That pillow lavas are usually accompanied by radiolarian cherts is now a well established fact."[14]

Origin of the red rocks. Red rocks are not generally concentrated near the bases of flows, as would be expected if the lavas were poured out on limy muds. Locally the red rocks are abundant at the tops of flows and might be marine sediments deposited on the flows. This relationship will not explain, however, the sporadic distribution of limestone through thick flows,

[10] Broderick, T. M.: 1935, Differentiation in lavas of the Michigan Keweenawan: Geol. Soc. Amer., Bull. 46, 505.

[11] Teall, J. J. H.: 1899, The Silurian rocks of Great Britain, vol. 1, Scotland: Memoir, Geol. Survey Great Britain, p. 85

Benson, W. N.: 1913, The geology and petrology of the great serpentine belt of New South Wales: Proc. Linnean Soc., N. S. W., 38, 496-497.

[12] Sundius, N.: 1930, On the spilitic rocks: Geol. Mag., 67, p. 1.

[13] Pardee, J. T.: 1922, Deposits of manganese ore in Montana, Utah, Oregon, and Washington: U. S. Geol. Survey, Bull. 725C, p. 232.

[14] Dewey, H., and Flett, J. S.: 1911, Some British pillow lavas and the rocks associated with them: Geol. Mag., 8, 202-209; 241-248.

Teall, J. J. H.: 1894, On greenstones associated with radiolarian cherts: Royal Geog. Soc. Cornwall, p. 3.

Taliaferro, N. L., and Hudson, F. S.: 1943, Genesis of the manganese deposits of the Coast Ranges of California: Calif. State Div. of Mines, Bull. 125, 225; 259-260.

Taliaferro, N. L.: 1943, Manganese deposits of the Sierra Nevada, their genesis and metamorphism: Calif. State Div. of Mines, Bull. 125, 321.

and settling through cracks and other openings likewise is inadequate. The explanation that seems best to account for the distribution and character of the red rocks is that they are finely divided volcanic debris and chemical precipitates, deposited during submarine extrusion and fumarolic activity. Limestone would be deposited through the release of CO_2 from bicarbonate in the sea water by agitation and possibly by slight rise in temperature.[15] Limestone formed in such a manner would be impure, as it would be mixed with volcanic muds and debris (Table I). The hematite is thought to have been formed by alteration of the iron-bearing minerals in the basalts and to have been present in considerable quantity.

The thickness of the limestone layers is not directly proportional to the size of the flows, though in general the thicker limestones are with the thicker flows. The sporadic thick limestones may have resulted from long continued agitation caused by the escape of fluids. Locally convection and other currents brought new supplies of sea water to the place of activity and thus speeded the accumulation.

It may be suggested here that large quantities of calcium were set free during albitization of the basalts. This calcium was a potential source of considerable limestone.

MANGANESE DEPOSITS.

The manganese minerals are an unusual suite. They include hausmannite (Mn_3O_4), rhodonite ($MnSiO_3$), the complex silicates bementite, neotocite, tephroite(?) manganophyllite, inesite, piedmontite, and probably others, and the carbonates rhodocrosite and manganiferous calcite. Irregular bodies of these minerals are associates of the red rocks, which they vein and replace. The deposits are usually small irregular lenses and pockets, though a few larger and more persistent tabular bodies, such as those of the Crescent mine, are found. The silicates generally accompany larger jasper or siliceous masses, but the hausmannite and carbonates are commonly in the unsilicified red rocks. In a very few places pockets of manganese silicates replace the tops of spilitic flows, where no red rocks are present. All of the manganese deposits seen are asso-

[15] Kania, J. E. A.: 1929, Precipitation of limestone by submarine vents, fumaroles, and lava flows: Amer. Jour. Sci., (5) 18, 347-359.

ciated with the spilites and are generally in the red rocks near the flows.[16]

TABLE I.

Partial analyses of red limestones and argillites.

	1	2	3	4	5	6	7	8
Insol. in HNO_3	32.07	42.33	61.70	57.63	21.09	26.05	27.73	....
CaO	35.30	28.28	13.24	19.38	36.94	36.78	36.18	31.70
MgO	0.56	1.48	3.00	1.90	0.82	0.76	1.04	3.03
MnO	0.90	1.11	0.96	0.23	0.39	0.99	2.82	8.52
FeO	0.42	0.90	1.25	0.92	3.05	1.79	0.34	....
CO_2 calc.	29.11	25.02	15.02	18.00	32.01	31.40	31.50	24.42
							SiO_2	11.53
							Al_2O_3	6.18
							Fe_2O_3	7.95
							TiO_2	0.60
							P_2O_5	0.40
Acid insol. contains								
MnO	0.28	0.02	0.14	tr.	tr.	0.08	2.13	
Fe_2O_3	....	....	....	....	....	....	....	10.65

1. Elev. 1500. Trail to Apex prospect from Lake Cushman. Analyst, R. E. Stevens.
2. Elev. 1950. Elkhorn prospect, Dosewallips River. Analyst, R. E. Stevens.
3. Elev. 1900. Northeast wall, Crescent mine open cut. Analyst, R. E. Stevens.
4. Blue Mountain fire lookout. Analyst, R. E. Stevens.
5. Elev. 1250. Lake Crescent, ½ mile north of Thompson Point. Analyst, R. E. Stevens.
6. Road cut, 1.2 miles south of Slab Creek guard station. Analyst, R. E. Stevens.
7. Elev. 4250. East layer of limestone on north Copper Mountain. Analyst, R. E. Stevens.
8. Lake Crescent, Wash. Analyst, J. G. Fairchild. Quoted by J. T. Pardee, U. S. G. S. Bull 795-A, p. 7, 1927.

Many of the lava flows, particularly near the manganese silicate lenses, are stained black by supergene manganese oxides. This feature may perhaps be the basis for the commonly made statement that tremendous bodies of manganese ores occur in the Olympic Mountains.

The origin of the manganese deposits presents an interesting problem. Pardee suggested that the manganese deposits resulted from regional metamorphism, and that the manganese

[16] Park, C. F., Jr.: 1942, Manganese resources of the Olympic Peninsula, Washington: U. S. Geol. Survey Bull. 931R.
Greene, S. R.: 1945, Manganese deposits of the Olympic Peninsula, Washington: Wash. Div. of Mines and Mining, Rept. Investigations No. 7.

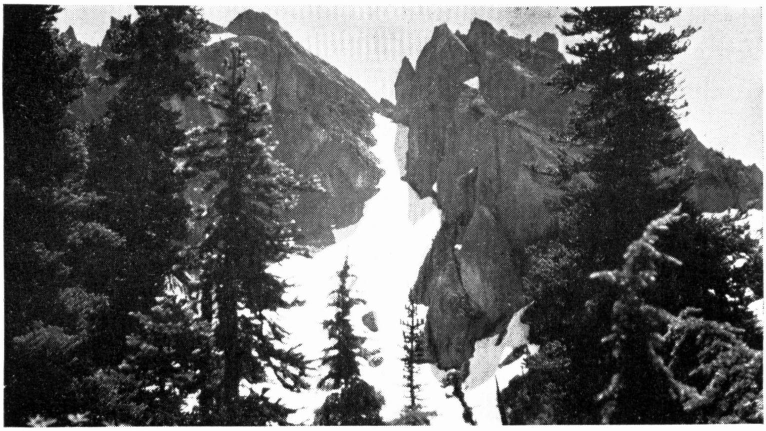

Figure 2. Sawtooth Mountain from Mt. Gladys. The ridge is resistant lavas, the valley in the foreground is underlain by tuffaceous sedimentary beds.

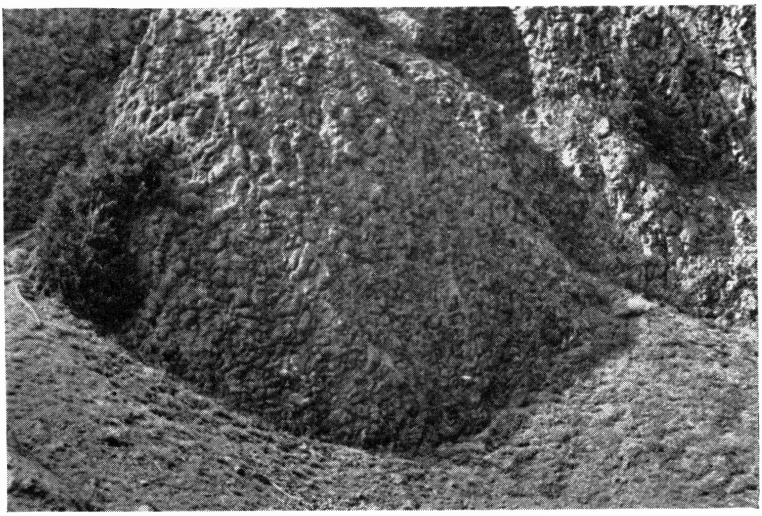

Figure 3. Flow of pillow lavas. Mt. Constance.

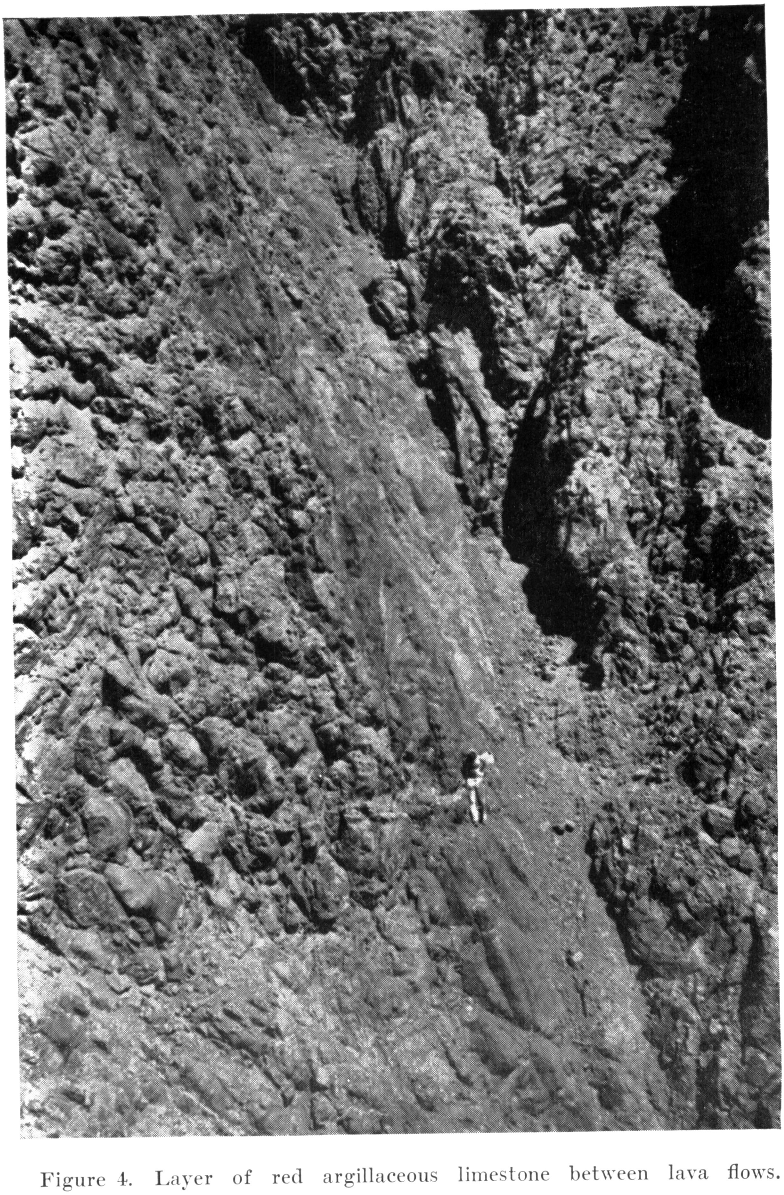

Figure 4. Layer of red argillaceous limestone between lava flows. Tubal Cain prospect.

originated as manganiferous marine sediments, presumably the red rocks.[17] Hodge suggested that: "Solutions, possibly of magmatic origin, leached manganese from the basalts, along with a little copper, and precipitated it in the limestones and in gouge zones in the basalt.[18] Hewett is inclined to stress the influence of hydrothermal solutions on manganese-bearing sediments.[19] The writer thinks that the manganese was a normal constituent of the basalt, that during spilitization the ferromagnesian minerals were broken down, and that the manganese, with other constituents, migrated to the tops of the flows where they were deposited. This process will be discussed further in the following pages.

JASPER DEPOSITS.

Fine-grained silica, and particularly red jasper, is abundant in the red rocks, in the manganese silicates, and in the spilites, where it is in interspaces among the pillows, in veinlets concentrated in the outer part of pillows, and, in a few places, is in nodular cores of pillows. The jasper in all of the rocks is similar and single bodies replace both red rocks and lavas. Jasper is intimately associated with small amounts of manganese silicates, particularly neotocite and bementite. Jasper was probably deposited after much but not all of the manganese, as it veins manganese silicates and forms borders around manganese nodules. Both jasper and manganese silicates vein albite, and in turn are veined by later zeolites. Jasper is abundantly deposited with spilitic submarine flows throughout the world, and is generally considered to be a syngenetic sediment, transported by warm waters associated with the flows.[20]

[17] Pardee, J. T.: 1922, Deposits of manganese ore in Montana, Utah, Oregon, and Washington: U. S. Geol. Survey Bull. 725C, 236.

[18] Hodge, E. T.: 1938, Preliminary report on some Northwest manganese deposits: U. S. Army, Corps of Engineers, Portland, Oregon, 38-45.

[19] Hewett, D. F.: 1941, personal communication.

[20] Lawson, A. C.: 1895, Sketch of the geology of the San Francisco Peninsula: 15th Ann. Rept., U. S. Geol. Survey, 420-426.

Van Hise, C. R., and Leith, C. K.: 1911, Geology of the Lake Superior Region: U. S. Geol. Survey, Mon. 52, 506-510.

Lawson, A. C.: 1914, San Francisco Folio (No. 193), U. S. Geol. Survey Atlas.

Davis, E. F.: 1918, Radiolarian cherts of the Franciscan group; Calif. Univ. Dept. Geol. Sci., Bull. 11, 235-432.

Taliaferro, N. L., and Hudson, F. S.: op. cit., 225-234.

In the Olympic Peninsula part of the silica in the sediments may have been dissolved, and, along with the silica from the basalts, formed the jasper. White quartz veinlets, in a few places containing epidote, cut both the basalts and the sedimentary beds. These quartz veinlets are thought to be later than the jasper and the other alteration products.

ALTERATION OF THE LAVAS.

CHARACTER.

The alteration of the lavas is similar to that characteristic of spilites throughout the world, though zeolites seem to be more abundant in the Olympic rocks than in most other areas. The rocks might well be called greenstones, and they have most of the outward appearances that this overworked term connotes. The feldspars, originally labradorite, are largely changed to albite. Jasper, hematite, calcite, and chlorite are common, and manganese silicates and hausmannite are widely distributed. Olivine is not found in the albitized pillow lavas, but fresh grains are present in a few quickly chilled and locally glassy tuffs and agglomerates. Most pyroxenes are highly altered, though in a few sections pyroxene is surprisingly fresh. In the extremely altered lavas, iron and manganese minerals have been partly removed and the rock is changed to an aggregate of albite, zeolites, quartz, and calcite. Samples of comparatively fresh diabasic basalt, slightly altered basalt, and intensely altered basalt were analysed in the Geological Survey laboratory, with the result given below (Table II). If the Na_2O in sample No. 3 is computed to albite, it (albite) makes up about 68.5 per cent of the rock. Most of the other constituents are in "chlorite" with a little free silica. As in other areas of spilites, the alteration is pre-deformation.[21] In the Olympic Peninsula albitized rocks, manganese minerals and other alteration products were crushed in fault selvage. Faulting and deformation that are post-manganese deposition are indicated

[21] Sundius, N.: 1930, On the spilitic rocks: Geol. Mag., 67, 5.
Greenly, E.: 1919, Geology of Anglesey: Memoir Geol. Survey Great Britain, 1, 71-75.

TABLE II.

	1	2	3	4	5
SiO_2	48.93	50.91	63.61	51.22	46.01
Al_2O_3	16.69	14.28	18.29	13.66	15.21
Fe_2O_3	1.43	1.87	1.68	2.84	1.35
FeO	6.34	8.66	3.33	9.20	8.69
MgO	8.35	5.84	1.06	4.55	4.18
CaO	10.28	9.42	0.96	6.89	8.64
Na_2O	3.02	3.45	8.14	4.93	4.97
K_2O	0.56	0.58	0.73	0.75	0.34
H_2O-	0.18	1.01	0.12	....	....
H_2O+	2.88	1.79	1.24	1.88	2.48
TiO_2	1.05	1.20	0.60	3.32	2.21
ZrO_2	....	....	0.01	....	....
CO_2	....	0.05	none	0.94	4.98
P_2O_5	none	0.08	0.03	0.29	0.61
SO_3	....	0.23	none	....	....
F	....	....	none	....	....
S	....	....	none	....	....
Cr_2O_3	....	0.03	none	....	....
V_2O_3	....	0.08	0.005	....	....
NiO	0.0008	0.004	0.003	....	....
MnO	0.18	0.23	0.13	0.25	0.33
BaO	0.13	0.01	0.01	....	....
WO_3	....	....	none	....	....
MoO_3	....	....	none	....	....
Total	100.02	99.72	99.94	100.72	100.00
Sp. Gr.	2.91	2.99	2.69	....	....

1. Diabasic basalt, south wall Ella Lode, Little River district, Olympic Peninsula, Washington. Analyst, Michael Fleischer.
2. Slightly altered basalt. Elev. 1350. Kloshi Naniche Lookout road, Olympic Peninsula, Washington. Analyst, J. M. Axelrod.
3. Albitized porphyritic basalt. Elev. 1500 feet, south face of Mt. Bretherton, Olympic Peninsula, Washington. Analyst, F. S. Grimaldi.
4. Average spilite according to Sundius, Geol. Mag. vol. 67, p. 9, 1930.
5. Average spilite according to A. K. Wells, Geol. Mag. vol. 60, p. 69, 1923.

at many of the properties, typical of which is the Crescent (Fig. 5).[22] The alteration products may be related to local and minor structural features, such as solution channels and volcanic structures, but seem to be independent of any regional structural control.

From its optical properties and from analysis No. 3 given above, the albite appears to be nearly pure $NaAlSi_3O_8$. Labradorite is the feldspar in the unaltered lava. Relationships between the two feldspars are generally obscure, but in a few

[22] Pardee, J. T.; 1927, Manganese-bearing deposits near Lake Crescent and Humptulips, Washington: U. S. Geol. Survey Bull. 795A, 16-20.

places albite forms vague borders around dusty labradorite(?) cores. Albite is certainly secondary where it veins and embays pyroxene and glassy groundmass. Most, or possibly all of the albite is considered to be secondary.

Manganese minerals replace the red rocks, as shown by transected bedding and preserved structures and textures, and a few globigerina. Deposits of manganese are found in a few places in the lavas, and in at least three flows pillows are replaced by manganese minerals and the pillow structure remains. Manganese silicates are generally associated with bright red jasper and cryptocrystalline quartz, and are widely distributed in small amount in interpillow filling.

Associated with the manganese minerals is a little native copper and very small amounts of barite, chalcocite, chalcopyrite, and cinnabar. These materials may have been introduced into the flows by normal magmatic processes, and were probably reworked during the formation of the manganese deposits. A small amount of native copper is widely distributed through the basalts, but this type of occurrence is known in many places and presents nothing unusual.

Laumontite is locally abundant in both the red rocks and the spilites, and small amounts of analcite and prehnite are present as well as other zeolites not yet identified with certainty. Laumontite cuts the other alteration products and is one of the last minerals to form. Geijer[23] comments on the lack of zeolites in many spilites, but zeolites are abundant in the Olympic Peninsula and are known from other areas of spilites.[24]

Calcite is in veinlets throughout the rocks and is in amygdules in spilites. Much calcite is a late alteration product, but it has formed apparently throughout the process of alteration and its value in a study of the genesis is questionable. In many places calcite contains small amounts of iron and manganese, and black calcite, similar to material from New Mexico and Arizona, is found. This black calcite contains microscopic radiating clusters of manganese oxide needles which give a homogeneous black appearance to the mineral. Somewhat simi-

[23] Geijer, P.: 1916, Notes on albitization and the magnetite-syenite-porphyries: Geol. Fören, Förhandl., Bd. 38, 243-264.

[24] Clapp, C. H.: 1917, Sooke and Duncan Map-area. Vancouver Island: Geol. Survey, Canada, Memoir 96, 261-262.

Balsillie, D.: 1932, The Ballantrae igneous complex, S. Ayrshire: Geol. Mag., 69, 107-130.

lar brownish calcite contains clusters of brownish bementite(?) needles.

DISTRIBUTION.

With one very poorly exposed exception, the red rocks are everywhere in or next to spilites, and the manganese deposits are found only in the red rocks and spilites, particularly near the tops of flows. Where red rocks, jasper, and manganese silicates are present, the nearby volcanic rocks contain albite and zeolites, and, conversely, many of the albitized lavas are associated with the red rocks, jasper, and manganese silicates. The co-distribution of spilites, red rocks, and manganese deposits through several miles of section and for over 150 miles along the strike is not chance (Fig. 1). The lavas, red rocks, and manganese minerals at any one locality are similar to those at other places, either along or across the strike, and the close association of the materials argues for a common genetic process.[25] The distribution can best be explained by considering the associated products to have resulted from the alteration of the flows, or, possibly, to have been introduced by solutions that accompanied the flows at the time of their formation.

DISCUSSION OF THE ALTERATION.

Albitization is commonly explained as the result of action of soda-rich magmas[26] or of late hydrothermal magmatic solutions[27] on pre-existing rocks, and the evidence in many spilitic

[25] Taliaferro, N. L., and Hudson, F. S., op. cit., 226-227; 272-274.
————: op. cit., 330-331.

[26] Goldschmidt, V. M.: 1922, Stammestypen der Eruptivgesteine: Vidensk. Skr. Mat. Naturwiss, Klasse I, No. 10.
Hatch, F. H., and Wells, A. K.: 1937, The petrology of the igneous rocks, 220.

[27] Knopf, A.: 1912, The Eagle River region, Southeastern Alaska: U. S. Geol. Survey, Bull. 502, 36.
————: 1924, Geology and ore deposits of the Rochester district, Nevada: U. S. Geol. Survey Bull. 762, 20; 22.
Sundius, N.: 1930, On the spilitic rocks: Geol. Mag., 67, 1-17.
Gilluly, James: 1935, Keratophyres of eastern Oregon and the spilite problem: Amer. Jour. Sci., (5) 29, 225-252; 336-352.
Kato, T.: 1931, Mineralization sequence in the formation of the gold-silver veins of the Toi mine: Jap. Jour. Geol. Geog., 9, 7-86.
Balsillie, D.: 1932, The Ballantrae igneous complex, S. Ayrshire: Geol. Mag., 69, 125.
Nolan, T. B.: 1936, The Tuscarora mining district, Elko County, Nevada: Univ. Nevada Bull. 30, No. 1, 24-28.
Odman, O. H.: 1939, Uebergs geologiska undersökningar inom norrböttens län: Sver. Geol. Unders. Arsbok 33, No. 6, 29-38.
Chumakov, A. A.: 1940, Origin of sodium in spilites: Bull. Acad. Sci., U. S. S. R., Ser. Geol. No. 2, 40-43

flows and mining districts is convincing. A few geologists have suggested that albitization can result from the reaction of submarine basalts and sea water,[28] possibly in part resurgent[29] and aided by such solutions and volatiles as would normally be present in basaltic magmas (about 1.6—4.0 per cent water).[30]

Albitization by the reaction of sea waters and basalt has not been widely accepted, partly because some albitized basalts are not submarine, partly because some submarine basalts are not albitized, partly because of physical-chemical reasons such as rapid cooling of the basalt in contact with sea water, lack of proof of bulk changes in composition, and the lack of demonstration of a mechanism by which soda could be introduced.

The physical conditions set up by the extrusion of lava on the sea floor are not simple, and in general must be highly variable from place to place. A thin flow of lava can be expected to subdivide rapidly into pillows, the molten rock would chill quickly on contact with sea water, and the thermal agitation in the water would subside rapidly. Inter-flow fumarolic activity would be at a minimum, and because of rapid congealing, most of the gases in the flow would probably be trapped in the glassy lava itself. If the flow covered unconsolidated sediments, some heated connate water might be expected to rise from these sediments, but, due to rapid chilling of the flow, the volume of heated waters would be small and the amount of alteration resulting from it would be negligible. Thermal agitation of the open sea water above the flow might result in the deposition of a little limestone and volcanic debris, but the volume of such sediment would not be great.

On the other hand, in the Columbia River Plateau and in other areas of plateau lavas, there is abundant evidence that locally large volumes of lava were extruded in very short periods of time. At a number of localities it can be demonstrated that flows were poured out so rapidly that one flow covered another

[28] Beskow, G.: 1927, Södra Stortjället im sudlichen Lappland: Sver. Geol. Undersökn, Arsbok 21, Ser. C, No. 35, 287-289, 1929.

Clapp, C. H.: 1927, Sooke and Duncan May-areas, Vancouver Island: Canada Dept. Mines, Geol. Survey, Memoir 96, 270.

[29] Daly, R. A.: 1914, Igneous rocks and their origin: 339-340.

————: 1933, Igneous rocks and the depths of the earth: McGraw Hill Book Co., N. Y., 419-421.

[30] Daly, R. A.: loc. cit., p. 17.

Gilluly, James: 1937, The water content of magmas: Amer. Jour. Sci., 33, 441.

before the central part of the first flow was solid. In the Columbia Plateau such rapid extrusion of the lava sequence is indicated by joints and other openings filled with frothy red scoria which originated in the central parts of flows and filtered upward along the joints through the top of the flow and into fractures in the flow above, and also by spiracles (gas vents) that originate in the interiors of thick flows and have been observed to pass upward through as many as three overlying flows.[31]

On the sea floor rapid accumulation of lava in volumes equivalent to the subaerial extrusions just cited must necessarily result in very different thermal conditions than those occurring during the extrusion of a thin flow. The first lava would subdivide into pillows that almost as quickly as they were formed would be covered by new outpourings of lava. Thermal agitation in the open sea water above would be both increased and prolonged by the large volume of lava and by the consequently greater amount of fumarolic activity. As a result, deposition of limestone and volcanic debris would occur much more rapidly and in greater volume than with a thin flow. During extrusion such deposits would be likely to be broken up and partially or completely engulfed by renewed outpourings of lava, or merely by superficial agitation of the steam-charged pile of pillows immediately beneath. Upon cessation of lava extrusion, however, the lava pile would doubtless be covered rapidly by a relatively thick accumulation of limestone and finely divided volcanic debris. Beneath this cap of newly deposited limestone the physical conditions within the pile of pillows would be very different than in the thin flow previously described. The large pile would retain considerable heat. Protected from the chilling effect of the open sea water by the overlying newly deposited blanket of limestone, the interiors of the pillows might remain molten for long periods of time. Between the pillows steam or heated aqueous solutions derived in large part from sea water trapped in the interspace between the pillows or distilled from the underlying muds would circulate freely. Primary gases escaping from the crystallizing lava would mingle with the heated aqueous solutions between the pillows, and the heat of crystallization of the lava would furnish enough thermal energy to prevent the system from cooling

[31] Waters, A. C.: 1945, personal communication.

off rapidly. The hot pillows would therefore be subjected to the stewing action of these heated aqueous fluids for considerable periods of time. Under these conditions it has been demonstrated experimentally by Eskola, Vuoristo, and Rankama.[32] that anorthite is changed to albite-rich plagioclase. The Finnish authors state: "Anorthite heated under water vapor pressure with soda and silica, either in the form of quartz or of an orthosilicate with an excess of CO_2 . . . was changed into albite-rich plagioclase." Best results were obtained between 310°–330° C., but albite formed from 264° to 331° C. Calcite or dolomite formed in experiments where CO_2 pressure was low. "Apparently the spilite reaction is due to the mass action of the sodium ions in the presence of free silicic acid."

The equation given in the Finnish paper is reproduced below:

$$Na_2CO_3+CaAl_2Si_2O_8+4SiO_2 \rightarrow CaCO_3+2NaAlSi_3O_8$$

The speculation that sodium ion, derived from the trapped and heated sea water, may be substituted for Na_2CO_3 seems to be a reasonable one, and a possible equation is:

$$2Na^{+}+CaAl_2Si_2O_8+4SiO_2 \rightarrow Ca^{++}+2NaAlSi_3O_8$$

The temperature of 300° C. suggested in the experiments, and the necessary pressure, could readily be obtained in nature under the conditions pictured. The time factor should be considered, as the reaction might proceed slowly at lower temperatures. The trapped sea water constitutes an ample source of sodium.

In addition to the transformation of labradorite to albite, many other reactions would be expected, among them the solution of the ferromagnesian constituents of the rock, including manganese, and the enrichment of the solutions in silica by the dissolving of silica directly from the muds, and more particularly as a result of the decomposition of the ferromagnesian and other silicate minerals. Alteration would be most profound in the still hot but permeable pillows, and would be at a minimum in quickly chilled parts of the volcanic pile. This may explain the common occurrence of unaltered olivine and labradorite in small fragments of glassy lava in agglomerates and breccias, and the almost complete alteration of the holocrystalline portions of the lavas. The solutions, enriched in dissolved silica,

[32] Eskola, Pentte, Vuoristo, Urho, and Rankama, Kalervo: 1937, An experimental illustration of the spilite reaction: Finland Comm. Geol. Bull. 119, 61-68.

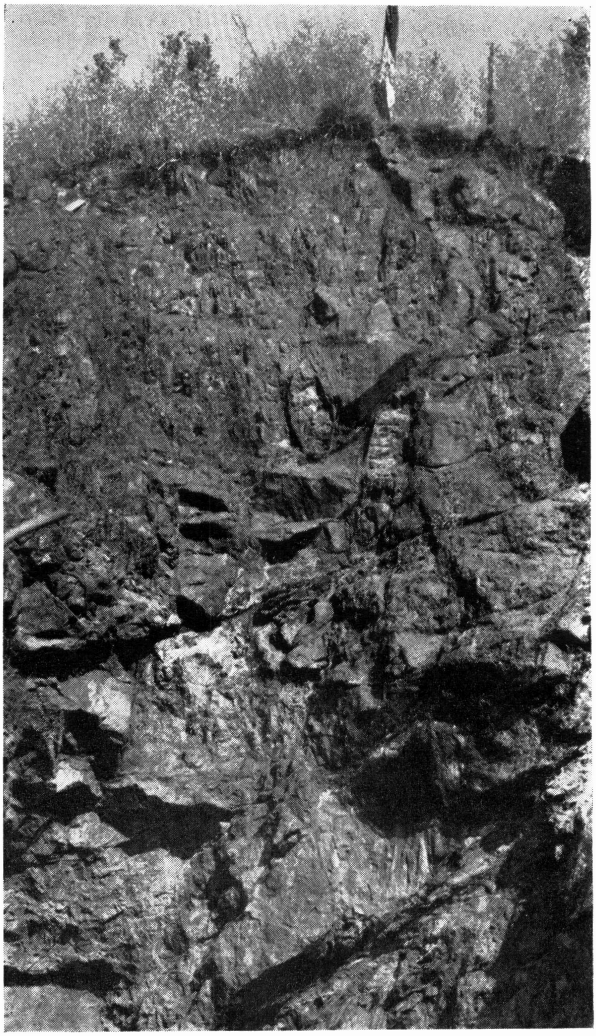

Figure 5. Open cut at the Crescent mine. The massive blocks are manganese ore. The country rock is a chocolate-colored limestone.

Figure 6. Photograph of spilitic lava. Note the vesicular character. Flow on Mt. Gladys.

manganese, and iron, as well as in calcium set free in the process of albitization, would migrate upward toward the top of the volcanic pile. As they come into the cooler zone near the top, silica would be deposited as impure jaspery masses and might locally replace tuffs, limestones, or lavas. The manganese would enter into combination with silica and be precipitated in openings or as replacements of limestone. Eventually the heated solutions would find their way through channels in the limestone cover to the open sea water above, where thermal agitation caused by their emission might increase the precipitation of limestone. The large quantities of calcium ion set free as a result of the spilite reaction might also be a factor in causing the precipitation of more limestone.

In deep water, such as is postulated here, the pressure of the overlying water would also tend to cause gases, particularly CO_2 and steam, to be retained in the flows, and would thus facilitate reaction. The large amount of tuffs and agglomerates present, as well as the almost uniformly vesicular and amygdular character of the lavas indicates that great quantities of gas were present, Fig. 6. A reasonable source of part of this gas is trapped and heated sea water.

Where silica was present in sufficient quantity jasper and manganese silicates resulted; where silica was deficient hausmannite appears to have been formed. Hausmannite may also have been formed as a result of oxidation of other manganese minerals by steam, somewhat in the manner described by Trengrove.[33]

The lavas extrusion, the accumulation of red rocks, and the alteration produced are thought to result from one continuous process, and all evidence so far obtained tends to support this statement. Pardee contended that the alteration of the lavas and the formation of the manganese silicates were part of the same process. He said: "The alteration of the lavas to greenstone was probably effected at the same time (as the formation of manganese oxides and silicates)[34] by the same or similar solutions, a conclusion that is perhaps supported by the fact that similar zeolites were deposited in both the ores and the coun-

[33] Trengrove, S. A.: 1936, The hydrothermal oxidation of manganese minerals: Econ. Geol., **31**, 29-47.

[34] Parenthetical expression inserted.

try rock."[35] In many places zeolites extend from the lavas into both the ores and the enclosing red rocks.

In many of the albitized lavas the ferromagnesian minerals are decomposed and in part removed. The resulting decrease in ferromagnesian constituents is clearly shown in the comparison of the analyses of altered and unaltered lava given in table 2. It is interesting to note that ordinary basalt generally contains 0.17 to 0.31 per cent MnO.[36] On the assumption that only .01 per cent MnO is removed, alteration of a cubic mile of basalt of specific gravity 2.90 would yield about 1,333,980 tons of MnO, or a flow 1 mile square and 100 feet deep would yield about 25,264 tons of MnO. The altered basalt in the Olympic Peninsula is much more than an adequate source for the known manganese deposits.

The results of the Challenger deep-sea expedition yielded interesting results concerning manganese on the sea floor.[37] Murray said the deep sea manganese nodules were formed by subaqueous deposition from alteration of volcanic debris. He claimed they were most abundant near augitic or heavy lavas. Hewett[38] and Clarke[39] agreed with Murray and pointed out that manganese nodules are distributed near volcanic debris. Clarke further said: "The nodules occur in close association with red clay of similar origin; furthermore their impurities are of the kind which the suggested mode of formation would lead us to expect."

In referring to the alteration of the Mechosin volcanics on Vancouver Island Clapp[40] said: "Since in the Mechosin volcanics zeolitization and albitization are virtually confined to the pillow lavas, the conditions producing the pillow lavas must have been responsible also for their peculiar alteration. It is believed . . . that the pillow lavas are of shallow marine

[35] Pardee, J. T.: 1927, Manganese-bearing deposits near Lake Crescent and Humptulips, Washington: U. S. Geol. Survey, Bull. 795A, 15.

[36] Daly, R. A.: 1933, Igneous rocks and the depths of the earth: 17.

[37] Murray, John: 1876, On the distribution of volcanic debris over the floor of the ocean, its character, source, and some of the products of its distintegration and decomposition: Proc. Roy. Soc. Edinburgh, 9, 255-258.

[38] Hewett, D. F.: 1926, Manganese in sedimentary rocks. In Treatise on Sedimentation, edited by W. H. Twenhofel, 411.

[39] Clarke, F. W.: 1924, The data of geochemistry: U. S. Geol. Survey, Bull. 770, 135.

[40] Clapp, C. H.: 1917, Sooke and Duncan Map-areas, Vancouver Island: Canada Dept. Mines, Geol. Survey Memoir 96, 270.

origin and that they were altered by the hot sea water mingled with emanations from the cooling volcanics." Weaver correlates the Mechosin volcanics with the upper part of the volcanics of the Olympic Peninsula.[41] In the Olympic Peninsula most pillow lavas are at least in part albitized, but, as mentioned previously, diabases thought to be intrusive are also partly albitized.

Zeolites mark the end of the alteration in the Olympic Peninsula, while albite was formed at the beginning. This observation was also made by Fenner in New Jersey.[42] where albite replaced labradorite and was followed by zeolites. Fenner described the alteration in the Watchung basalt as resulting from the reaction between basalts and saline playas. He stressed quick chilling of the lavas and reaction with trapped vapors working upward from below the flows.

Economic Considerations.

If the origin of the spilites and manganese deposits discussed above is correct, it follows that the manganese deposits will be generally small and dispersed. The field evidence supports this statement. The bodies likely to yield the largest tonnages are in red limestones and red argillites near the thicker and larger pillow flows. So far but one body of commercial size and grade has been found—the Crescent mine, though others may be discovered in the future.

Large tonnages of low grade manganese-bearing rock (about 5 per cent Mn) may possibly be found in the red rocks, though on the basis of available analyses (Table I) this is by no means a certainty.

U. S. Geological Survey,
Washington, D. C.

[41] Weaver, C. E.: 1937, Tertiary stratigraphy of Western Washington and Northwestern Oregon: Univ. of Wash., publications in Geology, 4, 22.

[42] Fenner, C. N.: 1910, The Watchung basalt and the paragenesis of the zeolites and other secondary minerals: Annals N. Y. Acad. Sci., 20, 93-187.

Schaller, W. T.: 1932, The crystal cavities of the New Jersey zeolite region: U. S. Geol. Survey, Bull. 832, 9-22.