Geology and Manganese Deposits of the Maple and Hovey Mountains Area Aroostook County, Maine

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U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Geology and Manganese Deposits of the Maple and Hovey Mountains Area Aroostook County, Maine

By LOUIS PAVLIDES

With a section on

Lithology and Mineralogy of the Deposits

By LOUIS PAVLIDES *and* CHARLES MILTON

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Describes the geology and manganese deposits of a part of the Paleozoic terrane of northeastern Maine

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GEOLOGY AND MANGANESE DEPOSITS OF THE MAPLE AND HOVEY MOUNTAINS AREA, AROOSTOOK COUNTY, MAINE

By Louis Pavlides

ABSTRACT

The manganese deposits of eastern Aroostook County, Maine, lie in a discontinuous belt about 65 miles long. They are grouped within three general areas: the northern manganese district, which includes the deposits west of Caribou and Presque Isle; the southern manganese district, which centers at Houlton; and—the area of this report—the Maple and Hovey Mountains area, which is in the heavily wooded region west of Bridgewater.

The Maple and Hovey Mountains area includes sedimentary and igneous rocks that have been mildly metamorphosed to somewhat different levels within the greenschist facies. These rocks are complexly folded and faulted with steep to vertical regional slaty cleavage transecting most of them. Bedding is steep to vertical throughout the district.

Slate, graywacke, and impure limestone constitute the most abundant rocks of sedimentary origin. A great variety of igneous rocks is also present. These include greenstone (metabasalt, meta-andesite, and metadiorite), keratophyre, acidic tuff, rhyolite, and volcanic breccia. Serpentinite and metagabbroic rocks are present in one small part of the area. A small mass of garnet porphyry also crops out locally.

The sedimentary and igneous rocks are probably all of post-Early Ordovician age. The sedimentary rocks and some of the volcanic rocks belong to two formations. The Meduxnekeag formation of Middle Ordovician age is in fault contact with the Hovey formation of Silurian (?) and Silurian age. The Meduxnekeag contains slate, interbedded slate and limy layers, and graywacke. The lithology of the Meduxnekeag differs from the younger Hovey formation within the area mapped in that its slate lacks intercalated volcanic rocks and manganese deposits, and it contains a distinct ribbon rock sequence.

The Hovey formation is divisible into two parts: a lower part of slate and graywacke, which contains several lenses of devitrified flow rock (Saddleback Mountain member), and an upper part chiefly of slate, which also contains several lenticular units of metavolcanic rock near its base (Dunn Brook member and volcanic breccia unit). Stratigraphically above these volcanic rocks, the slate of the upper part of the Hovey formation contains the manganese- and iron-bearing deposits of the district.

The Spruce Top greenstone is a separate igneous unit that is believed to have been emplaced as sills(?). Other igneous rocks of the area are small masses of garnet porphyry, serpentinite, metagabbro, and granite(?).

The bedded manganese- and iron-bearing rocks of Maple and Hovey Mountains are of two primary lithologies: an oxide facies, which mostly includes hematitic shale and slate and banded hematite ironstone; and a carbonate facies, composed chiefly of siliceous carbonate rocks. Magnetite of metamorphic origin is locally a prominent constituent of both these primary facies; therefore, these primary types may be further distinguished by magnetite-bearing and magnetite-free varieties.

Crystalline hematite is commonly the most abundant mineral of the bedded rocks of the hematitic manganese deposits. Braunite and rhodochrositic carbonate are the principal manganese minerals. Spessartite and bementite are generally present in lesser amounts; hausmannite was found at only one place in minute quantities. Cryptocrystalline apatite is normally an abundant accessory; additional common accessories include fine-grained quartz, muscovite, chlorite, and alkalic feldspar. Barite, phlogopite, and chert are less common accessories.

In the siliceous carbonate deposits, rhodochrositic carbonate is the chief manganese mineral; this carbonate and iron chlorite are the chief mineral constituents of these deposits. Minerals similar to stilpnomelane(?) are also present. Pyrite is rarely absent and is a major constituent in some laminae of the siliceous carbonate rocks. Quartz, alkalic feldspar, and white mica are other accessories.

The chief manganese mineral and one of the abundant constituents of the magnetite-bearing deposits is a manganoan carbonate close to rhodochrosite in composition. Iron chlorite is also abundant, and magnetite may be either a major or minor constituent. Accessory constituents are cryptocrystalline apatite, quartz, alkalic feldspar, biotite, muscovite, stilpnomelane(?), and bementite(?). In deposits originally of the siliceous carbonate type, pyrite and pyrrhotite (rare) are additional accessories; unreplaced hematite is commonly found in deposits that were originally of the hematitic type. Braunite is absent in magnetite-bearing deposits formed by metamorphism of hematitic rocks.

Thin relatively coarse-grained veinlets commonly cut the fine-grained layered iron- and manganese-bearing rocks of the different types of deposits. The mineralogy of the veinlets typically reflects that of the host rocks. Rhodonite is generally present in the veinlets that cut manganiferous banded hematite ironstone of the Maple-Hovey deposit, but it is absent in veinlets in the other rocks.

The iron- and manganese-bearing rocks on Maple and Hovey Mountains, as well as those elsewhere in the Aroostook manganese belt, generally contain large amounts of phosphorus (more than 1 percent in parts of some deposits). Many of the constituents, such as Fe, Mn, CaO, SiO_2, and Al_2O_3, vary in direct proportion to the phosphorus content of the deposits. There is no unusual concentration of metalloids in the deposits and the traces that are present are not systematically related, in abundance, to the iron and manganese. Chiefly on the basis of the indirect evidence furnished by the chemical constituents, as well as on their distribution within mineral components (that is, Ca is present mostly as apatite and not calcite), the deposits are considered to have formed as lenses of impure chemical sediment in a brackish environment in which the pH was close to or slightly less than 7.8. Oxides of iron and more especially oxides of manganese formed under oxidizing conditions. The layered pyrite in the siliceous carbonate sediments accumulated under reducing conditions and most of the siliceous carbonate rocks free of pyrite also formed in a reducing environment. The deposits probably formed in numerous nearshore barred basins that had a highly restricted circulation, that is, a unidirectional seaward flow of water. In this way, a relatively low pH inherited, in part, from the streams draining into the basins, could be maintained throughout most of the depositional history of the basins. The Eh was, in part, a function of the depth of the basins. The succession of different types of ironstone within any one deposit reflects the structural history of the basin.

In addition to mineral reconstitution through diagenesis, the manganese- and iron-bearing deposits of Maple and Hovey Mountains were also altered by regional metamorphism at about the time they were folded. Regional metamorphism probably took place under a thick cover of younger rocks. A level of metamorphism higher than the regional one was attained in parts of the deposits, especially where the rocks were closely folded. At such places magnetite was formed in both the carbonate and hematite-bearing rocks and braunite was destroyed in hematitic rocks. Apparently the metamorphism was isochemical, except for volatiles, and chiefly involved oxidation-reduction reactions and hydration.

Through erosion, the upturned ends and limbs of the folded and moderately metamorphosed deposits have been exposed at the bedrock surface. Weathering has slightly increased the tenor of both manganese and iron, mostly through oxidation of carbonate. This minor enrichment is chiefly localized within 1 foot or so of the bedrock surface in the deposits on Maple and Hovey Mountains.

The larger hematitic manganese deposits in the area are generally divisible into several units. The Maple-Hovey deposit (main manganiferous lens) contains three rather distinct lithologic units designated the upper, middle, and lower manganiferous units. These units have fairly persistent chemical features and tenor of manganese and iron along strike and downdip. The upper manganiferous unit contains about 7 percent manganese and 13 percent iron, the middle manganiferous unit contains about 11 percent managanese and 24 percent iron, and the lower manganiferous unit contains about 7 percent manganese and 20 percent iron. The different types of rock that are interlayered in these units, however, have a wide range in metal content. For example, beds of green slate commonly contain less than 1 percent manganese and only a few percent iron; red slate contains somewhat more manganese and iron; and rocks such as banded hematite ironstone are the most metalliferous. One sample of hematitic ironstone contains 26 percent manganese and 19 percent iron and another contains 40 percent iron and 7 percent manganese. Without exception, composite samples of several layers of a unit contain more iron than manganese.

The oxide-facies deposits (including the more metamorphosed type) on Maple and Hovey Mountains contain 322 million long tons of manganese "ore" that average about 7 percent manganese and 17 percent iron; the carbonate-facies deposits (including the more metamorphosed type) contain about 3 million long tons of such "ore." The total reserves in the area, therefore, are in the order of 325 million long tons of "ore" and average about 7 percent manganese and 17 percent iron. The contained manganese reserves of the Aroostook province represent the theoretical equivalent (assuming 100 percent recovery), in terms of standard-grade ore (48 percent Mn), of about 30 years reserves at the consumption level of metallurgical manganese in the United States in 1953. About 20 percent of this material is within 200 feet of the surface. The ultimate exploitation of the Aroostook deposits for their manganese content (and possibly for iron) must await, however, the development of an efficient and relatively cheap extractive process.

INTRODUCTION

PURPOSE AND SCOPE OF THE INVESTIGATION

During the field seasons of 1949 through 1951, the U.S. Bureau of Mines carried out a detailed physical exploration program on some of the manganese- and iron-bearing deposits of Aroostook County, Maine, with particular emphasis on those on Maple and Hovey Mountains. The writer was assigned to be project geologist for these investigations by the U.S. Geological Survey at the request of the Bureau of Mines. The exploration program included extensive trenching, diamond drilling, and assaying, which afforded a good opportunity to study the deposits in great detail. At the completion of the program, the U.S. Geological Survey continued geologic investigations within the area. A little more than 4 months, in all, were spent by the writer during the field seasons of 1952 and 1953 in reconnaissance geologic mapping of the area. The reconnaissance served, in part, as a field test to judge the practicality of areal geologic mapping in this terrain.

The engineering data compiled from the physical exploration of the deposits on Maple and Hovey Mountains have been published by Eilertsen (1952). The present report contains a fuller discussion of the geology of the deposits than that in Eilertsen's report (Pavlides, 1952, p. 6–9). In the present report only relatively few of the assays published by Eilertsen have been used, though many have been combined here to illustrate some of the geologically significant chemical properties of the deposits. Likewise, comparatively few cross sections of diamond-drill holes, necessary to illustrate the geologic structure of the deposits, are contained in this report. The reader should consult Eilertsen's report for the detailed assay data on trenches and diamond-drill core.

Although this report principally describes the geology and manganese deposits of the Maple and Hovey Mountains area, the regional geology and the manganese- and iron-bearing deposits of the other parts of the Aroostook manganese belt are also briefly discussed, insofar as it is necessary to present the geologic setting. The reports of White (1943) and Miller (1947) contain detailed descriptions of the geology and deposits of the northern and southern manganese districts and have been freely drawn upon for pertinent data concerning those districts.

GEOGRAPHY OF THE AROOSTOOK MANGANESE BELT

The manganese deposits of eastern Aroostook County, Maine, are located in three areas (fig. 1) designated as districts by Miller (1947, p. 2). The northern manganese district includes the belt of deposits west of Caribou and Presque Isle, the Maple-Hovey Mountains area is in the heavily wooded region west of Bridgewater, and the southern manganese district centers at Houlton. The deposits of the three areas form a discontinuous belt about 65 miles long that extends from the vicinity of New Sweden to about 3 miles south of Hodgdon. Geographically, they are within the "Northwest Lake and Forest Region" and the "Aroostook Potato District" (Trefethen and Trefethen, 1938, p. 4), an area of mature topography characterized, in general, by gently rolling to rough hills and by numerous lakes, chiefly of glacial origin. Glacial drift is the chief surficial deposit. Eskers are a prominent feature of the southern manganese district, they are less conspicuous in the Maple-Hovey Mountains area, and they are absent in the northern manganese district (Leavitt and Perkins, 1935, Supplemental Map).

Bedrock is commonly exposed on the slopes and crests of hills but exposures are generally small and discontinuous. In the areas under cultivation outcrops may be exposed by plowing during one season and covered by soil the next. The mantle of glacial drift is relatively thin on the hills, commonly less than 10 feet thick, and is somewhat thicker in the valleys.

Cultivation is confined to a long, narrow belt in eastern Aroostook County where potatoes are the chief crop. Virtually an unbroken forest lies west of the agricultural belt. The northern and southern manganese districts lie within the cultivated region and are for the most part readily accessible. The Maple-Hovey Mountains area is more remotely situated in the forested region west of Bridgewater. The deposits of this area are on and between Maple and Hovey Mountains in the Howe Brook quadrangle. Maple Mountain lies in the extreme west-central part of T.D., R. 2, and Hovey Mountain is in the southeastern part of T. 9, R. 3.

The Maple and Hovey Mountains area is accessible by automobile over graveled roads starting with the Boutford Road, which branches westward from U.S. Highway 1 at Bridgewater, Maine. The P.D. road, a graveled tote road maintained by the Penobscot Development Company, continues from the end of the Boutford Road through the wooded area and low-lying hills to the west. The U.S. Bureau of Mines built a graveled access road to the deposits. This road branches southward from the Penobscot Development road, extends to the outlet of Number Nine Lake, and continues thence to Maple Mountain (fig. 2). From Maple Mountain, another road extends southwestward to Hovey Mountain.

HISTORY OF DISCOVERY AND EXPLORATION

Jackson (1838, p. 34–38) discovered the first deposit of manganiferous hematite in Aroostook County over a century ago. His description is vague and the exact identity of this deposit is not certain, although Miller (1947, p. 50–51) believed that Jackson had examined the Haines prospect. The manganese deposits of Aroostook County received very little attention as potential manganese ore until shortly before the second World War. In the late 1930's, the deposits near Houlton were visited by G. F. Loughlin, of the U.S. Geological Survey; he recognized the potential magnitude of the resources in Aroostook County, and in early 1941 assigned W. S. White and P. E. Cloud to make a preliminary study of the deposits. They made a reconnaissance map of the northern and southern manganese districts, and, at the same time, P. F. Eckstorm trenched and sampled many of the deposits in both districts for the State of Maine. From 1942 through 1944, the Manganese Ore Company, a subsidiary of the M. A. Hanna Company of Cleveland, sampled and explored many of the Aroostook deposits by trenching, and two deposits by both trenching and diamond drilling. Shafts and test pits were also used in the exploration of the Dudley deposit in the northern manganese dis-

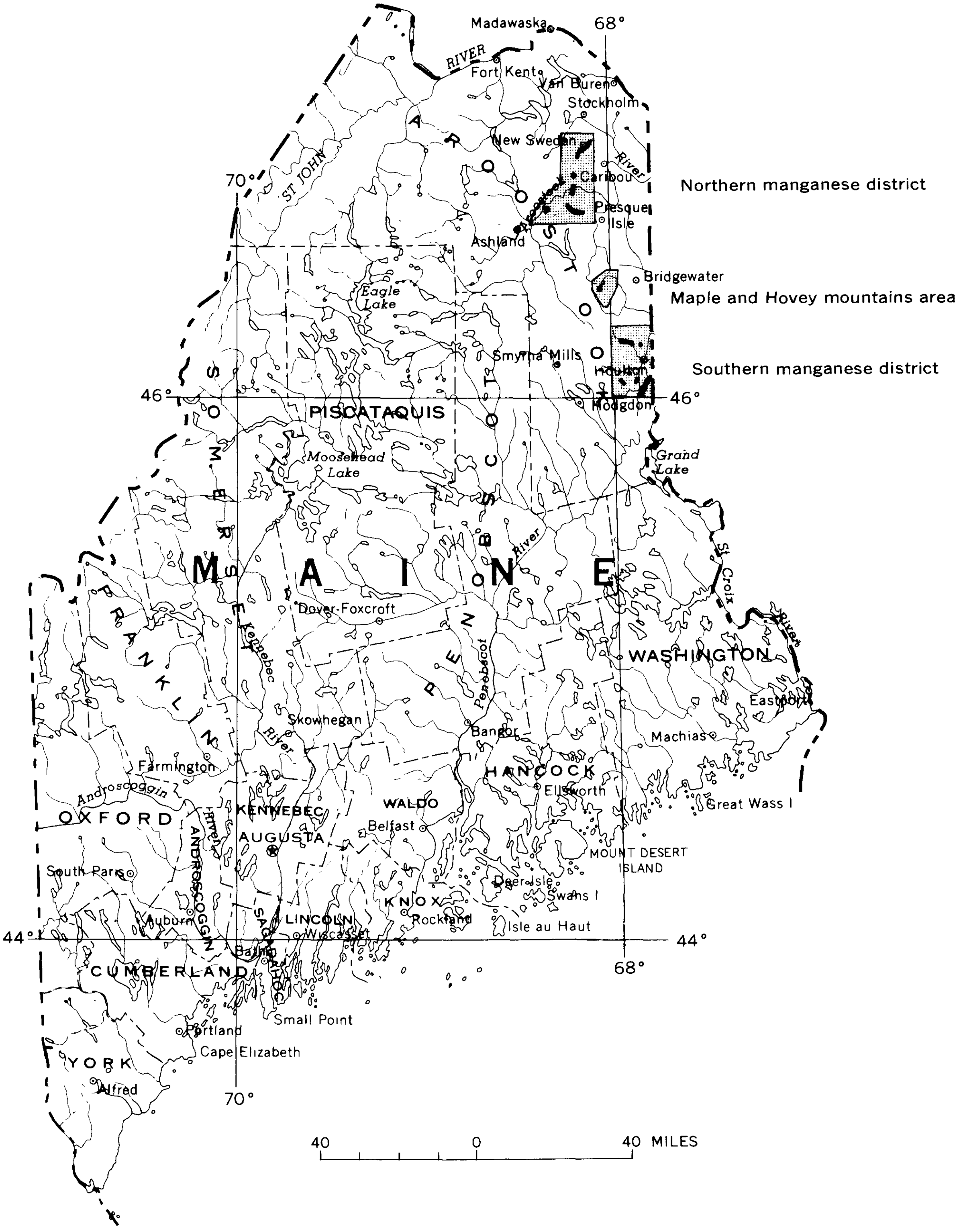

FIGURE 1.—Index map showing general distribution of the deposits within the northern and southern manganese districts and the Maple and Hovey Mountains area of Aroostook County, Maine.

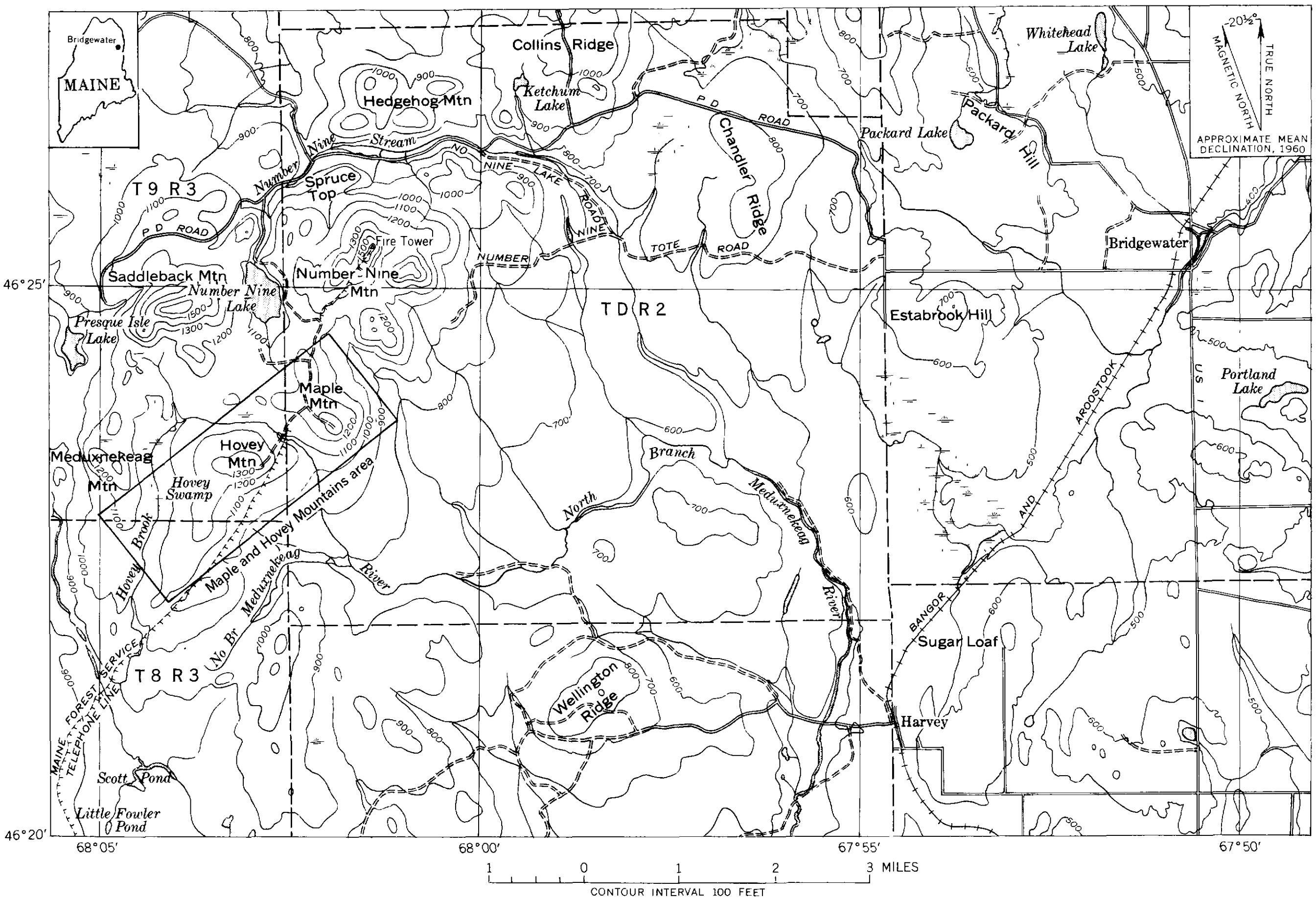

Figure 2.—Location map of the Maple and Hovey Mountains area, Aroostook County, Maine.

trict. R. L. Miller reexamined many of the deposits and carried on further reconnaissance regional mapping in the Aroostook manganese belt during 1943 and 1944. Most of the deposits in the northern manganese district explored during the above investigations had been originally discovered by Olaf Nylander, and those in the southern manganese district had been found by Harry Thwaites. The manganese deposits on Maple and Hovey Mountains were discovered by woodsmen who submitted specimens to the State Geologist of Maine for identification, and also called the attention of the land owners to the existence of these deposits (Eilertsen, 1952, p. 6).

Paul Eckstorm first prospected the manganiferous rocks exposed on Maple Mountain in 1941 (Miller, 1947, p. 63). He dug and sampled three trenches. In 1943, Mr. Clarence Harrar, of the Manganese Ore Company, visited this deposit and presumably collected grab samples from Hovey Mountain (Miller, 1947, p. 62). The Manganese Ore Company further explored the manganese- and iron-bearing rocks on the crest of Maple Mountain in 1944 by trenching and sampling (Miller, 1947, pl. 18). From 1949 through 1951, the U.S. Bureau of Mines carried out the extensive physical exploration program mentioned above (Eilertsen, 1952).

An airborne magnetometer survey of most of the Aroostook manganese belt, including the Maple and Hovey Mountains area, was made by the U.S. Geological Survey and in cooperation with the U.S. Bureau of Mines during 1950 and 1951. The survey was under the direction of W. J. Dempsey. The magnetic anomalies located by the aeromagnetic survey were checked by ground surveys during 1950 and 1951.

In 1953, the E. S. Nossen Laboratories, Inc., of Paterson, N.J., and the Southwest Engineering Company of Los Angeles, Calif., obtained samples from the Maple-Hovey deposit for metallurgical testing. Other deposits in the Aroostook manganese belt, including the Dudley of the northern district, were also sampled by the above organizations. These investigations were supported by the Federal Government through grants made by the Defense Minerals Production Administration.

Despite the rather extensive exploration done on the Aroostook deposits in recent years, there has been no commercial mining of any of them. However, deposits of similar character near Woodstock, New Brunswick, about 15 miles east of Houlton, were mined as iron ores between 1848 and 1884 (Caley, 1936, p. 20).

FIELDWORK AND METHODS USED

Geologic guidance for the physical exploration of the manganese deposits on Maple and Hovey Mountains consisted of locating the manganese- and iron-bearing strata of the deposits, interpreting their structure, and projecting their extension along strike and downdip. This enabled systematic and orderly exploration by trenching and diamond drilling to be planned and carried out. Sampling boundaries were placed at the lithologic boundaries established by mapping trenches and logging diamond-drill core. The engineering aspects of the trenching, drilling, and preparation of samples have been described by Eilertsen (1952) and will not be discussed in this report.

The manganese- and iron-bearing strata were traced by using whatever bedrock information was available from the scattered outcrops protruding through the glacial till in this thickly forested region. Cleavage-bedding relations were helpful in the location and identification of folds. Float was generally distinguished from glacial material by the more marked angularity of the ironstone fragments and was also useful in locating beds of "ore" beneath the glacial mantle.

A vertical magnetometer survey by R. M. Shuler, of the U.S. Geological Survey, was started about the middle of the first field season and thereafter was continued through the course of the exploration program. It proved to be valuable in tracing the continuity of the manganiferous strata in areas where outcrops and float were absent. A standard temperature-compensated vertical mangetometer was used. The sensitivity of the instrument was 20.0 gammas per scale division and readings were made to the nearest tenth of a scale division. Readings at base stations were taken four times daily to permit correcting for effects of diurnal change in the magnetic fields and instrument drift: one reading in the early morning, two readings 1 hour apart at midday, and one reading in the late afternoon. The locations of the traverses and base lines are shown on the index map of plate 2. The traverses cover an area of approximately 760 acres on Maple and Hovey Mountains. The 4 base lines were surveyed by transit. All traverses were spaced at approximately 200-foot intervals perpendicular to the base lines and magnetometer readings were made at 20- and 50-foot intervals along these lines.

Most of the information about the bedrock acquired during regional geologic mapping in the Maple and Hovey Mountains area was obtained by walking out streams. Steep slopes and crests of ridges contain fewer outcrops, and in the lowlands outcrops are sparse or lacking. In general, after the drainage and ridge lines of an area had been walked out, the area was also crossed by several pace-and-compass traverses. The relatively uniform regional northeast strike and steep or vertical dip of cleavage in the area is most helpful in distinguishing bedrock from glacial erratics.

ACKNOWLEDGMENTS

The writer was ably assisted in the field during the physical exploration of the deposits on Maple and Hovey Mountains successively by R. G. Hagerman, R. K. Sorem, J. A. Parkinson, D. W. White, and J. E. O'Rourke. G. N. Neuerberg and A. M. White assisted in the checking of the aeromagnetic anomalies, by ground surveys. L. A. Brubaker assisted the writer with the regional geologic mapping during the field seasons of 1952 and 1953. He also carried out most of the ore reserve calculations and helped to compile many of the maps of this report.

Among the numerous colleagues of the U.S. Geological Survey who freely gave of their time and talents, special thanks are due W. S. White who spent several weeks in the field with the writer, acquainting him with the Aroostook manganese belt, as well as making many valuable suggestions concerning the geologic problems of the area. He also offered many constructive suggestions and ideas during the preparation of this report. R. L. Miller generously made available all his field data as well as thin sections. Charles Milton, J. J. Glass, J. M. Axelrod, F. A. Hildebrand, Leonard Shapiro, C. M. Warshaw, W. J. Blake, A. A. Chodos, K. J. Murata, R. N. Eccher, H. F. Phillips, P. L. D. Elmore, P. W. Scott, and S. M. Berthold performed mineralogic, X-ray, chemical and spectrographic analyses. A. J. Boucot and the late Josiah Bridge examined and tentatively dated fossils collected by the writer. R. W. Bromery supervised the compilation and drafting of the magnetic contours (pl. 2). The writer is also

grateful to Mr. A. E. Walker, of the Manganese Ore Company, who made it possible to examine the diamond-drill core from the Dudley deposit in the northern manganese district.

It is a pleasure to acknowledge the innumerable courtesies accorded the writer by Messrs. N. A. Eilertsen, W. T. Millar, K. M. Earl, and the late McHenry Mosier of the U.S. Bureau of Mines, during the course of the field investigations of the deposits on Maple and Hovey Mountains, and in the preparation of this report. Information on the deposits, including heretofore unpublished spectrographic analyses, was made available to the writer.

GENERAL REGIONAL GEOLOGY

Relatively little is known about the bedrock geology of Aroostook County, Maine. Geologic mapping thus far has been of a reconnaissance type and has been confined to the cultivated areas in the eastern part of the county; there is very little geologic information about the less accessible forested western part. Williams and Gregory (1900) made the first regional geologic study of eastern Aroostook County, but their extremely generalized map (1900, pl. 4), is of limited value. The geologic map of the State of Maine (Keith, 1933) shows the geology of the county in greater detail, but it also is necessarily very generalized and requires revision in the light of more recent work.

NORTHERN MANGANESE DISTRICT

W. S. White and P. E. Cloud were the first to map systematically parts of the area included within the northern manganese district. Their stratigraphic subdivisions are different and in general more detailed than those of Williams and Gregory. Table 1 lists the stratigraphic sequence in the northern district as described by White and Cloud (White, 1943, p. 129). The manganese deposits there are localized along three horizons in the Middle Silurian rocks, "one being in the greenish argillite immediately above the Aroostook limestone and two in the lower slate and calcareous slate member of the Aroostook limestone" (White, 1943, p. 130). The siliceous carbonate type of manganese deposit, which White refers to as chlorite-carbonate rock, is located along the stratigraphically lowest horizon, whereas at the stratigraphically higher horizons, manganese is associated with hematitic rocks (White, 1943, p. 131).

TABLE 1.—*Sequence and character of the rocks in the northern manganese district*

[After White, 1943, p. 129]

Age	Formation	Lithology	Apparent thickness (feet)
Late Devonian	Mapleton sandstone	Upper 500 feet are red and greenish sandstone, the remainder red conglomerate and sandstone.	1,800-2,500
		—Marked angular unconformity—	
Early Devonian	Chapman sandstone	Greenish sandstone, Becraft or Oriskany funa.	>700
	Volcanics	Calcareous tuffs and breccias, New Scotland fauna.	2,000
		——Slight unconformity——	
Middle Silurian	Shale and slate [1]	Upper member blue and gray calcareous shale with limestone lenses; lower member greenish argillite with thin calcareous layers.	5,000±
	Aroostook limestone	Upper member gray, nubbly argillaceous limestone; middle member ribbon limestone; lower member slate, partly calcareous.	18,000±
	Sandstone [2]	Sandstone and conglomerate with a little slate and calcareous argillite.	5,000±
		—Marked angular unconformity—	
Middle Ordovician	Undifferentiated gray-blue calcareous siltstone, greenish argillite, black shale, and chert. Three fossil zones recognized.		Unknown

[1] Ashland shale and Ashland limestone (Williams and Gregory, 1900, p. 21).
[2] Sheridan sandstone (Williams and Gregory, 1900, p. 21).

White (1943, p. 128) states that the stratigraphic section (table 1) is "based on the simplest interpretation of the stratigraphy and structure in the light of what is known at the present time," and indicates that the Middle Silurian rocks (table 1) may be several times thicker or thinner than the true thicknesses due to thickening and thinning by folding and faulting. He also points out the possibility of the "erroneous separation of different sedimentary facies of the same stratigraphic units" (1943, p. 128); namely, the lowest member of the Aroostook limestone may be equivalent to the shale placed above the Aroostook. Twenhofel (1941, p. 166–174) thought that the Sheridan formation overlies the Ashland formation but White and Cloud do not agree (see table 1). Recently, graptolites of Middle Ordovician age (Pavlides and others, 1961) have been found in rocks mapped by White as belonging to the middle member of the Aroostook limestone, which he dated as being Middle Silurian (table 1). Thus, as anticipated by White, it is apparent that considerable revision of the stratigraphy, age assignments, and nomenclature of formations in the region will result when it is mapped in detail.

The intrusive rocks of the area are shown as post-Upper Devonian by White (1943, pl. 24, Explanation); but his map and sections on the same plate show the Mapleton sandstone of Late Devonian age unconformably overlying the intrusive rocks, and these intrusive rocks should therefore have been called pre-Upper

Devonian (or pre-Mapleton). Keith (1933) had previously assigned a Mississippian age to the Mapleton.

White considers the andesite, trachyte, and porphyritic quartz trachyte of the district to be "small, narrow, subparallel intrusive bodies" (1943, p. 128) and has mapped the Quoggy Joe quartz trachyte of Williams and Gregory (1900, p. 111) as part of the intrusive rocks he shows as post-Upper Devonian. Williams and Gregory (1900, p. 108, 112, 113; fig. 3, p. 109 and fig. 4, p. 113) regarded the trachyte, quartz trachyte, and andesite of the district as extrusive bodies that overlie the upturned, truncated sedimentary rocks. They did not observe any contacts between the extrusive rocks and the sedimentary rocks, and the chief reason for considering these rocks effusive is probably their amygdaloidal character (1900, p. 108). The Chapman sandstone of Early Devonian age is exposed in places within a semielliptical, discontinuous ring of hills which bound the southern end of the district in the Presque Isle quadrangle (outside the area mapped by White). These hills encircling the Chapman sandstone are formed of igneous rocks. The eastern hills are underlain by quartz trachyte (Williams and Gregory, 1900, p. 111), the western hills mostly by trachyte (1900, p. 110), and the northern hills by andesite (1900, p. 112). It is conceivable that these igneous rocks may underlie the Chapman sandstone in a broad syncline similar to that formed by the Mapleton sandstone (White, 1943, pl. 24). Keith's map (1933) in part suggests such an interpretation. Further work is necessary to date these rocks as well as to determine whether they are extrusive, intrusive, or both, in origin.

Teschenite (analcime-basalt) dikes and a small granite body, which crop out in the south-central and northeastern parts, respectively, of Mapleton township of the northern manganese district, are the only igneous rocks of proved intrusive origin; they have thermally metamorphosed the sedimentary rocks they intrude (Williams and Gregory, 1900, p. 106 and 116, fig. 5, pl. 4). The teschenite dikes may be among the youngest intrusive rocks in the county. They are petrologically similar to the feldspathoidal rocks of the White Mountain plutonic-volcanic series of New Hampshire, Vermont, and southwestern Maine, as well as of the Monteregian Hills in Quebec. The White Mountain plutonic-volcanic series is of post-Devonian and pre-Pennsylvanian age and hence tentatively dated as Mississippian by Billings (1956, p. 105).

The rocks of the northern manganese district have been folded and faulted, but deformation is not equally intense throughout (White, 1943, pl. 24). The southern part of the district is characterized by broad folds plunging gently southward. Competent sandstone in this region probably accounts for the development of open rather than close folds (White, 1943, p. 129–130). The unconformably overlying Mapleton sandstone forms a broad structural basin with low dips. In the northern part of the district, where incompetent argillite and thin-bedded limestone were involved in the deformation, the beds dip steeply and the folds are tighter, in places being nearly isoclinal (White, 1943, p. 130). Slaty cleavage has been developed in some places. White (1943, pl. 24, p. 130) has postulated the presence of at least two large reverse faults dipping steeply to the west, and has inferred minor faults of the same type at various other places. Inasmuch as most of these faults were postulated for stratigraphic reasons, their number and location may vary with the interpretation of the stratigraphy (Miller, 1947, p. 15). Miller believes the faults in the district are high-angle strike faults.

SOUTHERN MANGANESE DISTRICT

The manganese deposits of the southern manganese district have been mapped by White (1943) and Miller (1947). A reconnaissance geologic map of the district was made by Miller (1947, pl. 4), but owing to the complexity of the geology, only a broad generalized stratigraphic subdivision was attempted. The Ordovician and Silurian slates were mapped as an undifferentiated unit because of the difficulty of separating these rocks where fossils are lacking. Manganiferous rocks occur in both Silurian and Ordovician slates. Miller's stratigraphic section (1947, p. 18) is given in table 2. Since Miller's study (1947, pl. 4), several new deposits have been discovered and outlined in part by magnetic

TABLE 2.—*Stratigraphic section of the southern manganese district*

[After Miller, 1947, p. 18]

Description	Estimated thickness (feet)	Age
Granitic stocks at Drew Hill and Nickerson Lake, and acidic dike rocks.	----------	Post-Silurian
Thin-bedded siliceous limestone. Underlies northern and northwestern parts of district, except Littleton Ridge.	2,000+	Silurian
Buff even-bedded calcareous sandstone and siliceous limestone. Forms belt ¼ to 1 mile wide across central part of district.	1,000±	
Gray slate, locally containing interbedded sandstone. Lenses of manganiferous shale at several horizons.	3,000±	
Gray slate, containing Ordovician graptolites. May contain interbedded manganiferous shale.	1,000+	Ordovician

surveying and physical prospecting. These deposits generally are as much as 5 miles west of the Littleton Ridge deposit. The Littleton Ridge deposit is about 5 miles northwest of Houlton.

The stratigraphy of the southern manganese district differs from the northern manganese district both in the type of sedimentary rocks it contains and in that it lacks igneous rocks such as rhyolite, trachyte, and andesite. The granitic pluton cited by Miller (table 2) at Drew Hill is shown by Keith on the geologic map of Maine as a large continuous intrusive body that extends across the southern part of the Smyrna Mills quadrangle and the northern part of the Mattawamkeag Lake quadrangle. Geologic reconnaissance during the checking of aeromagnetic anomalies by ground surveys suggests that this is a compound pluton probably composed of at least two intrusive bodies, which generally underlie the lowlands. Arcuate and semiarcuate ridges, composed in part of thermally metamorphosed rocks, encircle the plutons. Tremolitic and cordieritic hornfelses are the principal rocks thus far recognized in the contact metamorphic zones.

Deformation in the southern manganese district is more complex and intense than in the northern district. The strike of the sedimentary rocks in many places is nearly west or northwest, whereas in the northern manganese district the regional trend is northeast or northward. The region probably contains a number of faults (White, 1943, pl. 28), but they are difficult to recognize over most of the area because of the general lack of adequate outcrops. Cleavage is well developed and is believed to be younger than the folding as it was locally noted crossing the axial planes of major and minor folds at a high angle (White, 1943, p. 137).

MAPLE AND HOVEY MOUNTAINS AREA

The stratigraphy and structure of the Maple and Hovey Mountains area is incompletely known. The sedimentary and igneous rocks within this area have been tentatively divided into two formations, which are believed to be separated by faults (pl. 1). This twofold subdivision is based on the simplest interpretation of stratigraphy and structure, insofar as it can be deduced from the outcrops available within the small area mapped to date.

The great diversity of rocks, the small size, sparseness, and discontinuity of exposures, the lack of any widely distributed marker beds, the general unfossiliferous character of the rocks, and the probability of numerous faults make it difficult to establish the stratigraphic sequence. Furthermore the green and gray-green slates that comprise large parts of the two formations are megascopically indistinguishable from one another. The separation of the slates within the Maple and Hovey Mountains area is, therefore, based on indirect and rather inconclusive evidence, chief of which is the distribution of the slate with respect both to structural features, and to other, more distinct, lithologic types in the area. The degree of complexity of the local structure is illustrated by the manganese- and iron-bearing deposits on Maple and Hovey Mountains (see pl. 2), where data from the extensive physical exploration program enabled the individual stratigraphic units to be followed in considerable detail, both on the surface and underground.

Additional mapping around the area described in this report may furnish further information that will ultimately permit a more detailed stratigraphic subdivision to be made than has been attempted here, and may necessitate a considerable revision of the stratigraphy and structure outlined below.

The thicknesses assigned to the rock units in the area (see fig. 3), with the exception of the manganese deposits, are only order-of-magnitude estimates based on measurement in cross sections. Undoubtedly, some of the figures are excessive; for example, the upper green slate sequence of the Meduxnekeag formation may be repeated by close isoclinal folds and by faulting, but exposures are not adequate to furnish reliable correction factors.

STRATIGRAPHY

MEDUXNEKEAG FORMATION

The Meduxnekeag formation includes all the rocks in the eastern part of the area (see pl. 1). The formation is named herein after the Meduxnekeag River, along whose headwater tributary streams it crops out. The various lithofacies of this formation are discontinuously exposed within the Bridgewater quadrangle, chiefly in the stream beds and along the banks of the North Branch Meduxnekeag River and of Number Nine Stream.

The Meduxnekeag formation contains slate, interbedded slate and impure calcareous layers, and graywacke sandstone and conglomeratic graywacke. The differences in lithofacies between the Meduxnekeag and Hovey formations are generally reflected in the topography of the region. The relatively resistant igneous rocks of the Hovey formation form ridges 500 to 900 feet above the level of the lowlands, which are underlain in large part by the less resistant metasedimentary rocks of the Meduxnekeag formation (see pl. 1).

Bedding and cleavage relations suggest that the Meduxnekeag formation has a regional westward dip and top directions in bedding face west. Bedding is mainly vertical or dips steeply westward, with probable minor and local overturning to the west in a few places. The Meduxnekeag formation is, therefore, considered to consist of a sequence of beds increasing in age eastward from the fault that separates it from the Hovey formation. A generalized section of the Meduxnekeag formation is given in figure 3.

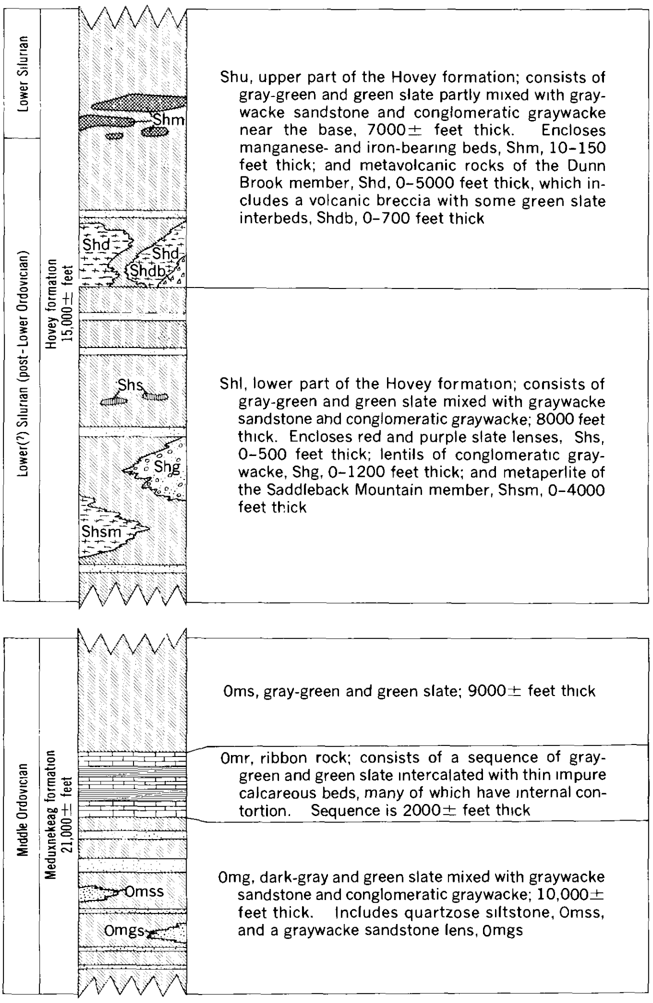

Figure 3.—Generalized stratigraphic column of the Maple and Hovey Mountains area.

Rocks of the slate and graywacke unit assigned to the Meduxnekeag in the wedge-shaped fault block in the northeastern part of the map (pl. 1) are poorly exposed. They are placed in the Meduxnekeag chiefly because irregularly interlayered slate and graywacke beds typical of this unit are present north and south of the easternmost exposures of Spruce Top greenstone within the fault block. It may be that the rocks in the southern part of this block may belong to the Hovey formation but the exposures are not adequate to make such a separation and all the rocks in the block are therefore assigned to the Meduxnekeag in this report.

SLATE AND GRAYWACKE MEMBER

The oldest rocks of the Meduxnekeag formation are chiefly dark-gray slate and gray-green slate irregularly interlayered with graywacke sandstone and conglomeratic graywacke. Because of poor exposures there is no adequate section for determing the proportion and frequency of interlayering of the slates with each other and with the graywackes. In general, the graywacke occurs as massive beds a few feet to at least 10 feet thick, commonly separated by thicker layers of slate. Enclosed within the sequence of mixed slate and graywacke are mappable lenses of graywacke sandstone and quartzose siltstone. (See fig. 3.)

Slate.—The slate of this unit is of two types: a gray-green slate such as in the Hovey formation, and a dark-gray to nearly black slate that has not been found elsewhere in the area. Both the gray-green and the dark-gray slates are finely laminated in many places and locally have small amounts of pyrite.

Graywacke.—The graywacke layers commonly interlayed with slate are typically dark-gray sandstone or conglomeratic layers whose detrital constituents are characteristically embedded in an argillaceous or micaceous matrix. Grains generally range from medium sand to fine pebble size. Microscopic examination of graywacke collected along Number Nine Stream (pl. 1) reveal that it contains abundant fragments of volcanic rocks (see fig. 4).

Graywacke sandstone lens.—A lens of graywacke sandstone within the wedge-shaped fault block in the northeastern part of the map (pl. 1) is of different lithology from the graywacke interlayered with slate in the unit as a whole. It does not contain fragments of rock, although it does have a micaceous and argillaceous matrix within which detrital quartz and feldspar are embedded. It thus has the typically poor sorting of graywacke. It differs in composition to some extent from other graywacke in the Maple and Hovey Mountains area in that it more typically contains rutilated quartz. Both strained and unstrained quartz are common. The feldspar is almost entirely albite, oligoclase,

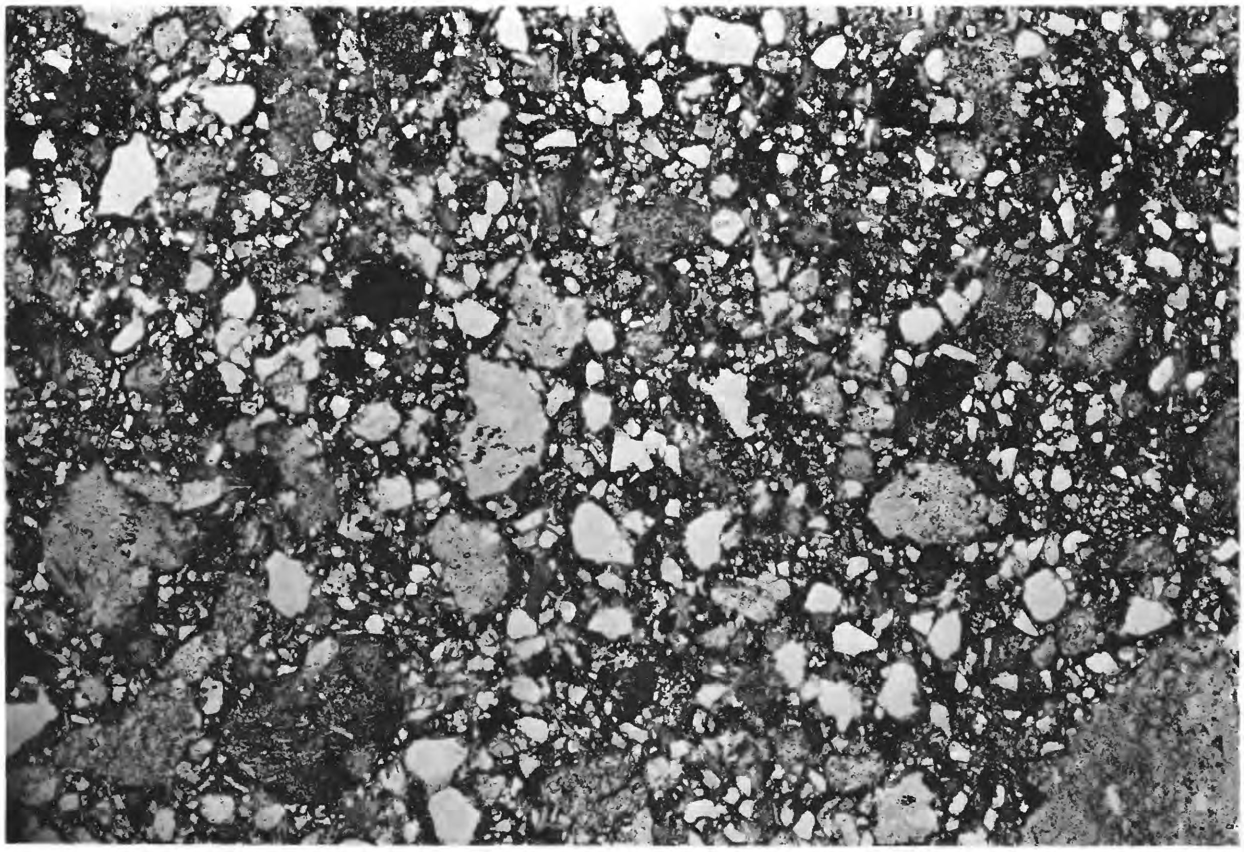

FIGURE 4.—Photomicrograph of graywacke sandstone from the Meduxnekeag formation. Note the abundant fragments of metavolcanic rock one of which (lower left-hand corner) has a trachytic texture. The bulk of the other clastic constituents is quartz and feldspar. Plane light; × 15.

and andesine. The matrix is chiefly chloritic and sericitic; muscovite in distinct flakes is generally a minor constituent. Quartz, typically, is marginally embayed and replaced by sericite, chlorite, and less commonly by muscovite.

Quartzose siltstone lens.—A quartzose siltstone enclosed by the Spruce Top greenstone in the northern part of the wedge-shaped fault block (pl. 1) is assumed to be a lens within the slate and graywacke member of the Meduxnekeag formation (fig. 3). The Spruce Top greenstone enclosing it is believed to be a sill within the slate and graywacke member of the Meduxnekeag formation. The quartzose siltstone may be a xenolithic block in the Spruce Top greenstone sill, or may actually underlie the sill and have been brought to the present surface on a local anticline.

The rocks mapped as quartzose siltstone are gray to gray green, tough, and very fine grained. They have a closely spaced fracture or cleavage that generally is conformable with the cleavage of slate of the region. At one place the rocks have faint dark, irregular spots about one-quarter of an inch in maximum diameter and resemble spotted hornfels. Most of the thin sections resemble those of quartzose siltstone, but some contain subangular plagioclase grains of coarser grain size than the groundmass and such rocks may be partly tuffaceous. White mica in the ground mass is generally alined parallel to cleavage.

RIBBON ROCK MEMBER

A very distinctive unit of intercalated slate and argillaceous and quartzose limestone overlies the slate-graywacke member of the Meduxnekeag formation. Commonly, the impure limestone beds are irregularly contorted between even-layered uncontorted shale and shale partings. The layers of slate and limestone range from less than one inch to several feet in thickness, but most of the layers of limestone are less than half a foot thick. The limestone layers, being more susceptible to solution, stand in lower relief than the slate partings on weathered outcrops, so that the unit has a striking ribbed or ribbonlike appearance in most exposures. Veinlets and gash fractures filled with calcite are commonly associated with this unit of the Meduxnekeag formation. The calcite is probably of local origin derived from the limestone layers of the sequence during the regional deformation.

The slate and limestone of this unit have not been studied petrographically.

SLATE MEMBER

The youngest unit of the Meduxnekeag formation within the area mapped consists almost entirely of gray and gray-green slate. The slate of this unit, for the most part, is not distinguishable in outcrop from similar slate in other parts of the stratigraphic column, as for example the gray and gray-green slate of the upper part of the Hovey formation. At one place, though (designated by *E* on pl. 1 at the south end of the mapped area), the slate is distinctive in that it weathers to a buff color, it is very calcareous, and it contains deformed and fragmentary pelmatazoan columnals.

HOVEY FORMATION

The younger of the two formations recognized in the vicinity of Maple and Hovey Mountains is here named the Hovey formation after Hovey Mountain. The rocks of this formation are generally exposed west of the easternmost fault within the mapped area (pl. 1) and of the north-south fault that joins this major fault about 2 miles northeast of Maple Mountain. A generalized stratigraphic section of the Hovey formation is presented in figure 3.

LOWER PART OF THE HOVEY FORMATION

SLATE AND GRAYWACKE

The lower part of the Hovey formation as observed in the northwest part of T. D., R. 2 (pl. 1) consists of gray-green and green slate mixed with graywacke sandstone and conglomeratic graywacke. Except for the mappable lentils described below, the lower unit of the Hovey formation consists mainly of slate. Wherever layers of graywacke are present they commonly are a few inches to a few feet thick and are separated by layers of slate a few inches to a dozen or more feet thick.

Slate.—The slate of the lower part of the Hovey formation typically has a well-developed cleavage with steep to vertical dips. Generally the slate is smooth to the touch, although in a few places where it contains appreciable amounts of coarse silt-sized grains it is gritty. Some of the slate is calcareous and some noncalcareous insofar as it may or may not effervesce when treated with dilute hydrochloric acid. Laminated slate is commonly composed of irregularly interlayered calcareous and noncalcareous laminae. Pyrite is generally a sparse constituent of slate although it may be locally abundant.

On the basis of microscopic features the slate of the lower part of the Hovey formation can be broadly subdivided into two general types, mica-chlorite slate and quartzose slate, although slate with features gradational between these two types is common.

Mica-chlorite slate is characterized by a matrix of finely divided matter, composed chiefly of sericitic mica, chlorite, and quartz. Coarser grained particles are embedded within the matrix. These include angular to subrounded quartz and feldspar, muscovite, chlorite, slate fragments, and the accessory minerals sphene and ilmenite (often coated with leucoxene[1]), magnetite, pyrite, epidote, and tourmaline. The matrix of some thin sections of mica-chlorite slate is too fine grained for identification of individual minerals, although finely divided mica appears to be abundant. Much of this fine-grained mica has the color, habit, and birefringence of sericite. Sericite and chlorite commonly surround and embay detrital grains of quartz, and probably have replaced the quartz. Quartz or chlorite, or both, in places form secondary peripheral wedge-shaped growths on accessory magnetite and pyrite. Mica-chlorite slate is often interlayered with or closely associated with graywacke sandstone and conglomeratic graywacke.

Quartzose slate is microscopically separable from mica-chlorite slate in that its matrix is composed chiefly of finely comminuted quartz rather than of micaceous matter. Fine-grained sericite and chlorite are subordinate intergranular constituents of the quartzose matrix. Coarser grained particles of angular to subrounded quartz and feldspar, relatively coarse flakes of muscovite and chlorite, and accessory constituents similar to those of mica-chlorite slate are embedded in the quartzose matrix.

Slate with a matrix compositionally gradational between a micaceous paste of the mica-chlorite slate and finely comminuted quartz of the quartzose slate is also present in the district.

Graywacke.—The beds of graywacke commonly interlayered with slate in the lower part of the Hovey forma-

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[1] Leucoxene is used in this report for the opaque material that has a white color under reflected light and coats sphene and ilmenite.

tion include slightly metamorphosed sandstone and conglomerate. Although the rocks within the Maple and Hovey Mountains area have been weakly metamorphosed, the original character of many is still well preserved. Metamorphic rock names or prefixes have not been used, therefore, for all rocks; the nomenclature of sedimentary rocks is used for such rocks as graywacke sandstone and conglomeratic graywacke, and the carbonate rocks, for example, even though all these rocks are, in a sense, metasedimentary rocks.

"Sandstone" is used here to denote rocks of sedimentary origin that contain grains with a diameter between approximately 0.06 and 2 mm. In "conglomerate" the particles are larger than 2 mm in diameter. Graywacke sandstone is exposed along Number Nine Stream immediately north of the area of lenses of red and purple slate near Finnemore's camp in the northwest part of T.D., R. 2 (pl. 1). Typically, the graywacke sandstone is a fine-grained dark-gray to gray-green highly indurated rock that forms layers one to a few feet thick and has a faint layering caused by bedding in a few places. They are mostly fine-grained rocks; a few of them have a salt-and-pepper appearance.

In thin section the graywacke sandstone is seen to be made up of poorly sorted angular quartz and feldspar (chiefly plagioclase) cemented by a matrix of finely divided mica and quartz. Chlorite commonly occurs in discrete grains of fine sand size and may have formed through diagenesis, metamorphism, or both. Chlorite also occurs as small flakes in the matrix. Magnetite, pyrite, leucoxene-coated sphene, epidote, carbonate, fragments of slate, and fragments that resemble devitrified volcanic glass are minor constituents in a few of these rocks. With the exception of pyrite, and possibly some magnetite, the minor constituents (judging from their subspherical shape and round to subround outlines) are of detrital origin. Some of the magnetite and much of the pyrite have angular euhedral to subhedral outlines and are probably authigenic. Pyrite commonly is bounded by wedge-shaped growths of chlorite.

In addition to the graywacke sandstone described above there is a distinct conglomeratic graywacke found in the lower part of the Hovey formation. It occurs as one or more layers only a few feet thick and has been found at a few widely separated places, such as those designated by *C* and *D* on plate 1. The exposure at *C* is immediately south of the tote road, where it crosses the north-south township line common to T. D, R. 2, and T. 9, R. 3, west of Hedgehog Mountain. The exposure at *D* is on the southwest side of the Spruce Top greenstone on Meduxnekeag Mountain. The conglomerate is composed of an argillaceous matrix that cements rock fragments ranging in size from granules to small cobbles. These fragments consists of chert, slate, felsite, and limestone. The felsite and fragments of limestone commonly are fossiliferous.

SADDLEBACK MOUNTAIN MEMBER

Metaperlite, exposed principally on Saddleback Mountain, immediately west of Number Nine Lake, and on the northwesternmost hill of Hedgehog Mountain (pl. 1), is herein named the Saddleback Mountain member of the Hovey formation. It consists mostly of devitrified glass, chiefly keratophyre, but also contains minor amounts of other rocks. The metaperlite is believed to form two separate lenses of penecontemporaneous age in the lower part of the Hovey formation, below the horizon of the lens of conglomeratic graywacke that is exposed on Hedgehog Mountain. One reason for placing the Saddleback Mountain member in the lower part of the Hovey formation is because devitrified glass fragments and rounded pebbles, closely resembling vesicle fillings in the metaperlite, are observable under the microscope in some of the graywacke sandstone above the Dunn Brook member, which is at the base of the upper part of the Hovey formation. The position of the Saddleback Mountain member below the conglomeratic graywacke lens of Hedgehog Mountain is suggested by the areal distribution and structural relations of the metaperlite to this lens of conglomeratic graywacke.

Outcrops of the metaperlite characteristically have a cream-white to pale-tan weathered surface (rind) as much as half an inch thick; unweathered surfaces are green to gray green. Typically, the metaperlite is a tough and structureless aphanitic rock, commonly without secondary structures such as cleavage or regularly developed joints. Locally it contains quartzose amygdules as much as half an inch long, as well as small black amygdules of chlorite that grade down to the size of a pinhead.

Most of the metaperlite on Saddleback and Hedgehog Mountains is highly sodic (see chemical analyses 4 to 6, table 3), and contains albite or sodic oligoclase as a dominant constituent. Under the microscope, the keratophyre appears as devitrified glass with perlitic structure and a dusty, pale-orange cast, or as a completely crystalline rock whose perlitic structure has been destroyed. Albite and sodic oligoclase, along with

TABLE 3.—*Chemical analysis of the metavolcanic rocks in the Hovey formation, Aroostook County, Maine*

[Analyses by rapid method (Shapiro and Brannock, 1952)]

	1	2	3	4	5	6	7	8
SiO_2	52.3	61.3	65.6	65.8	67.3	67.3	68.4	72.8
Al_2O_3	12.7	14.4	14.2	14.1	13.6	14.2	12.3	15.4
FeO	10.1	6.2	4.6	3.7	3.6	4.2	5.4	.98
Fe_2O_3	4.6	1.2	1.1	2.3	2.2	1.5	1.0	1.5
MgO	2.7	3.5	1.6	1.3	.97	.79	1.4	.63
CaO	6.3	2.3	1.9	2.8	2.6	2.0	2.1	.48
Na_2O	1.9	4.0	5.4	5.5	6.2	5.0	1.8	7.7
K_2O	1.9	1.9	1.4	1.4	.70	2.0	3.2	.46
TiO_2	2.0	.93	.92	.90	.86	.80	.78	.34
P_2O_5	.71	.22	.35	.16	.17	.19	.23	.09
MnO	.30	.10	.16	.18	.21	.16	.20	.02
H_2O+	3.6	2.9	1.9	1.5	1.4	1.5	2.4	.63
H_2O-	.35	.07	.07	.12	.09	.06	.04	.03
CO_2[1]	.04	.06	.34	<.05	<.05	<.05	1.2	<.05
Sum	99.50	99.08	99.54	99.76	99.90	99.70	100.45	101.06

[1] CO_2 reported as 0<.05, not included in summation.

1. Specimen P-51-20. Volcanic breccia; serpentine-sphene-prehnite-stilpnomelane greenstone; Number Nine Mountain. Analysts: H. F. Phillips, K. E. White, and P. L. D. Elmore.
2. Specimen P-51-9. Meta-andesitic tuffaceous groundmass of volcanic breccia.; Birch Mountain. Analysts: H. F. Phillips, K. E. White, and P. L. D. Elmore.
3. Specimen P-51-11. Metakeratophyre; Birch Mountain. Analysts: H. F. Phillips, K. E. White, and P. L. D. Elmore.
4. Specimen P-50-89. Keratophyre (devitrified glass?); albite-actinolite-chlorite-stilpnomelane-sphene; Saddleback Mountain. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
5. Specimen P-50-97. Keratophyre (devitrified glass?); Saddleback Mountain. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
6. Specimen P-50-81. Perlitic keratophyre; albite-chlorite-sphene-actinolite-stilpnomelane; Hedgehog Mountain. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
7. Specimen P-50-78. Perlitic metarhyolite; Hedgehog Mountain. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
8. Specimen P-50-3. Metarhyolitic tuff or tuffaceous siltstone; "Spruce" Mountain. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.

subordinate amounts of quartz, are the dominant leucocratic minerals of the metaperlite; pyroxene is an essential dark-colored constituent and in places is spherulitic. Green antigoritic chlorite is very abundant, both as an intersertal groundmass constituent and as a replacement of devitrified glass, and possibly as a replacement of pyroxene. Leucoxene-coated finely granular sphene is also abundant; it occurs in the groundmass and enclosed within patches of antigoritic chlorite. Epidote with anomalous blue interference colors is a common accessory. Some of it has a spherulitic habit similar to that of the pyroxene, and in some places it appears to have formed from pyroxene. Epidote also occurs in the core of some amygdules where it is mantled by chert or quartz. Most amygdules, however, are filled with mosaic-textured quartz.

Needles of pale-green, weakly pleochroic actinolite occur as a metamorphic alteration product at the ends of laths of pyroxene in many of these rocks (see fig. 5). The chemical analysis of the specimen shown in figure 5 is listed in column 4 of table 3.

Albite and minor amounts of quartz, chlorite, and other minerals have recemented much of the perlitic keratophyre, which commonly is microbrecciated (see fig. 6).

FIGURE 5.—Photomicrograph of a crystalline keratophyre derived from recrystallized glass. Pyroxene (large dark-gray commonly prismatic crystals) partially replaced along the edges of its long axis by needles of actinolite (light gray) formed through metamorphism. Metamorphically formed actinolite needles also are scattered throughout the light-colored groundmass composed chiefly of albite and minor amounts of quartz. Plane light; ×140.

Stilpnomelane is generally an abundant accessory mineral in the metaperlitic keratophyre of Saddleback and Hedgehog Mountains, and it typically occurs as sheaflike bundles of very fine grained needles. It is markedly pleochroic from bright yellow to deep olive brown and may be ferristilpnomelane (Winchell and Winchell, 1951, p. 390). A mineral with similar habit but with pleochroism ranging from pale yellow to deep green and resembling ferrostilpnomelane is a sparse constituent in a few of the metaperlitic keratophyres examined.

Almost all the keratophyre in the Maple and Hovey Mountains area is characterized by a high Na_2O content, greatly in excess of K_2O (table 3, columns 3–6). The rock represented by analysis 7 (table 3) is a devitrified glass (see fig. 7) associated with the keratophyre on Hedgehog Mountain. In this rock K_2O exceeds Na_2O, and the Na_2O is much lower than it is for the keratophyre analyses in table 3. Not all the

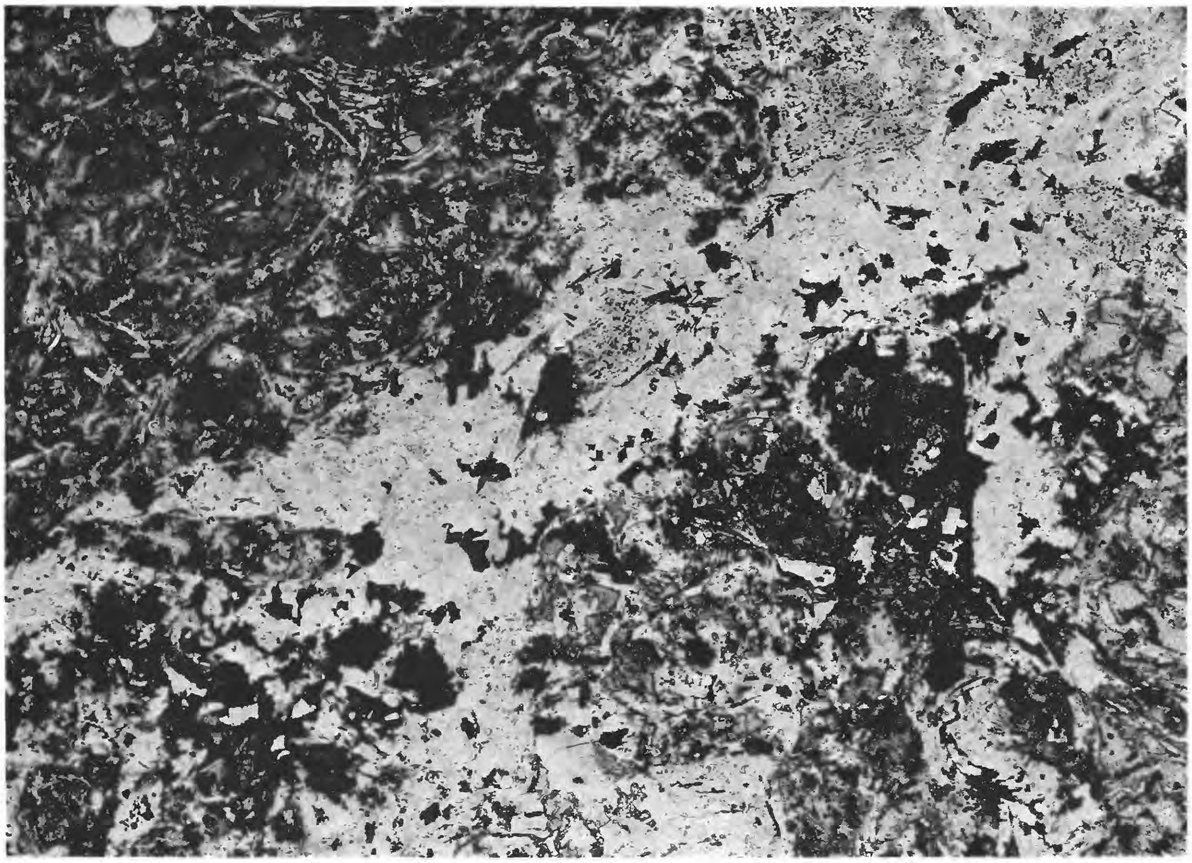


FIGURE 6.—Photomicrograph of a microbrecciated perlitic keratophyre from Saddleback Mountain. Perlitic structure is outlined in the dark fragment in the upper left-hand part of the photograph by long thin laths of albite that crystallized parallel with the concentric pattern of the perlitic cracks. The rock fragments are cemented by finely crystalline, fairly clear albite, and more coarsely grained albite mottled with chlorite flakes, as in the upper right-hand corner of the photograph. The fine needles in the albitic groundmass of the gash veinlet are actinolite. The very dark grains with high relief in the perlitic fragment in the lower right-hand corner of the photograph, and also in parts of the veinlet, are mostly epidote, whereas the lighter gray, more even textured grains are antigoritic chlorite. The amygdule in the upper left-hand part of the photograph is filled with quartz. Plane light; × 50.

minerals in this rock have been identified. Judging, however, from its high K_2O content, untwinned microcline or orthoclase may be abundant but not readily recognizable in thin section. At any rate, the absence of other potassium-bearing minerals and the minor amounts of accessory muscovite in this rock suport such an inference. The relatively high CO_2 content represents carbonate, which occurs chiefly as a replacement of devitrified glass and of feldspar. The devitrified glass has a pale reddish-brown color and a frosted appearance under polarized light even when recrystallized to a leucocratic mineral aggregate. A green chloritelike mineral of patchy habit and weak pleochroism, anomalous blue birefringence, and uneven extinction, is an abundant groundmass constituent and also replaces some of the part devitrified leucocratic constituents. Quartz is abundant, mostly as a filling in cracks between areas of devitrified glass, and plagioclase is present in small amounts. This rock is probably a metarhyolite or metalatite.

CONGLOMERATIC GRAYWACKE LENS

A distinctive conglomeratic graywacke crops out principally at and near the crest of the northwesternmost hill of Hedgehog Mountain (pl. 1). The limited distribution of this unit suggests that it is a lens. Typically the conglomeratic graywacke has a medium to fine sand-size matrix in which fragments of sedimentary rock greater than 2 mm in diameter are sparse. Microscopically, the cementing matrix is composed mostly of sand-size particles of quartz and feldspar embedded in a micaceous paste. (See fig. 8.)

Feldspar is generally present in different amounts (as much as 30 percent in one rock) from place to place

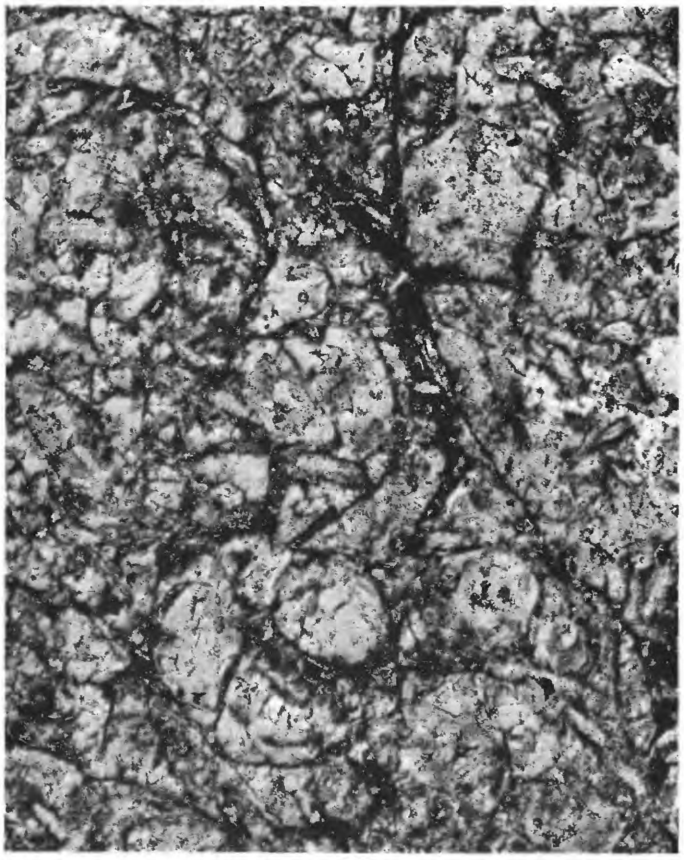


FIGURE 7.—Photomicrograph of metaperlite from Hedgehog Mountain. The perlitic cracks are accentuated by a fine-grained fibrous green material with anomalous blue birefringence that may be a variety of chlorite. Plane light; ×50.

in this graywacke. Sodic plagioclase (An_{5-20}) is the most abundant, and commonly the only feldspar in most of the rocks microscopically examined, although potassic feldspar has been observed in a few specimens. The plagioclase may be free of secondary minerals or speckled by varying amounts of sericite.

The type of plagioclase was identified chiefly in thin sections by measuring extinction angles of albite twinning, optic sign, and indices of refraction against balsam or quartz. In addition, coarser grained plagioclase from graywacke was determined by oil-immersion with index oils graduated to two decimal places.

RED AND PURPLE SLATE LENSES

Two small lenses of purple and pale-red slate interlayered with green slate are discontinuously exposed in the vicinity of Finnemore's camp on the low ridge northeast of the fire tower on Number Nine Mountain, and along Number Nine Stream just west of the place where it is crossed by the P.D. road (pl. 1). The slate in the lower part of the Hovey formation is lithologically similar to the red and purple slate of the upper manganiferous unit in the Maple-Hovey manganese deposit to be described later. The pale red and purple color of the slate results from finely disseminated hematite, which is more concentrated in some laminae than in others and imparts a megascopic layering to the slate in many places. With the exception of the hematite content, the slate is compositionally intermediate between the quartzose and mica-chlorite slate of the lower part of the Hovey formation.

UPPER PART OF THE HOVEY FORMATION

SLATE AND GRAYWACKE

The upper part of the Hovey formation typically contains mostly green and gray-green slate, although near its base it also is irregularly interlayered with graywacke sandstone and conglomeratic graywacke in much the same manner as in the lower part of the Hovey formation. Metavolcanic rocks of the Dunn Brook member are at the base of the upper part of the Hovey formation (fig. 3). The lenticular manganese- and iron-bearing deposits on Maple and Hovey Mountains are enclosed entirely by gray and gray-green slate, and are the youngest rocks that can be mapped in the upper part of the Hovey.

Slate.—The gray and gray-green slate of the upper part of the Hovey formation is megascopically indistinguishable from similar slate in the lower part of the Hovey. It is best exposed where it encloses the manganese deposits on Maple and Hovey Mountains. Gritty slate in the upper part of the Hovey formation is exposed along the road to Maple Mountain immedately northwest of the junction of the northeastward-trending faults that cut the deposits on Maple and Hovey Mountains (pl. 1).

Graywacke.—The beds of graywacke interlayered with slate near the base of the upper part of the Hovey formation resemble many of the graywacke beds interlayered with slate in the lower part of the Hovey formation.

A distinctive conglomeratic graywacke with abundant pebble-size fragments of black slate, which generally are alined parallel with the crude foliation of the rock, is exposed on the west bank of Hovey Brook where the Maine Forest Service telephone line crosses the brook (pl. 1). Approximately 2,500 feet upstream along Hovey Brook a pebble conglomerate of graywacke without conspicuous fragments of black slate is interlayered with dark-gray slate. A massive graywacke sandstone containing pelmatozoan columnals forms a waterfall along Hovey Brook at the point indicated by *A* on plate 1.

A conglomeratic graywacke exposed mainly where the Maine Forest Service telephone line crosses the south side of Hovey Mountain has fragments of volcanic rock that petrographically resemble the Dunn Brook metavolcanic rocks immediately to the east (pl. 1). Similar conglomerate, found only as irregularly distributed fragments of angular float, is peripheral to the horseshoe-shaped area of Dunn Brook rocks south of Hovey Mountain. The horseshoe-shaped area outlines a northeastward-plunging anticline. The graywacke peripheral to the horseshoe-shaped area of metavolcanic rocks appears to be a locally developed basal conglomerate overlying the Dunn Brook. Conglomerate is also present at several places adjacent to the Dunn Brook north and northeast of the manganese deposits on Maple and Hovey Mountains (pl. 1), and one such exposure along Hill Brook contains the remains of crinoids and branching stony bryozoans of unknown genus.

DUNN BROOK MEMBER

The Dunn Brook member of the Hovey formation is herein named after Dunn Brook which originates in the valley between the two hills on which these rocks are generally exposed.

The stratigraphic position of the metavolcanic rocks of the Dunn Brook member is inferred mainly from structural relations to be below the manganese deposits of the upper part of the Hovey formation. The Dunn Brook rocks to the northeast and south of the doubly plunging syncline that constitutes the Maple-Hovey manganese deposit (see pl. 1 and index map of pl. 2) are structurally and stratigraphically conformable with this fold. The top direction of the southwestward-plunging end of the syncline on Maple Mountain is to the southwest; therefore, the Dunn Brook rocks, half

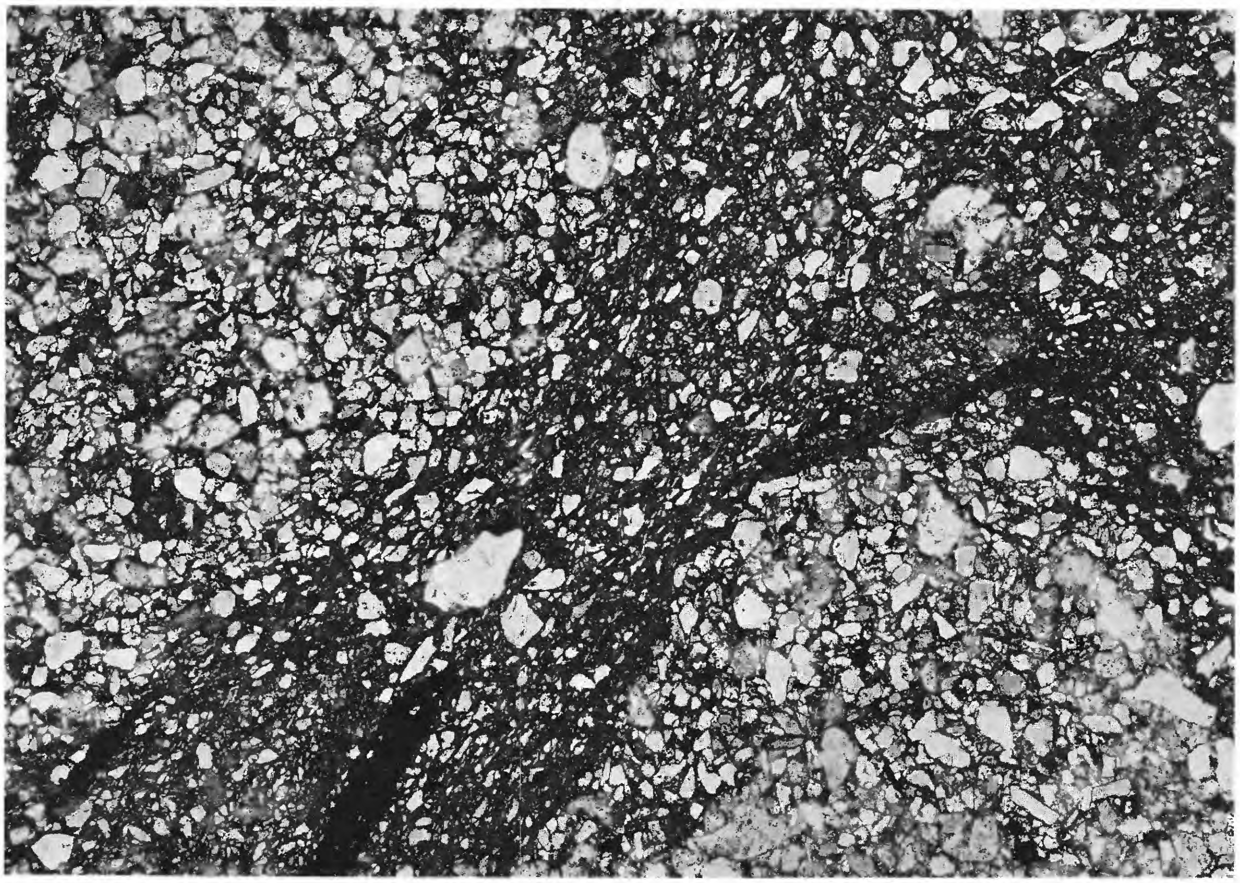


FIGURE 8.—Photomicrograph of conglomeratic graywacke from the lens in the lower part of the Hovey formation on Hedgehog Mountain. Parts of two large pebbles of graywacke sandstone are separated by a matrix of graywacke sandstone that consists of quartz, feldspar, and part of a slate fragment suspended in micaceous paste. Plane light; × 15.

a mile northeast of Maple Mountain, are believed to be older than the manganiferous rocks at Maple Mountain. In comparable manner, the top direction of the northeastward-plunging end of the Maple-Hovey syncline on Hovey Mountain is to the northeast, so that the Dunn Brook rocks in the anticline 1 mile south of this end of the Maple-Hovey deposit are also believed to be older than the magniferous rocks comprising this deposit. Furthermore, on the anticline south of the Maple-Hovey deposit conglomeratic graywacke overlies Dunn Brook metavolcanic rocks, as noted above, and indicates a northward top direction at the north end of the horseshoe-shaped area of Dunn Brook rocks. The manganese deposits north of that area of Dunn Brook rocks, therefore, are stratigraphically above the Dunn Brook.

Rocks assigned to the Dunn Brook member crop out in three areas. It is probable that the metavolcanic rocks north and south of the manganiferous deposits on Maple and Hovey Mountains were formed separately, but contemporaneously or nearly so. They may have formed as separate small volcanic piles rather than as one layer with stratigraphic continuity below the manganese deposits. In this report, however, they have been mapped as one unit.

The Dunn Brook contains a highly diverse assemblage of slightly metamorphosed grayish-green to green silicic volcanic rocks that typically weather to a white or cream color. Included within this member are aphanitic rocks that are dense and brittle, less brittle and vesicular, or tough and microporphyritic. The separation of these rocks is possible only by microscopic examination. Megascopically, they generally lack primary structures, such a flow banding, and trachytic texture, but many of them have a secondary cleavage which is conformable with that of the slate in the area.

Northeast of the manganiferous deposits and in an area bounded on the northwest by the fault cutting the deposits (see pl. 1) the Dunn Brook member contains aphanitic rocks, tuff and fine-grained volcanic breccia.

The Dunn Brook metavolcanic rocks that bound the southeast limb of the horseshoe-shaped area of greenstone, north and northeast of Number Nine Lake, are chiefly albitic aphanite, devitrified glass, and tuff. Volcanic breccia with some slate interbeds bounds the greenstone to the southeast. The volcanic breccia is best exposed along the upper ridge line of Number Nine Mountain.

The Dunn Brook rocks in the anticline south of the manganese deposits on Maple and Hovey Mountains are chiefly keratophyre, some of which has ovoidal quartz-filled amygdules that stand out in marked relief on weathered surfaces.

Volcanic breccia lentils

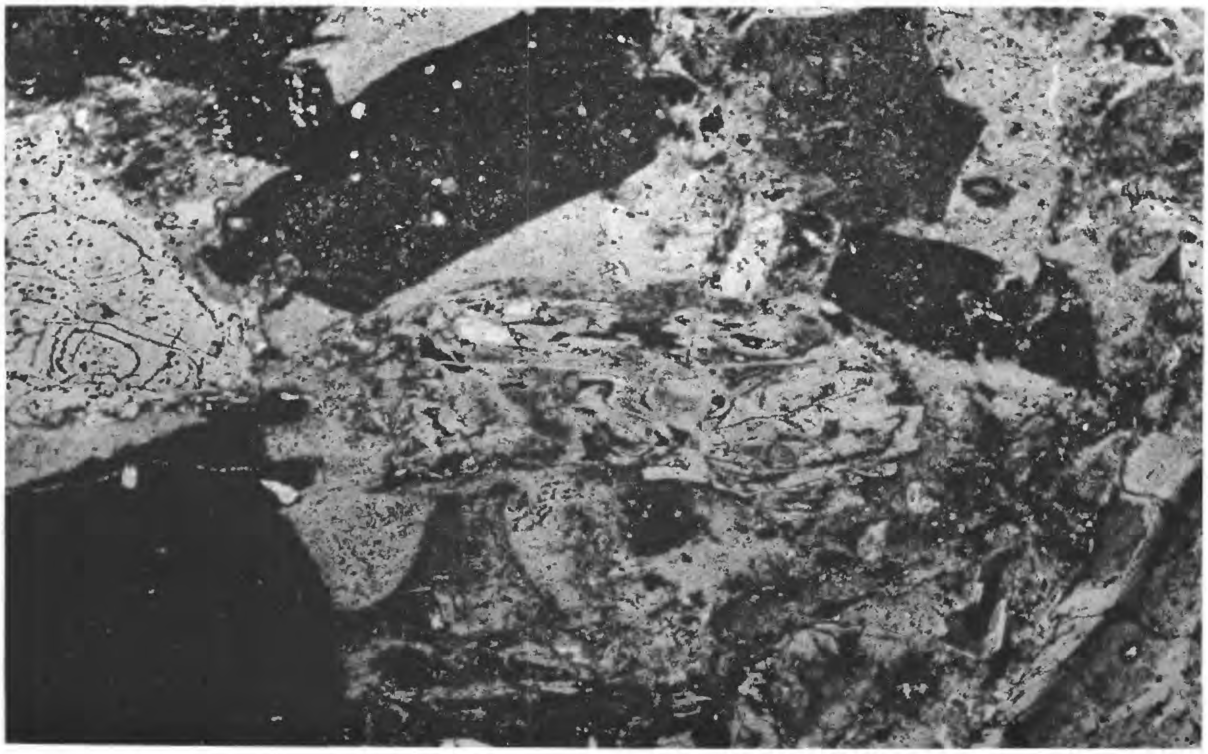
Breccia composed of fragments of volcanic rock is chiefly exposed in two lentils, believed to be at the base of the Dunn Brook member along the trail leading to the Maine Forest Service fire tower on Number Nine Mountain. (See pl. 1.) Although the breccia is believed to be largely of pyroclastic origin, it has some features which suggest it may be of mixed volcanic and sedimentary origin or that the volcanic fragments may have been reworked by water. In one specimen, for example, a layer of siltstone separates layers of breccia containing angular to subrounded fragments of metavolcanic rock. The matrix of the breccia appears to be a siltstone. This rock may have formed by the infall and mixing of silt and of volcanic fragments expelled explosively from a volcano, or through reworking of volcanic breccia fragments by water. In a volcanic breccia from Number Nine Mountain, abundant fragments of partly serpentinized volcanic slate and serpentinized and prehnitized volcanic glass fragments with remnant perlitic structure are the essential lithic constituents embedded in a fine-grained quartzose matrix (fig. 9). Column 1 of table 3 contains the chemical analysis of this rock.

Silicic volcanic rocks

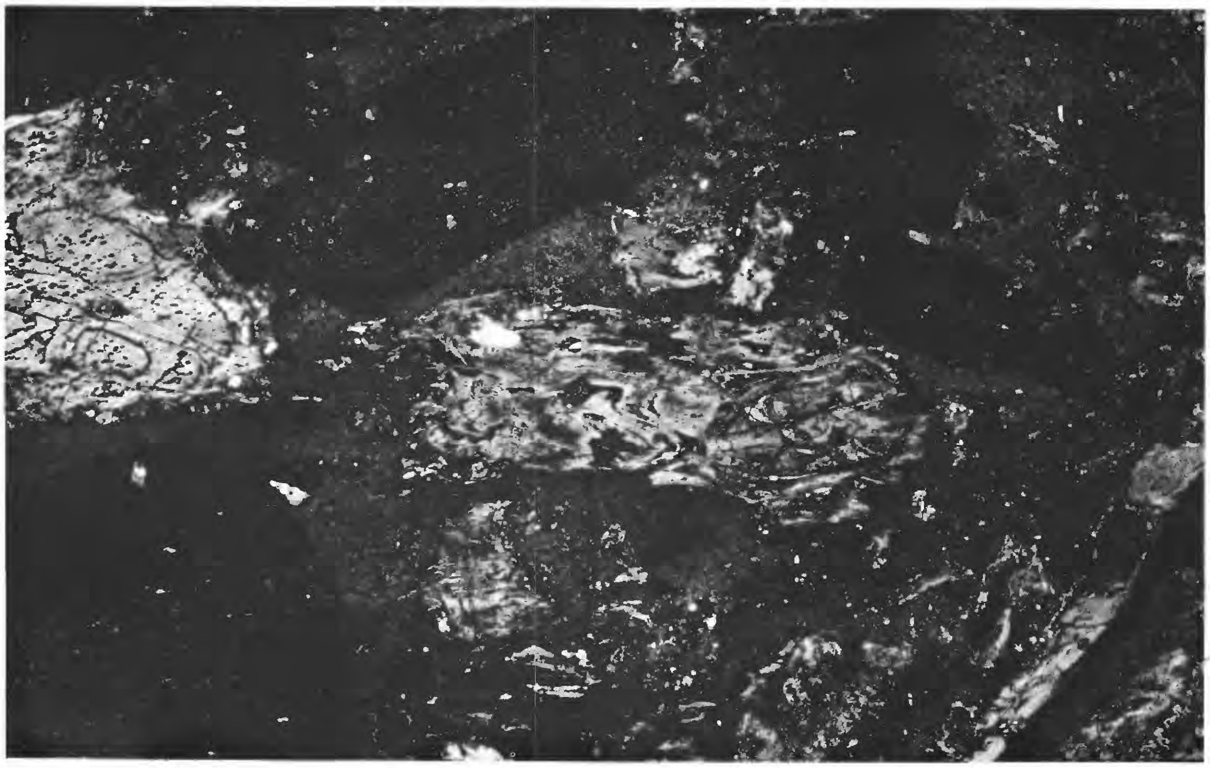
The principal rocks of the Dunn Brook member and their general distribution in different segments of the unit have been summarized above. The most abundant of these rocks are described below.

Explanation for figure 9

Typically, two types of altered volcanic fragments are embedded in a very fine grained quartzose matrix. The dark fragments are chiefly volcanic slate, partially altered to an antigoritelike material. The light-colored fragment with perlitic cracks (left margin of photographs) and the fragment (center of the photographs) with internal contortion (probably deformed perlitic structure) are volcanic glass altered to an antigorite mass. Fine grained leucoxene-coated sphene granules are embedded along and define the perlitic cracks in both fragments, and also occur as the small spherical granules that dot the perlitic fragment on the left margin of the photographs. Prehnite forms small spherulitic growths in most of the fragments; it has almost completely replaced the fragment lying left of the large sliverlike fragment near the lower right-hand corner of the photographs. The upper edge of the prehnitized fragment has low relief and weak birefringence and is devitrified glass. × 15.



A. Plane light



B. Crossed nicols

FIGURE 9.—Photomicrographs of volcanic breccia from Number Nine Mountain.

FIGURE 10.—Photomicrograph of keratophyre with felty texture. The feldspar laths of the groundmass and the feldspar phenocrysts are albite. Finely granular sphene coated with leucoxene is a very abundant groundmass constituent. Crossed nicols; × 50.

Keratophyre.—The keratophyre of the Dunn Brook member has mostly felty and trachytic textures (see fig. 10). Such keratophyre is typical of the Dunn Brook in the northeastward-plunging anticline south of the manganese deposits (pl. 1). Keratophyre that originally was glass, such as that of the Saddleback Mountain member in the lower part of the Hovey formation is not abundant in the Dunn Brook. It occurs locally, however, in the area of Dunn Brook rocks that crop out north of Number Nine Lake (pl. 1).

The felty-textured keratophyre illustrated in figure 10 is an amygdaloidal and, in places, glomeroporphyritic rock, although this feature can be seen only in thin section. The feldspar is albite; the groundmass laths are usually spotted with leucoxene-coated granular sphene, and the phenocrysts are mottled, in addition, by flakes of chlorite and grains of epidote. Leucoxene-coated sphene is also a very abundant groundmass constitutent. Epidote, in addition to being intimately associated with albite, also occurs as finely granular material in ptygmatic veinlets, which cut across all the textural and structural features of the rock, including the amygdules. The amygdules are filled mostly with chert. Some of the smaller amygdules are partly or completely filled with a pale yellow-green aggregate the grains of which have a blue interference color and fibrolamellar to flaky habit and may be penninite. Where epidote veinlets cut the chloritic amygdules, the epidote is well crystallized and tabular adjacent to the contacts with chlorite and finely granular within the veinlets. The well-crystallized epidote is colorless and has strong to moderate interference colors in yellow, orange, and blue. Some crystals have anomalous blue interference colors. The epidote is finely granular wherever the epidote veinlets cut chert-filled amygdules. The close association between epidote and albite, where albite appears to have been pseudomorphously replaced in part by epidote, suggests that the epidote may have formed to some extent through the replacement or breakdown of calcic plagioclase. Epidote, formed by such saussuritization of the keratophyre, may have been mobilized and concentrated into veinlets during deformation.

Other minerals noted in the felty keratophyre are secondary carbonate and sericite (the latter generally as an alteration of feldspar), and quartz which is commonly abundant enough to warrant naming the rock quartz keratophyre. One sample of quartz keratophyre contains a green chlorite with colorless to green pleochroism and abnormal violet interference colors.

Trachytic keratophyre is found on a hill locally known as Birch Mountain half a mile southeast of the fire tower on Number Nine Mountain (pl. 1). The rock has glomeroporphyritic texture as seen in thin section; the feldspar of both the phenocrysts and the groundmass is albite. Antigorite is an abundant groundmass constituent. Antigoritic chlorite occurs in large patches either in association with the clusters of albite phenocrysts or in irregular-shaped aggregates, some of which resemble fillings of microvesicles. Leucoxene-coated sphene, generally of granular habit, is abundant in the groundmass and also spots the groundmass feldspar. It also appears to have replaced some tabular crystals of ilmenite pseudomorphously. A few large patches of carbonate are present in thin section and probably account for the higher CO_2 content of this rock as compared with the CO_2 of the other keratophyre. (See table 3, column 3, as compared with columns 4, 5, and 6.)

Tuff.—Tuff in the Dunn Brook member is abundant on Birch Mountain. Typically, it is a green or gray-green fine-grained rock some of which is microporphyritic, or vesicular, or both. Much of the tuff is transected by the regional slaty cleavage. The tuffaceous character is for the most part apparent only under the microscope.

Mixed lithic and crystal tuff is the most abundant variety found in a random selection of specimens from which thin sections were prepared. In general, the tuff contains fragments of felty and trachytic volcanic rock and phenocrysts of single crystals of feldspar or clusters of feldspar crystals (glomeroporphyritic texture) embedded in a groundmass of variable composition. Rounded to subangular quartz phenocrysts are generally sparse.

The fragments of volcanic rock and the feldspathic phenocrysts show different degrees of alteration, even in tuffs located close to each other. Thus, rock fragments may show only slight antigoritic alteration or they may be completely altered to an antigoritelike aggregate.[2]

Feldspar, either in glomeroporphyritic growths or in single crystals, is partly to completely replaced by several minerals. These minerals include chlorite, antigorite, muscovite, clinozoisite, and carbonate. The feldspar is chiefly plagioclase and ranges from albite to andesine. Potassic feldspar was identified in one specimen. Some of the intermediate feldspars are crossed by thin veinlets of albite(?) (resembles the host crystal but has a markedly lower index of refraction). This relation was noted in two thin sections and is believed to be a local feature. Some of the feldspar phenocrysts in the more highly sheared tuff evidently were broken and pulled apart during deformation. Such crystals are commonly connected by antigoritic aggregates.

The groundmass of the tuff in the relatively unaltered rocks contains a large proportion of indeterminate microcrystalline grains. The identifiable grains are chiefly quartz and feldspar. In highly altered rocks, the groundmass is an aggregate of antigoritelike material. Deformed angular shardlike fragments are present in a few specimens, but the degree of alteration of these particular rocks makes their identification uncertain.

Minerals that are alteration products of feldspar are also accessory groundmass constituents along with sphene, epidote, ilmenite, magnetite, apatite, and hornblende (rare). In some specimens, ilmenite is partially altered to sphene. Both ilmenite and sphene are invariably coated by leucoxene.

A meta-andesitic fine-grained tuff forms the groundmass of a volcanic breccia in the Dunn Brook member on Birch Mountain (for chemical analysis of this groundmass see table 3, column 2). The breccia has a fine-grained semitrachytic groundmass composed of thin laths of albitic feldspar, antigoritic aggregates, quartz, and microscopically unresolvable material. Feldspar phenocrysts and fragments of acidic volcanic rock are embedded in the groundmass. Sphene, partly coated with leucoxene, is a coarse-grained accessory as well as a fine-grained groundmass constituent. Fine-grained apatite is a minor accessory. The feldspar phenocrysts are highly altered; they are flaked by white mica, contain chloritic aggregates, and locally contain epidote. A few albite-filled gash veinlets cut the groundmass.

Rocks that may be mixtures of volcanic tuff and sedimentary rocks generally appear tuffaceous, insofar as can be judged by the angular volcanic fragments they contain, but also contain an ill-defined fine layering and rounded possibly detrital quartz grains. The fineness of grain size and the alteration preclude their being identified with confidence. Some of the rocks classed as mixed sedimentary rocks and tuff in reality may simply represent tuff, or possibly graywackelike slate. One such rock of indeterminate features appears in thin section as a highly altered rock with sericitized porphyritic and glomeroporphyritic feldspar set in a fine-grained groundmass. Fine-grained rounded quartz grains are abundant. Accessory chlorite, epidote, sphene, ilmenite coated with leucoxene, and small flakes of stilpnomelane in chlorite are groundmass constituents. The chemical analysis for this rock is listed in table 3 (column 8).

LENTICULAR MANGANESE DEPOSITS

The lenticular manganese deposits on Maple and Hovey Mountains generally appear to be about 3,000 to 5,000 feet stratigraphically above the top of the Dunn Brook member. Their stratigraphy and lithologic features are described in a later section.

AGE RELATIONS OF THE MEDUXNEKEAG AND HOVEY FORMATIONS

Within the area described in this report only one fossil locality, *E* on plate 1, was found in the Medux-

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[2] An antigoritelike aggregate is a material with an irregular patchy or bleblike habit that has a rough-looking surface. It may be colorless to green and weakly pleochroic. Under polarized light it is generally a weakly birefringent fibrolamellar aggregate with colors seldom above first-order gray but which may have various hues of anomalous blue.

TABLE 4.—*Identification and dating of fossils in the Meduxnekeag and Hovey formations, Aroostook County, Maine*

Formation	Locality (see pls. 1 and 2 for location)	Rock type	Fossils	Age	Authority
Meduxnekeag; upper slate member.	*E*	Buff calcareous slate	Pelmatozoan columnals	Post-Early Ordovician.	A. J. Boucot, written communication, 1953.
Hovey: Upper part	*A*	Graywacke sandstone.	Schuchertella sp.; Dalmanella?; rhipidomellid? sp.; homolanotid segment; meristellid; pelmatozoan columnals.	Post-Early Ordovician.	A. J. Boucot, written communications, 1953, 1960, 1961.
Do	*B*	Conglomeratic graywacke.	Pelmatozoan columnals (probably crinoids); branching bryozoans (probably of a trepostomatous type); brachiopod valve (poorly preserved and fragmentary).	do	A. J. Boucot, written communication, 1953.
Hovey: Lower part	*C*	do	Fossiliferous pebbles: Felsite tuff pebbles containing bryozoans (probably trepostomes). Limestone pebbles, some of which are almost entirely composed of pelmatozoan fragments (probably crinoids).	do	Do.
Do	*D*	do	Fossiliferous pebbles as at locality *C*; not studied in detail.	do	Do.
Do	*F*	Silty slate	Pelmatozoan columnals (mostly crinoids and some fragmentary cystoids).	Silurian(?)	R. B. Neuman, written communication, 1957.
Hovey: Upper part	Hovey Mountain DDH 52.	Limestone breccia	Pelmatozoan columnals	Post-Early Ordovician.	A. J. Boucot, oral communication, 1953.
Do	Maple Mountain DDH 31.	Green slate	Graptolite	Silurian	E. O. M. Bulman, written communication, 1955.

nekeag formation. This consists of pelmatozoan columnals and cannot be dated more closely than post-Early Ordovician (see table 4). Since the original mapping in this area, additional fieldwork has been carried out around the Maple and Hovey Mountains area and elsewhere and will be reported on by separate publications. In the course of such mapping to the east, in the Bridgewater quadrangle (Pavlides and others, 1961, p. 66),

> * * * elongate aggregates of ovoid pellets * * * were found [in ribbon rock of the Meduxnekeag formation] about 1¾ miles southeast of Bridgewater * * *. These aggregates are about 5 cm long, and 1 cm in cross section. The individual pellets are closely packed and ranged parallel to the borders of the aggregates. They are 2 to 3 mm long, and slightly more than ½ mm in diameter. Dr. Walter Häntzschel of the Geologisches Staatsinstitut, Hamburg, examined these pellets in 1958, and he suggested that they were the work of mud-ingesting worms, perhaps worms that had been given the generic name *Tomaculum* by Groom (1902). Such pellets were originally found in Ordovician rocks in England, and they have also been found in the Ordovician rocks of France, Germany, and Czechoslovakia (Pénau, 1941).

In 1960, W. H. Forbes, amateur paleontologist of Washburn, Maine, discovered graptolites in ribbon rock in a roadside exposure 2 miles east of Colby, Maine (Pavlides and others, 1961, p. 65–66).

> The fossils occur through several feet of calcareous siltstone. They are on the whole poorly preserved, most having been stretched or compressed. Many, however, are preserved in relief, and some that are preserved as molds yielded latex peels that afford good material for study.
>
> W. B. N. Berry examined the collection and identified the following forms:
>
> *Amplexograptus* sp.
> *Amplexograptus* cf. *A. perexcavatus* (Lapworth)

Climacograptus cf. *C. typicalis* mut. *posterus* Ruedemann
Diplograptus? spp. (two distinct kinds of this form are represented; one is long and slender, the other shorter and wider)
Orthograptus aff. *O. truncatus* (Lapworth)
Orthograptus truncatus cf. var. *intermedius* (Elles and Wood)
Other orthograptids of the *O. truncatus* type

Some of the orthograptids of the *O. truncatus* type are probably new. Their poor preservation, however, and that of the questionable *Diplograptus*, prohibits more certain identification.

The assemblage of many orthograptids of the *truncatus* group (especially the presence of *O. truncatus* cf. var. *intermedius*), other large diplograptids, and the *Climacograptus* of the *C. typicalis* group, is probably representative of the zone of *Orthograptus truncatus* var. *intermedius*. Closely similar assemblages have been recognized by Berry (1960, p. 38) from the Snake Hill and Canajoharie shales in New York, and the Magog shale in Quebec.

The ribbon rock near Colby, Maine, was mapped by White (1943, pl. 24) as ribbon limestone of the Aroostook and thought to be of Middle Silurian age (see table 1.) At the time White mapped in this region evidence from fossils relating to the age of the Aroostook limestone, however, was both sparse and inconclusive. It consisted of "fucoids, and trails and markings of worms or some other marine animals" (Williams and Gregory, 1900, p. 44). In addition, Williams states, "Specimens in light-greenish shales at Caribou and Presque Isle resemble * * * *Buthotrephis gracilis* * * *. Traces of *Acidaspis* are also seen, and in calcareous layers in Presque Isle and Mapleton *Bilobites bilobus*, an orthis close to *O. elegantula* [now *Parmorthis elegantula*] and *Nucleospira pisiformis* have been discovered" (Williams and Gregory, 1900, p. 44). These fossil genera are possibly of Middle Silurian age, and may even be of Late Silurian, but it is not known exactly from what part of the Aroostook limestone they were collected. In addition, the name Aroostook limestone as used by Williams included the shales and slates along the Aroostook River from Wade Township in Aroostook County, Maine, to its confluence with the St. John River in New Brunswick, Canada. In the United States, however, this section includes parts of both the Aroostook limestone and the overlying shale and slate as mapped by White and Cloud (White, 1943, pl. 24). The Silurian fossils cited by Williams as belonging to the Aroostook may be from the shale and slate unit mapped by White and Cloud as equivalent to the Ashland formation of former usage.

Twenhofel (1941, p. 168–169) was impressed by the greater amount of deformation and metamorphism the Aroostook limestone has undergone in comparison to the younger rocks that contain identifiable Silurian fossils. He pointed out that the Aroostook limestone has great similarity with some parts of the Ordovician Matapedia division of Crickmay (1932), or the Upper Ordovician Whitehead (Cape Blanc) formation of Schuchert and Cooper (1930). He thought these things might indicate that the Aroostook limestone was Ordovician and hence had undergone Taconic deformation in addition to later deformation. He felt, however, that Williams' fossil list tended to controvert such an interpretation. White (1943, p. 129–130), on the other hand, has indicated that the degree of deformation, at least in the northern manganese district, is a function of lithologic character of the rock sequence deformed.

The ribbon limestone member of the Aroostook limestone (White, 1943) is herein assigned a Middle Ordovician age and reassigned to the ribbon rock member of the Meduxnekeag formation.

Although the Middle Ordovician age of the ribbon rock member is established, the age of overlying and underlying members in the Maple and Hovey Mountains area is less certain. However, because they appear to be conformable with the ribbon rock member, they are tentatively considered also to be of Middle Ordovician age.

The age assigned the Hovey formation depends mainly upon the identification and dating of a few fragmentary and poorly preserved fossils. Seven of these localities are listed in table 4.

The only fossil of real use in dating any of these rocks is the graptolite found in one of the manganese deposits in the upper part of the Hovey formation. This fossil was in the core of diamond-drill hole 31 on Maple Mountain. According to Bulman, "this specimen is almost certainly a *Monograptus*. I do not consider it specifically identifiable, but it is perhaps more likely to be Lower than Upper Silurian in age" (Prof. E. O. M. Bulman, Sedwick Museum, Cambridge, England, written communication, 1955).

Most of the other fossils of the Hovey formation are of limited value in establishing the age of the rocks. As all the assemblages at localities *B–D* (see pl. 1) and some of the core in diamond-drill hole 52 contain crinoidal fragments, and as crinoids are not known from the Cambrian, the crinoid-bearing rocks must be Ordovician or younger. A. J. Boucot, of the U.S. Geological Survey (written communication, 1953) considered the fossils to be of post-Early Ordovician age. According to R. B. Neuman of the U.S. Geological Survey, (written communication, 1957), the cystoid fragments collected at locality *F* are "not incompatible with the Silurian age inferred for these rocks."

Recently (1959) a brachiopod fauna was found at locality *A* of plate 1, and supplements the original discovery of pelmatazoan columnals here. This fauna is listed in table 4. The fossils here are badly deformed and despite the examination of very large collections of fossiliferous rock it has not been possible to recognize fossils that closely date these rocks. According to A. J. Boucot (written communications, 1960 and 1961), the fossils from locality *A* of plate 1 may be of Silurian or Early Devonian age. Therefore, until more conclusive paleontologic evidence is obtainable, the upper part of the Hovey is assigned a Silurian age chiefly on the basis of the graptolite identified in one of the manganese deposits. The lower part of the Hovey, which is certainly of post-Early Ordovician age, tentatively is also considered to be of Silurian (?) age.

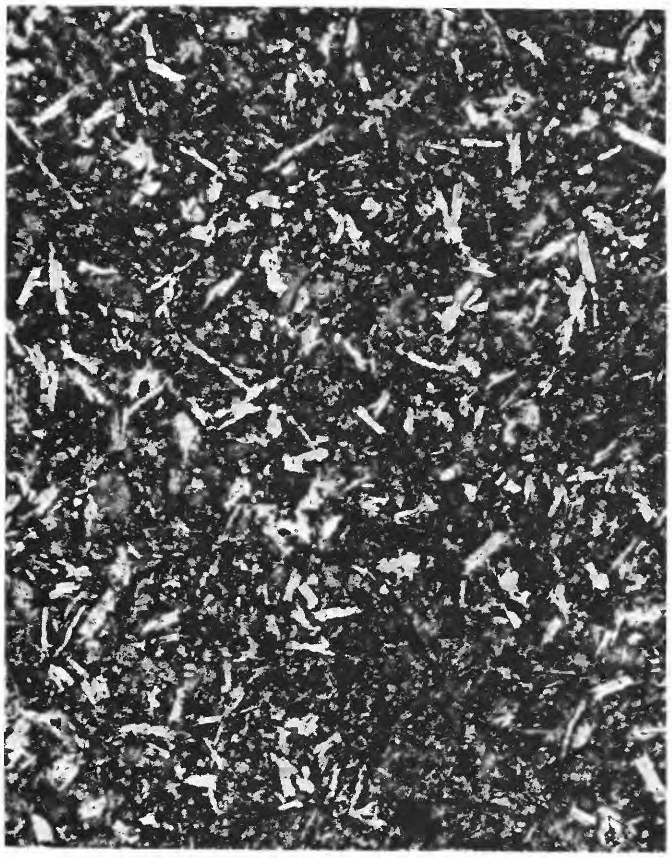


FIGURE 11.—Photomicrograph of albite-pyroxene-chlorite-sphene greenstone with intersertal texture. Albite occurs mostly as laths, some of which have scalloped sides. Pyroxene is the gray mineral with the rough surface. Sphene is the finely granular dark material, and chlorite occurs as very fine grained intersertal material not resolvable at the magnification used. Plane light; × 50.

SPRUCE TOP GREENSTONE

The name greenstone is used in this report as a field term, applied to dark-green metamorphic aphanites and phanerites with either basaltic or diabasic aspects.

Most of the greenstone occurs as large and distinct, apparently concordant, masses. The name Spruce Top greenstone is here applied to the rock, after Spruce Top, a small conical hill three-quarters of a mile north of the fire tower on Number Nine Mountain. Good exposures are present along parts of the north slope and at the crest of this hill.

Contacts between the Spruce Top greenstone of Silurian (?) age and the enclosing sedimentary rocks are not exposed in the area; therefore, whether the greenstone is a flow or sill must be inferred largely from indirect evidence. The outcrop pattern, the degree of crystallinity, and the textural features of the greenstone are inconclusive as to mode of origin. The abundant amygdules in a few of the fine-grained greenstone is no conclusive proof of effusive origin. However, as all these rocks are petrographically similar and because they occur in both the Meduxnekeag and Hovey formations, the parental rocks of the Spruce Top greenstone are believed to have been emplaced as sills after the Meduxnekeag and Hovey formation had formed but prior to the regional metamorphism of the area.

For the most part, the greenstone is dark green, but light-green varieties are also common. It is massive and commonly jointed, but lacks the regional cleavage which transects most of the other rocks in the district. Texturally, it ranges from aphanitic to phaneritic. The phanerites are fine to medium grained but in some places they are very coarse grained, as on the westernmost pinnacle of Meduxnekeag Mountain. The fine-grained greenstone generally has small black chlorite amygdules, similar to those in the metaperlite. Calcite-filled vesicles are present in a few of these rocks. Thin epidote-rich veinlets are irregularly distributed in some of the greenstone, and prehnite veinlets cut the greenstone on the southern hill of Collins Ridge east of Ketchum Lake (pl. 1).

The mineralogy of the greenstone, as determined by microscopic examination, is fairly constant. The different minerals within individual specimens of greenstone, however, show considerable range in abundance. The essential minerals in most of these rocks are sodic plagioclase, chlorite, sphene, pyroxene, amphibole, and epidote, all or part of which may be present in the thin section of any one rock. Quartz, apatite, carbonate, clinozoisite, prehnite, muscovite, stilpnomelane, scapo-

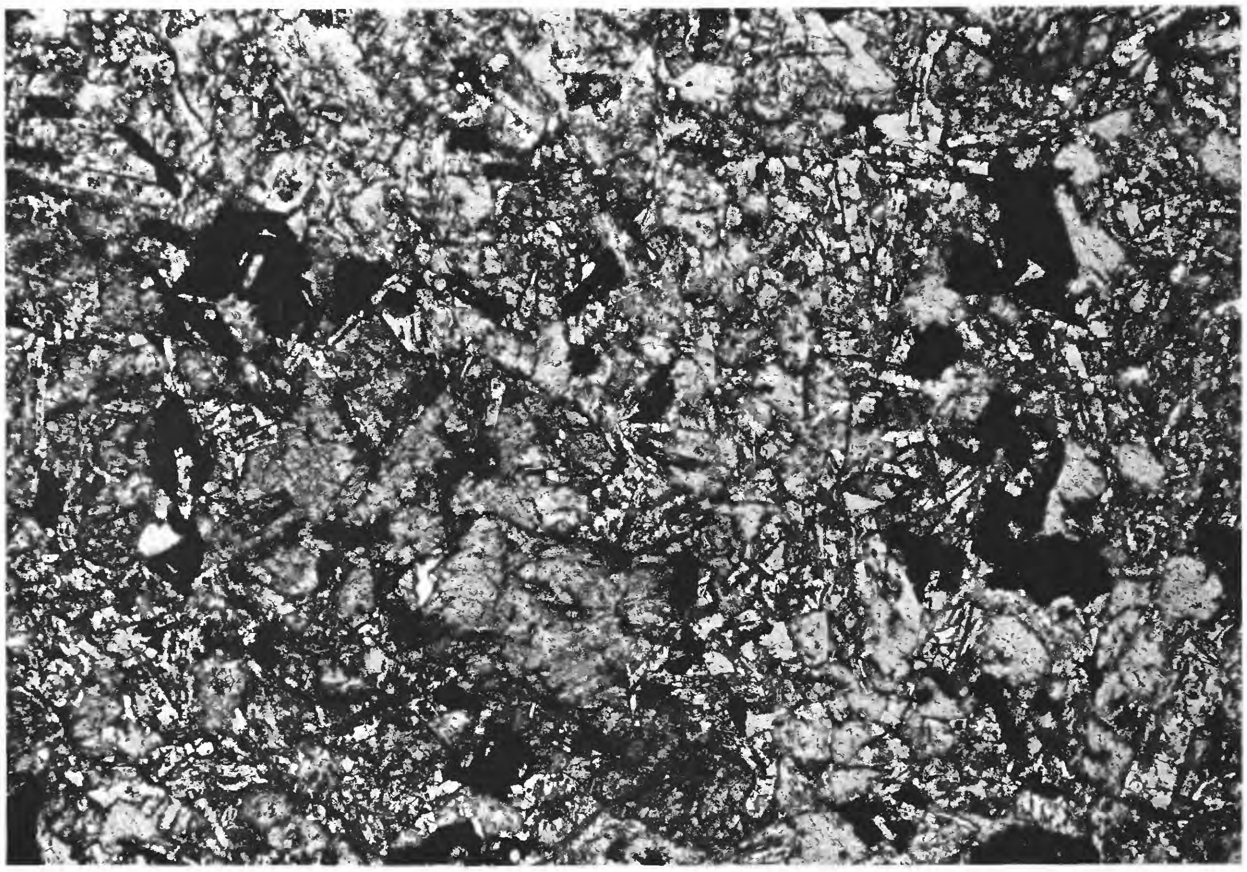


FIGURE 12.—Photomicrograph of albite-pyroxene-chlorite greenstone with ophitic texture. Sodic plagioclase occurs as tabular crystals enclosed in pyroxene. Much of the albite is coated with small scales and granules of pale-green chlorite, which impart a dark, rough-surfaced appearance to many of the albite laths. Most of the dark-gray mineral grains are pyroxene, although some are chlorite, which occurs as an abundant intersertal constituent of the rock. Chlorite bounds the right edges of the two large opaque grains at the right side of the photograph. The large opaque grains are skeletal crystals of ilmenite that have been almost completely replaced by leucoxene-coated sphene. Some of the smaller opaque grains are relatively unaltered ilmenite and magnetite. Plane light; × 50.

lite, magnetite, pyrite, pyrrhotite, and ilmenite are the subordinate minerals. Some of these, such as scapolite, prehnite, and pyrrhotite, are relatively rare, and prehnite is generally also restricted in areal distribution.

The greenstone commonly has intergranular and intersertal textures (see fig. 11), and a few of the coarser grained rocks have ophitic texture (see fig. 12). Some of the greenstone, especially that close to the contacts with the metasedimentary rocks, has variolitic to subvariolitic textures (fig. 13; for chemical analysis, see table 5, column 6).

Highly altered tachylite is closely associated with the variolitic aphanite. The analysis in column 2 of table 5 is of an epidotized metatachylite from Spruce Top hill. (See pl. 1.) Its microscopic features include perlitic structure and patchy areas with the reddish-brown color typical of glass. Lath-shaped, untwinned feldspar phenocrysts generally speckled with chlorite, and with indices less than that of canada balsam, are scattered throughout the slide. Judging from the K_2O:Na_2O ratio of this rock (table 5, column 2) as compared to the other greenstones in the area (table 5, columns 1, 3–9), the feldspar is probably potassic rather than sodic. Unaltered pyroxene occurs as microphenocrysts. Epidote, the most abundant mineral, appears to have replaced glass which has a reddish-brown tone and is perlitic. The microscopic features of the metatachylite suggest that the feldspar and pyroxene crystals were formed in a cooling melt that was later quenched to a glass when suddenly emplaced within cooler rocks near the earth's surface. The glassy portion was subsequently altered to epidote. The high CaO content of the tachylite, as compared with the CaO content of the other greenstones listed in

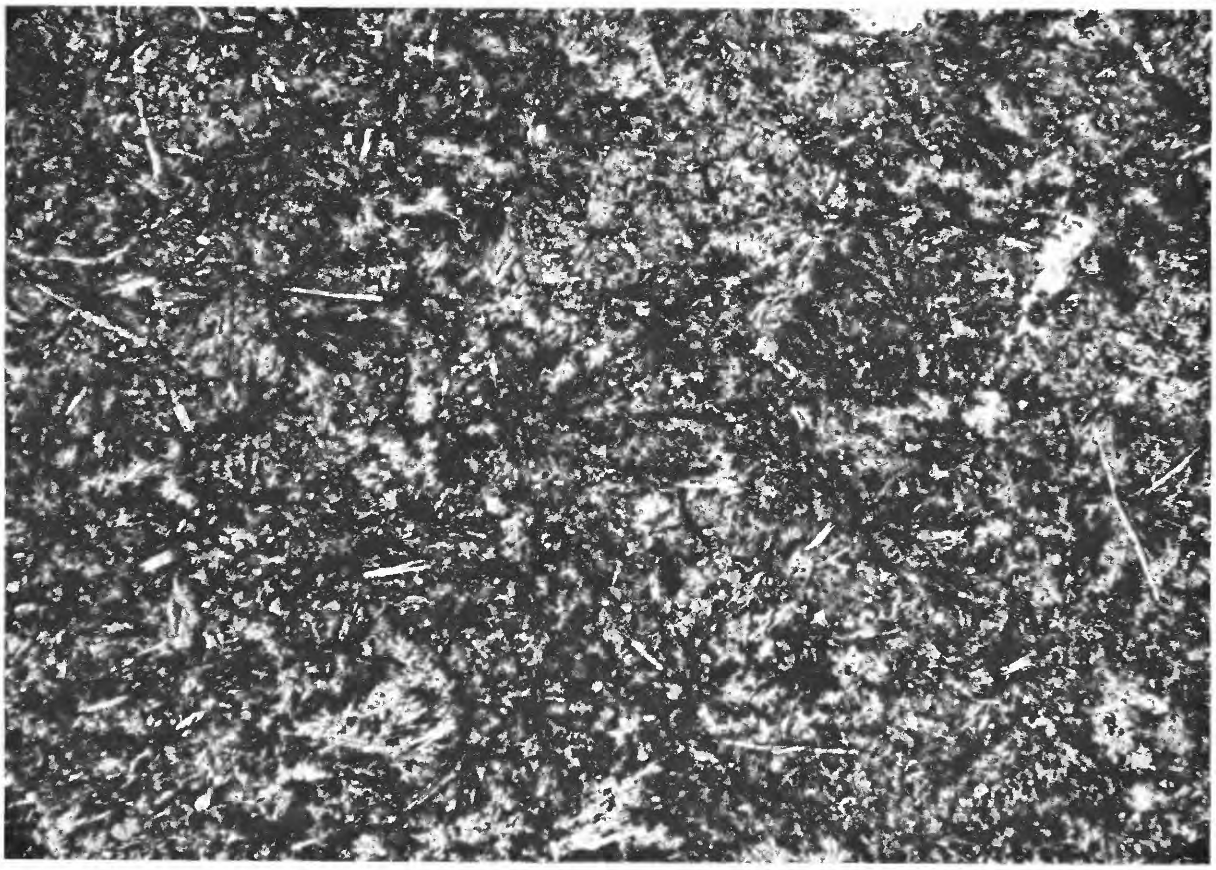


FIGURE 13.—Photomicrograph of albite-chlorite-sphene-pyroxene greenstone with subvariolitic texture. Albite occurs as thin laths; pyroxenes are the gray rough-surfaced grains. Sphene, mostly with a heavy coating of leucoxene, is the dark finely granular material. Green chlorite is a fine-grained intersertal constituent not resolvable with the magnification used. The variolitic texture consists chiefly of irregular sheaves of feldspar laths in radiate arrangement and with radial extinction. This texture is generally obscured by the fine-grained sphene that occurs as small granules on much of the plagioclase. Plane light; × 50.

table 5, suggests that its epidote formed by CaO metasomatism rather than as a product of saussuritization.

Sodic plagioclase in the Spruce Top greenstone is typically lath shaped and occurs either as a groundmass constituent, as distinct phenocrysts, or as glomeroporphyritic clusters. Few crystals are unaltered; rather plagioclase tends to be speckled with chlorite and less commonly with muscovite, or to be spotted with granular leucoxene-coated sphene. In many rocks, sphene and chlorite also commonly impinge upon and embay plagioclase marginally, giving it a scalloped or irregular outline. (See fig. 11.) Judging from extinction angles against albite twins, optically positive character, and refractive indices (mostly below or, in a few rocks, close to that of canada balsam), it has a composition ranging from An_{10} to nearly pure albite. Plagioclase with optical properties close to those of sodic oligoclase was also noted in a few rocks.

Several varieties of chlorite are present in the greenstone, but normally only one variety predominates in any given rock. Bright-green weakly pleochroic chlorite with low birefringence generally masked by the deep-green color is a common groundmass constituent in some of the greenstone. A light-green variety with low birefringence and pale anomalous blue tones commonly fills amygdules. Some of the coarser crystals of this chlorite are weakly pleochroic, have a small $2V$, and are optically negative. Optically positive chlorite has also been observed.

In many rocks, amygdules filled chiefly with chlorite enclose either pyrite, epidote, quartz, or chalcedony. Pyrite occurs mostly along the peripheral parts of chloritic amygdules and chalcedony forms the marginal lining of at least one amygdule whose core is filled with chlorite. Commonly, leucoxene-coated sphene is a peripheral constituent of such amygdules. Chlorite also occurs in veinlets, either alone or with other minerals. Some epidotic veinlets contain chlorite with anomalous blue or lavender interference colors. Chlorite also occurs as an alteration on plagioclase, amphibole, and pyroxene, and in some rocks appears to have completely replaced them. (See fig. 14.)

Apparently, two types of pyroxene are present in the greenstone. A colorless augitic variety with weak to moderate birefringence, and in places with hourglass structure, is the common type. The other type, noted in only a few rocks, may be pigeonitic; it is colorless, has weak to moderate birefringence, and a small 2*V*.

Actinolite is the only amphibole recognized in the Spruce Top greenstone. Most of it is present as fine-grained pale-green weakly pleochroic needles or fibers, which generally form as alteration or replacement growths along the ends of pyroxene laths, as in the metaperlite (fig. 5). Actinolite is also a groundmass constituent. In a few rocks, it occurs in coarser grained, bladed crystals, and in one rock it has a stubby subtabular habit. For the chemical analysis of an albite-actinolite greenstone see table 5 (column 7).

Epidote with optical properties close to those of pistacite is absent in many of the greenstones, is a minor constituent of some, and is very abundant in a few. It is normally colorless, biaxial positive, has a large 2*V*, and weak to moderate birefringence or is an anomalous blue. It may be tabular where well crystallized but more commonly it is in aggregate habit. Some granular epidotic material in several of the rocks has a low birefringence and is an anomalous blue; it is probably zoisite or clinozoisite rather than pistacite. The epidotic minerals appear to be of secondary origin. Epidote may extensively replace rocks such as the tachylite described above, but generally it is closely associated wih plagioclase and may be partly of saussuritic origin. It also coats and replaces both plagioclase and pyroxene. In addition, it occurs in thin veinlets and stringers and is associated with chlorite-filled amygdules.

Sphene is an ever-present constituent of the greenstone as well as of all the other igneous rocks of the area. It occurs in the groundmass as fine granules, almost invariably coated with leucoxene. The high birefringence of sphene is normally masked by the leucoxene alteration, but it can be seen in many thin sections under convergent light by using the substage condenser. Sphene also is closely associated with ilmenite and in some rocks has pseudomorphously replaced it. (See fig. 12.) It is intimately associated with pyroxene in a few greenstones. In one it fingers into albitic plagioclase along the twin lamellae but more commonly it corrodes albite marginally.

Brown stilpnomelane is generally subordinate in

TABLE 5.—*Chemical analyses of Spruce Top greenstone, Aroostook County, Maine*

[Analyses by rapid method (Shapiro and Brannock, 1952)]

	1	2	3	4	5	6	7	8	9
SiO_2	48. 1	48. 9	49. 4	51. 1	51. 4	52. 2	53. 2	53. 6	57. 5
Al_2O_3	17. 2	16. 4	12. 8	13. 2	14. 3	12. 1	17. 3	15. 1	13. 3
FeO	8. 1	6. 8	11. 7	8. 9	9. 0	9. 9	5. 5	10. 0	6. 9
Fe_2O_3	1. 0	6. 1	3. 0	3. 4	3. 5	1. 3	1. 3	1. 4	3. 8
MgO	7. 9	2. 4	3. 6	5. 0	3. 4	3. 9	6. 4	3. 4	2. 0
CaO	4. 4	11. 8	5. 8	6. 8	6. 8	7. 0	6. 0	4. 2	5. 0
Na_2O	3. 8	. 43	4. 1	4. 4	3. 4	4. 4	4. 6	3. 7	3. 6
K_2O	1. 2	2. 0	. 86	. 76	1. 0	. 80	1. 8	. 84	3. 4
TiO_2	1. 6	2. 6	3. 4	2. 5	3. 3	3. 2	. 40	2. 4	2. 0
P_2O_5	. 11	. 37	. 59	. 44	. 42	. 56	. 07	. 56	. 69
MnO	. 14	. 26	. 28	. 28	. 33	. 28	. 15	. 26	. 27
H_2O+	5. 0	2. 6	3. 3	2. 7	2. 7	2. 4	2. 6	3. 7	2. 4
H_2O-	. 07	. 08	. 24	. 18	. 19	. 23	. 09	. 10	. 15
CO_2*	2. 0	$<$. 05	. 06	. 03	$<$. 05	. 06	. 81	. 72	. 04
Sum	100. 62	100. 74	99. 13	99. 69	99. 74	98. 33	100. 22	99. 98	101. 05

*CO_2 reported as <0.05, not included in summation.

1. Specimen P-50-62. Chlorite-carbonate-sphene-albite greenstone; Porcupine Mountain. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
2. Specimen P-50-31. Epidotic metatachylite; Spruce Top hill. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
3. Specimen P-51-8. Albite-chlorite-pyroxene-sphene-zoisite greenstone; 1.05 miles N. 77° W. from fire tower on Number Nine Mountain. Analysts: H. F. Phillips, K. E. White, and P. L. D. Elmore.
4. Specimen P-50-45. Albite-actinolite-pyroxene-chlorite-sphene greenstone; Night Hawk Mountain. Analysts: H. F. Phillips, K. E. White, and P. L. D. Elmore.
5. Specimen P-50-28. Albite-augite-chlorite greenstone; Spruce Top hill. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
6. Specimen P-50-25. Albite-chlorite-sphene-pyroxene greenstone; Spruce Top hill. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
7. Specimen P-50-64. Albite-actinolite-chlorite-clinozoisite greenstone; Porcupine Mountain. Analysts: H. F. Phillips, S. M. Berthold, and P. W. Scott.
8. Specimen P-51-1. Albite-sphene-chlorite-scapolite greenstone; Meduxnekeag Mountain. Analysts: H. F. Phillips, K. E. White, and P. L. D. Elmore.
9. Specimen P-51-2. Albite-chlorite-augite-sphene-ilmenite-stilpnomelane greenstone; Meduxnekeag Mountain. Analysts: H. F. Phillips, K. E. White, and P. L. D. Elmore.

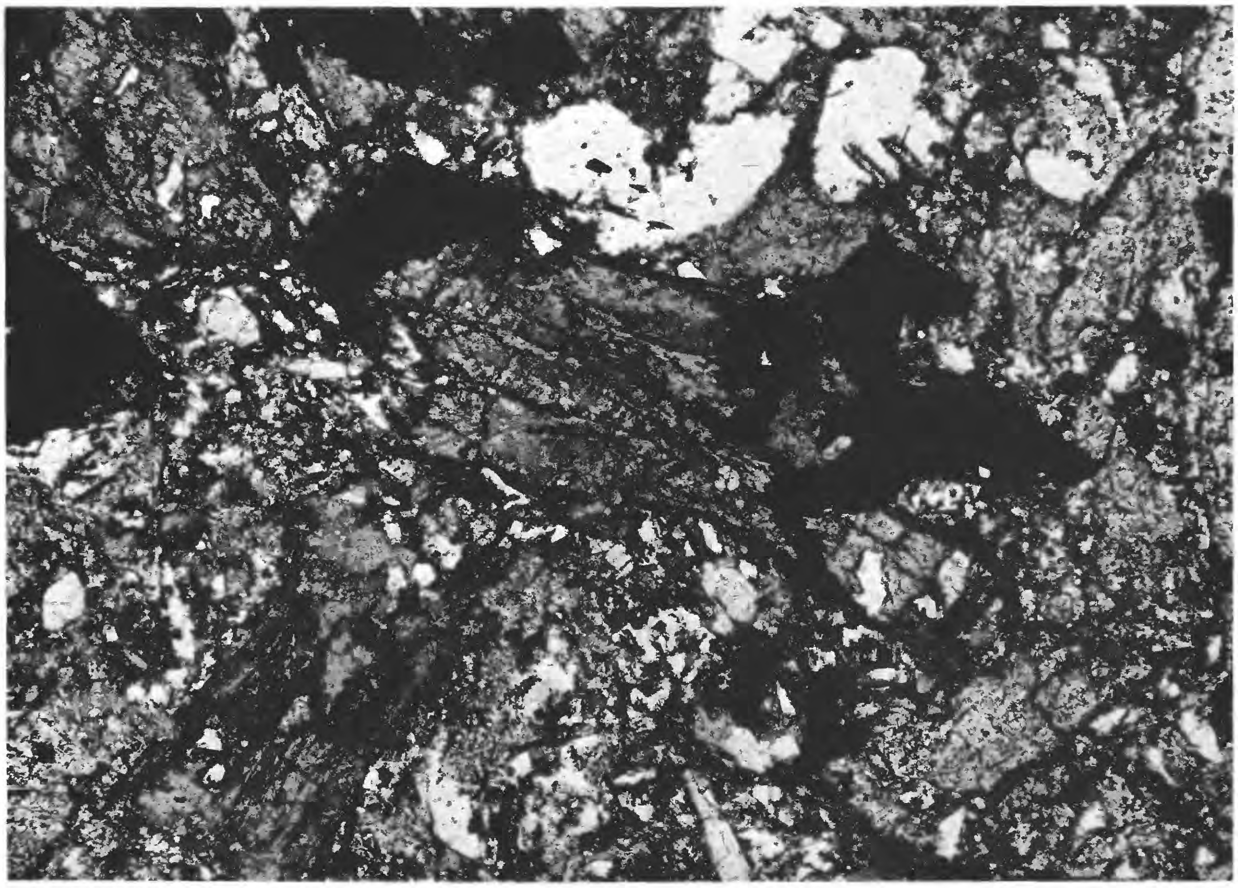


FIGURE 14.—Photomicrograph of chlorite-pyroxene-(albite) greenstone. Albite is not shown in the photomicrograph. The large dark-gray grains are pyroxene in different stages of alteration to green chlorite. The large tabular crystal of pyroxene in the lower left-hand corner of the photograph is almost entirely replaced by chlorite (lighter gray and lower relief). Apatite forms light-gray prismatic and stubby crystals throughout the photograph. The white grains in the upper part of the photograph are quartz. Subhedral crystals of ilmenite (opaque) are pseudomorphously altered to sphene along their edges. Plane light; × 50.

most of the greenstone. It occurs as bundles or sheaves of fine-grained needles and is markedly pleochroic, as in the silicic aphanites. Its pronounced amber to deep-brown pleochroism suggests that it may be ferristilpnomelane. A green variety, that may be ferrostilpnomelane, was noted in only one greenstone. In addition to its sheaflike occurrence in the groundmass, stilpnomelane occurs as an alteration on both pyroxene and albitic plagioclase, commonly with its long axis across the long axes of these minerals. Some stilpnomelane is also intimately associated with chlorite. In some chlorite-filled amygdules it may occur in the core of the amygdule and finger outward into the peripheral chlorite, suggesting that it formed through the alteration of chlorite.

Quartz is typically a subordinate primary constituent of many of the Spruce Top greenstones, and is fairly abundant in a few, such as those on Meduxnekeag Mountain (see pl. 1 and fig. 14); for chemical analysis, see table 5, column 9. Most of the other minor minerals generally occur as alterations and replacements of the other minerals. Thus, most carbonate and muscovite are alterations on plagioclase. Carbonate also forms veinlets either alone or associated with albite and chlorite. Prehnite occurs both in veinlets and in amygdules only in the greenstones on the southeast hill of Collins Ridge (pl. 1).

SERPENTINITE AND ASSOCIATED ROCKS

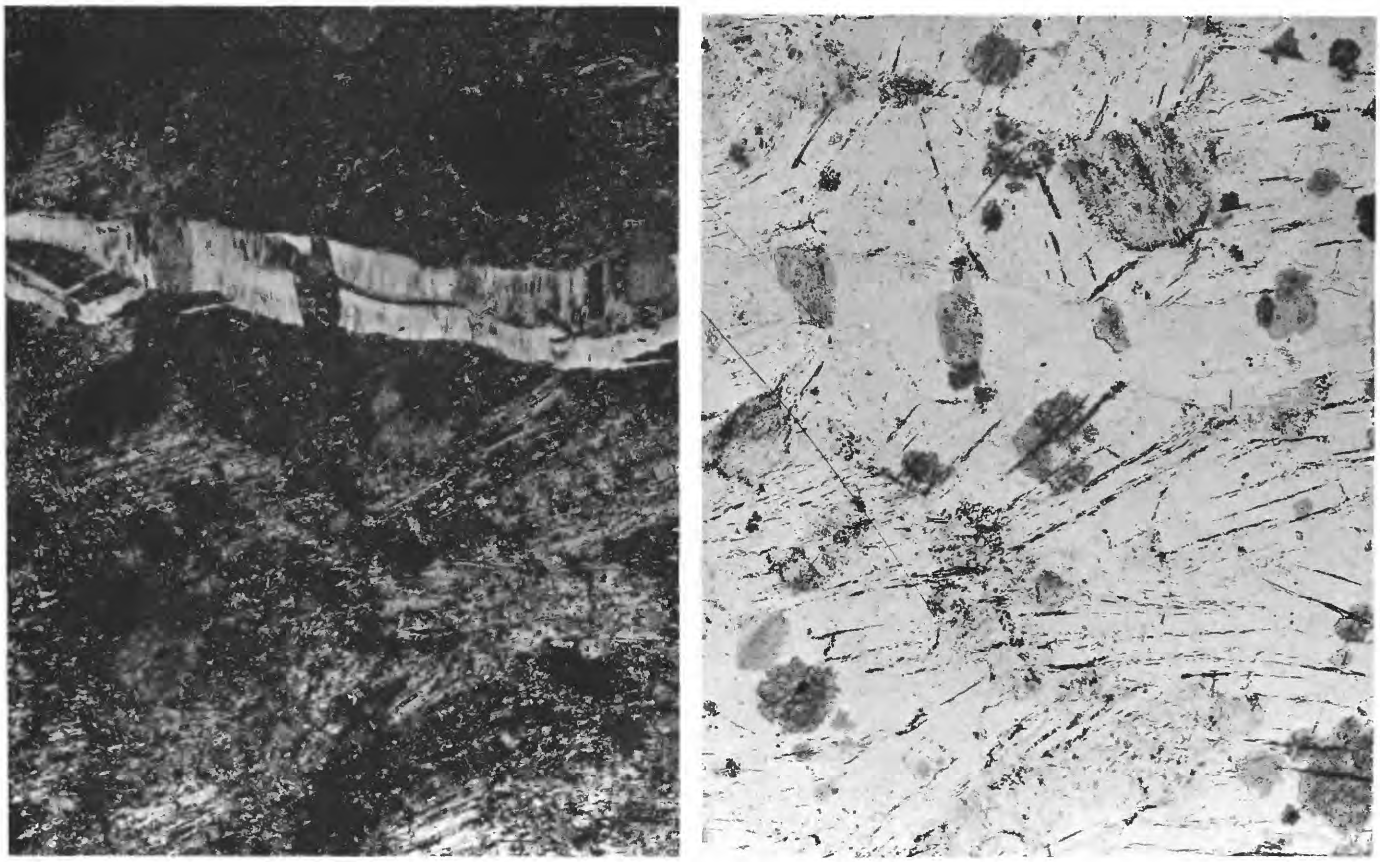
Serpentinite is exposed in two small areas on the small hill locally known as Porcupine Mountain, immediately south of Ketchum Lake. (See pl. 1.) The serpentinite is typically composed of fine-grained fibrolamellar antigorite. Original tabular crystals of the groundmass are now generally outlined by fine-grained magnetite as illustrated in figure 15. Chrysotile is in late veinlets that crosscut the antigorite. A minor amount of euhedral to subhedral chromite is found in the antigoritic groundmass. Carbonate is common in most of the serpentinite.

Some of the rocks on the lower northern slope of Porcupine Mountain are highly altered albite-pyroxene greenstone. The plagioclase and the pyroxene are extensively replaced by penninite (green or colorless chlorite with anomalous blue interference color).

Outcrops and boulders of coarse-grained gabbro with angular outlines which suggest float of local origin are abundant immediately north of the outcrops of serpentinite. The gabbro contains actinolitic amphibole, apparently pseudomorphous after pyroxene, as well as fresh pyroxene and pyroxene that is partly uralitized. The plagioclase of these rocks is highly altered to chlorite and coated with a kaolinitic dust. Antigorite is an abundant secondary constituent and and coarse-grained sphene is an abundant accessory. Pyroxene is partly or completely altered to antigorite in a few specimens. Carbonate is common.

One small outcrop of magnesite rock is exposed on the top of Porcupine Mountain close to outcrops of serpentinite. Carbonate-talc schist crops out in the gully of the stream immediately east of Porcupine Mountain, and is probably genetically related to the serpentinite.

The origin of the serpentinite and metagabbro is not clear. However, the close association of the serpentinite with a major fault conforms with the field association of many serpentinites (Turner and Verhoogen, 1951, p. 241). The greenstones which lie about 200 feet east of the serpentinite on Porcupine Mountain have a high content of both magnesia and carbon dioxide in com-



A. Plane light

B. Crossed nicols

FIGURE 15.—Photomicrographs of antigoritic serpentinite. Fine-grained magnetite outlines some of the original crystals as well as their internal partings or cleavages. The dark-gray patches with high relief in *A* are carbonate. The pseudomorphous replacement by antigorite is best illustrated in *B*, where antigorite has optical continuity in tabular habit conformable with grain outlines shown in *A*. The veinlet contains chrysotile. × 15.

parison to the other greenstones of the region. (See table 5, columns 1 and 7.) They also are the only rocks in which normative olivine appears (approximately 15 and 12 percent olivine in analyses 1 and 7, respectively). It is possible, therefore, that the Porcupine Mountain serpentinite formed through the alteration of an olivine-bearing rock, even possibly a dunite, emplaced along a fault near the close of the deformation of the region. The associated talc-carbonate and talcose schists probably were formed during the serpentization of the mafic rock or during its emplacement as a serpentine intrusive body.

GARNET PORPHYRY

A small mass of coarse-grained garnet porphyry crops out close to the point along the North Branch Meduxnekeag River where Burnt Brook flows into the river (pl. 1).

In thin sections the porphyry generally has a fine-grained quartzose and feldspathic groundmass with a minor amount of mica. Large phenocrysts of rounded, subspherical to irregular grains of quartz, feldspar, and probable quartz-feldspar rock fragments are the chief constituents of this rock. Commonly these constituents and particularly quartz are marginally embayed or corroded by fine-grained groundmass minerals.

The feldspars are highly altered to sericite and muscovite or clouded by kaolinite. Muscovite is a well-crystallized constituent but in many places it has altered pseudomorphously to chlorite. Commonly, the altered muscovite contains granular leucoxene-coated sphene along cleavage as does the biotite of the spotted hornfels. Reddish-brown biotite, generally associated with garnet, is commonly altered to pseudomorphs of chlorite. The garnet forms poikilitic grains. The margins of some of these garnets have retrogressed to chlorite; sharp dodecahedral corners of the original garnets are preserved by the chlorite rim. Carbonate is another common groundmass accessory of the porphyry, and also an alteration mineral on such minerals as feldspar. At one place pyrite is an abundant accessory both in the groundmass as well as within a muscovite mat that is pseudomorphous after a large feldspar crystal.

The coarse-grained porphyry may be a highly altered intrusive silicic porphyry. The clustered feldspars and the zoning of some feldspars strongly suggest magmatic origin. The garnet and the rounded and compound clastic-looking fragments suggest contamination through assimilation of country rock prior to freezing of the porphyritic melt. It probably provided the heat necessary for the thermal matamorphism of a wallrock of graywacke sandstone to the spotted hornfels which crops out near it. (See p. 33–34.) There is no evident baking effect, however, at the contact of this rock and calcareous slate, nor does the slate appear to be otherwise altered as might be expected if a porphyry had been injected into such a slate.

GRANITE

Granite at one place in Gould Brook and in several places closely spaced along an abandoned tote road in the southernmost part of the area (see location *G* on pl. 1) might be bedrock or glacial boulders. If these are glacial boulders, their nearest known source is the Mapleton granite (Williams and Gregory, 1900, p. 105) which crops out near the Aroostook River about 30 miles to the north. As similar granitic boulders have not been found north of these granitic exposures within the Maple and Hovey Mountains area, it is possible that they are actually bedrock or locally derived boulders from a granitic intrusive body.

STRUCTURE

The rocks of the Maple and Hovey Mountains area are folded and faulted. The dips of the layered rocks are mostly steep or vertical and many fold axes have steep or overturned plunges. The degree of deformation, however, varies between types of rock; the argillaceous rocks have been intricately folded, but the more competent rocks, such as the Spruce Top greenstone and many of the graywacke layers, are less disturbed.

The Hovey formation has been compressed into a series of parallel northeastward-trending, doubly plunging folds: southwest plunges predominate in the northeastern part of the area, and northeast plunges in the southwestern part of the area. The Maple-Hovey manganese deposit lies in the center of the structural depression between these areas of opposing plunge.

In the lowlands east of the Hovey formation, the Meduxnekeag formation is also folded along northeastward-trending axes. Within the limits of mapping, the formation appears, in part, to be on the east limb of a southwestward-plunging syncline; mapping has not been carried far enough southward to determine if the folds are doubly plunging on the same scale as in the Hovey formation.

Slaty cleavage with vertical or steep dips is well developed throughout the Maple and Hovey Mountains area. It has a persistent trend of about N. 50°–55° E. and is generally parallel to the axial planes of the regional folds. Cleavage with different northeast trends is also present. Such cleavage partly formed from local deflections induced in argillaceous rocks by areas of more brittle rocks around which the more plastic argillaceous rocks accommodated themselves at the time the cleavage was formed. The cleavage with the more easterly strike on the west side of Meduxnekeag Mountain at *D* on plate 1 may have formed in this way. In addition, some of the regionally aberrant cleavage is probably bedding cleavage. The cleavage in the lens of conglomeratic graywacke on Hedgehog Mountain appears to be such bedding cleavage. In some of the deposits on Maple and Hovey Mountains, such as the Central Hovey deposit, which is described in the next section of this report, cleavage does not parallel the axial planes of the folds. It appears therefore that the regional northeast cleavage of the area, which is so well developed in the argillaceous rocks, probably formed somewhat later than the folding. However, in most places it formed in a direction coincident with the axial planes of the major folds and is therefore generally usable, on a gross scale, for determining the plunges of folds and the position on the limbs of a fold by bedding-cleavage relations.

The dominant lineation in the district results from the intersection of bedding and cleavage planes. Minor crenulations with northeast and southwest orientation and plunge are present in the iron- and manganese-bearing rocks of the Maple-Hovey deposit (to be described in the next section), but have not been noted elsewhere in the district.

The joints in the area have not been systematically studied. Most of them have vertical to steep dips, and are more conspicuously developed in the brittle rocks of the district, such as the banded ironstone of the deposits (described later) or in the Spruce Top greenstone, than in the more plastic argillaceous rocks.

Numerous faults are believed to be present in the area. Most of those indicated on plate 1, however, have been mapped on the basis of indirect evidence. The major faults that cut the manganese deposits on Maple and Hovey Mountains are vertical or steeply dipping strike-slip faults. Diamond drilling suggests that a large strike-slip fault bounds the Maple-Hovey deposit on its northwest side and is curved as shown on the structure contour map (pl. 5). The other major faults in the district are probably also steeply dipping or vertical. Stratigraphic relations suggest that some of them are normal faults, but a few, at least, may be high-angle reverse faults similar to those mapped by White in the northern manganese district (White, 1943, p. 130). The northward-striking fault in the Bridgewater quadrangle in the northeastern part of the area (pl. 1) is along a pronounced positive magnetic anomaly detected during the course of the aeromagnetic survey of the Aroostook manganese belt.

METAMORPHISM

REGIONAL METAMORPHISM

The rocks within the Maple and Hovey Mountains area of Aroostook County, Maine, have all been slightly metamorphosed. The argillaceous rocks contain the association muscovite and chlorite, typical of the muscovite-chlorite subfacies of the greenschist facies as defined by Turner (1948, p. 96). Only a thermally metamorphosed hornfels, with red biotite and garnet, is of distinctly higher rank than the regionally metamorphosed rocks. The slaty cleavage of the low-grade metamorphosed argillaceous rocks results from the arrangement of muscovite and chlorite in subparallel to parallel planes.

The graywacke sandstone and conglomeratic graywacke either lack cleavage or are only crudely cleaved. The coarser grained flakes of chlorite in the graywacke probably were formed during metamorphism rather than diagenesis, but the time of formation of the fine-grained groundmass chlorite is more obscure. The scattered well-developed muscovite probably crystallized during metamorphism from the finer grained sericite of the matrix, and probably is more indicative of the metamorphism of the graywacke than is the chlorite. Nonetheless, the sandstone and onglomeratic graywacke have only been slightly recrystallized as compared to the slate with which they are intercalated. Apparently, the argillaceous rocks have an inherently greater susceptibility to metamorphism than do the coarser grained graywackes. A similar response to low-rank regional metamorphism by argillaceous rocks and graywacke has been reported by Turner (1936, p. 332) in the Te Anau Series of New Zealand.

Carbonate rocks, such as the calcareous ribbon rock member of the Meduxnekeag formation, probably recrystallized during deformation and metamorphism. Calcite, which fills the many gash veinlets in the limy layers, may have been dissolved from them and subsequently deposited in the fractures.

The effects of the low-rank metamorphism of the greenschist facies on the manganese- and iron-bearing deposits on Maple and Hovey Mountains are discussed in another part of the report.

The igneous rocks of the Maple and Hovey Mountains area have been reconstituted also by regional metamorphism, although metasomatic processes were responsible to some degree in determining the mineral suite of some of them. One of the problems of these rocks is distinguishing primary magmatic mineral suites, modified by mild metamorphism, from those formed almost entirely by metamorphism or metasomatism.

Albite or sodic oligoclase is a very common constituent in almost all the metavolcanic rocks of the Maple and Hovey Mountains area. The albite or sodic oligoclase of some of the keratophyre could be of primary pyrogenic origin, or it might be a product of soda metasomatism. The petrographic criteria cited by Gilluly (1935 fig. 1, p. 229–230) to support soda metasomatism were (a) "water-clear crystals of albite surrounding and radiating from mottled central crystals of albite," (b) "albite with radiate habit surrounding central crystals of either quartz or albite and so intergrown with quartz as to approach the granophyric texture," (c) albite veinlets with unmatched walls, (d) amygdules lined with water-clear albite, and (e) albite crystals with remnants of original more calcic plagioclase. In the present area, such features are either absent or of equivocal origin.

Some albite of the groundmass and phenocrysts of the keratophyre is probably a result of saussuritization of an originally more calcic plagioclase, as suggested by the speckling of epidote in albite phenocrysts and the epidote pesudomorphs after plagioclase in places. Irregular veinlets of epidote give evidence that at least some of this saussuritization of plagioclase during regional metamorphism took place in an open system in which such constituents as water and carbonate were able to circulate.

The groundmass chlorite of the keratophyre may have formed, in part, by deuteric alteration of interstitial glass, but the chlorite of amygdules and veinlets probably is secondary and may have formed during metamorphism, either by reworking of the groundmass chlorite or by the breakdown of pyroxene. (See fig. 14.) The actinolitic alteration of some of the pyroxene as well as the development of actinolite in the groundmass of some of the keratophyre probably formed during metamorphism. (See fig. 5.) The fine-grained sphene, which is ubiquitous in the metavolcanic rocks of the area, probably formed by the chemical combination of CaO (liberated during alteration of plagioclase and pyroxene) with titanium oxide exsolved from pyroxene or contained in ilmenite. The silica necessary for sphene came from these mineral transformations or from quartz. The pesudomorphic alteration of ilmenite crystals to sphene (see figs. 12 and 14) clearly demonstrates the secondary nature of the sphene.

Sausseuritization of calcic plagioclase was probably of particular importance in forming the albite and the other associated secondary minerals of the Spruce Top greenstone. Much of the greenstone apparently was originally of basaltic composition and contained fairly calcic plagioclase. The amount of CaO liberated by the saussuritization of the calcic plagioclase, as well as by the alteration of some augitic pyroxene (see fig. 14), must have been much greater than the CaO available in the silicic rocks. If metamorphism progressed in virtually an open system, the CaO so liberated, evidently having appreciable mobility, could have extensively replaced some of the rocks closely associated with the greenstone. The epidotic tachylite described above is enclosed by metabasaltic greenstone on Spruce Top hill. It has about twice the amount of CaO that the other greenstones in the area have (see column 2, table 5, and compare with columns 1, 3–9). Therefore, it probably was metasomatized by CaO mobilized during metamorphism of the basaltic rocks. Also, the prehnitic and epidotic metavolcanic breccia of the Dunn Brook member of the Hovey formation adjacent to the Spruce Top greenstone on Number Nine Mountain (pl. 1) probably underwent replacement by CaO which was mostly released through saussuritization in the adjoining greenstone. The prehnitic veinlets and amygdules in the ophitic greenstone on Collins Ridge (p. 24, 28) likewise are believed to have formed from saussuritically generated CaO.

Judging by observable alterations and similar textures, the secondary chlorite, sphene, and actinolite of the greenstone formed as they did in the keratophyre. Stilpnomelane appears to be somewhat more widely developed in the greenstone, however, than in the felsitic metavolcanic rocks. As might be expected, it is generally more abundant in both silicic rocks and greenstones that have a high ratio of iron oxides to magnesia (Turner, 1948, p. 97). (See table 3, columns 4, 5, and 6 and table 5, column 9.)

Although saussuritization of calcic plagioclase appears adequately to explain the origin of the albite in most of the Spruce Top greenstone, a special problem is presented by rocks with an ophitic texture, with fresh pyroxene enclosing albite laths that are generally somewhat mottled with chlorite (fig. 12). Saussuritization of calcic plagioclase seems inadequate to explain the albite ophitically enclosed by pyroxene because the expected association of epidote minerals are not found within the ophitic parts of the fabric (fig. 12) but only in the surrounding groundmass of the rock. If saussuritization actually produced the albite enclosed in the pyroxene, it would have necessitated the outward migration, through or from the pyroxene lattice and into the general groundmass of the rock, of at least calcium ions. Also, the reciprocal passage of at least magnesium ions through or from the pyroxene into the saussuritized plagioclase would have been necessary to produce the chlorite which mottles the ophitically enclosed albite.

An alternate hypothesis to saussuritization or soda metasomatism in explaining the origin of the ophitic albite greenstone of the Maple and Hovey Mountains area is that they are rocks crystallized directly from a spilitic magma. The existence of spilitic magmas, or spilitic melts formed through assimilation of sodic constituents by a normal basaltic magma, have been seriously questioned on physicochemical grounds. However, the rather wide distribution of albitic diabases as reported in the geologic literature strongly suggests that a magmatic origin cannot be entirely ruled out for such rocks. Turner (1948, p. 124) aptly summed up this situation when he stated, "On the whole, however, the hypothesis of simultaneous magmatic crystallization of albite and augite as a high-temperature equilibrium assemblage appears to be at least equally probable."

Although most of the rocks in the Maple and Hovey Mountains area have been subjected to temperatures and pressures representative of the lower part of the greenschists facies, some proved more susceptible to metamorphism than others, as described above in comparing graywacke with interbedded slate. Also, some higher rank minerals have persisted as unstable relicts (Turner, 1948, p. 18) within some of the rocks. The augite in many of the greenstones, for example, is partially or wholly altered to pseudomorphs of chlorite (see fig. 14), but occurs as fresh crystals in many others (see fig. 12). Likewise, possibly the sodic oligoclase in some of the graywacke and aphanites, and probably the andesine (?) in some tuffs are unstable relicts because the normal plagioclase of the greenschists facies is commonly highly albitic, and may even approach pure albite. The persistence of pyroxene and calcic plagioclase as unstable relicts reflects disequilibrium. Among the factors responsible for failure to reach equilibrium is the possibility that the pressure-temperature conditions during metamorphism did not persist long enough for complete chemical equilibrium to be attained, especially since retrogressive chemical reactions proceed at an extremely slow velocity as compared with progressive metamorphic reactions (Turner, 1948, p. 16). Also, the inherent physical properties of rocks, such as their ability to transmit stress or heat, may have been a factor contributing to the apparent chemical disequilibrium eventually attained.

CONTACT METAMORPHISM

Fine-grained spotted hornfels crops out near a small mass of coarse-grained garnet porphyry. (See p. 30 and pl. 1.) The hornfels is not shown on plate 1 because it is too small a unit to show at the scale of this map.

The spotted hornfels is a finely granular gray-green rock. Some rocks have a distinct purplish cast but in others this color is barely perceptible. Small round spots, normally a dark dull-purplish color, are a common megascopic feature. Small grains of porphyroblastic garnet and aggregates of garnet are chiefly responsible for the spotted appearance of the rock.

Thin sections show spotted hornfels consists of rounded to angular quartz grains, small amounts of feldspar, and fine grains of muscovite and reddish-brown biotite. Some of the quartz gains contain small flakes of biotite as inclusions. Large poikilitic garnets containing inclusions of biotite and quartz form conspicuous porphyroblasts. The garnet porphyroblasts normally have dodecahedral outlines but some garnet occurs in subhedral to anhedral habit in subspherical knots or clusters. The garnet is commonly highly fractured and its fractures are generally filled by muscovite. Other minerals are also present as fracture-filling constituents, but these are too fine grained and ill defined to be resolved in thin section.

Biotite and muscovite, in some of the spotted hornfels, have a decussate groundmass structure. In such rocks small garnets are intimately associated with reddish-brown biotite and quartz in small knots and clusters. A small amount of green biotite is present in one such garnetiferous knot. Much of the reddish-brown biotite has finely granular aggregates resembling leucoxene-coated sphene along cleavage. Randomly distributed rutilelike needles are common inclusions in reddish-brown biotite. In some garnetiferous clusters, biotite has altered to penninite (?) and to muscovite in places.

The spotted hornfels is probably a thermally metamorphosed clastic rock such as graywacke sandstone.

GENERAL GEOLOGY OF THE MANGANESE DEPOSITS

The bedded manganese deposits of Maple and Hovey Mountains are of two primary lithologies, namely, those consisting of manganiferous hematitic rocks and those with manganiferous siliceous carbonate rocks. In many respects, these rocks are similar to the sedimentary iron-formations of the Lake Superior region. They belong to the oxide facies and to the carbonate facies as described by James (1954). Metamorphism (described later) has locally modified the two primary lithologies into magnetite-bearing rocks. All the rocks in the region have been intensely deformed; the manganese deposits are in highly contorted, faulted folds with steep to vertical bedding. The lenses or parts of lenses that form the deposits are enclosed by green and gray-green slate. Their stratigraphic positions are partly deductible from the fault relations shown on the geologic map. (See pl. 2.)

Most of the information concerning the deposits comes from trenches and diamond-drill holes. The original trenches of the Manganese Ore Company were dug by pick and shovel; those of the U.S. Bureau of Mines were dug by bulldozer and hand-cleaned with pick and shovel and compressed air prior to sampling (Eilertsen, 1952, p. 11–12). The ends of the trenches shown on plate 2 for the most part expose bedrock and are not coincident with the ends of the bulldozed cuts, if bedrock was not exposed at these cuts. Inasmuch as many of the critical faults shown on plate 2 are inferred, the stratigraphic sequence assumed here is only as correct as the interpretation of the structure may be.

STRATIGRAPHY

The manganese- and iron-bearing rocks that form the deposits of Maple and Hovey Mountains are actually a series of lenses of different sizes which apparently lie at five different stratigraphic levels within green and gray-green slate in the upper part of the Hovey formation. (See explanation, pl. 2.) The order in which these lenses are described, namely, starting with the youngest and going to the oldest, is the reverse of the order normally followed. This organization is necessary, however, because a knowledge of the stratigraphy, distribution, and structural relations of the youngest and largest lens is fundamental in establishing the stratigraphic and structural relations of the other lenses.

The bedded manganiferous rocks on Maple and Hovey Mountains have been divided into four groups of deposits for purposes of description and reference in this report. This grouping has been made on the basis of structural, lithologic, and stratigraphic features common to the different deposits. The deposits so defined are the Maple-Hovey deposit, the Central Hovey deposit, the Southern Hovey deposit, and the small lenticular deposits. (See index map, pl. 2.)

UPPER SLATE

The slate immediately overlying the main manganiferous lens is referred to here for convenience as the upper slate. No upper stratigraphic limit is set for this rock and most of the description that follows deals with no more than 100 feet of slate immediately overlying the main manganiferous lens. This slate is generally grayish green to light green; it is unevenly interlayered with variably calcareous laminae. Small calcareous pellets or pods generally alined with the bedding are also common. Pyrite, which is sparse and sporadically distributed, occurs mostly as slightly distorted cubes as much as one-eighth of an inch in size. Cubes of pyrite commonly are alined within laminae and in some places are sufficiently abundant to form discrete thin layers. In a very few places, pyrite occurs as polished films along planes of rock cleavage. These films may be metacrysts smeared along planes of intense slippage.

The green and gray-green slate above the main manganiferous lens contains only a fraction of a percent of manganese.

MAIN MANGANIFEROUS LENS (MAPLE-HOVEY DEPOSIT)

The rocks that constitute the main manganiferous lens have been subdivided into three units designated the upper, middle, and lower manganiferous units, in order of increasing age. The Maple-Hovey deposit contains the most complete section of this lens. The units have fairly persistent chemical features and their stratigraphic boundaries coincide with certain manganese cutoff values. The thickness of each unit varies along strike in different parts of the deposit, probably, because of thickening and thinning of layers during deformation. The chief rock types in the three manganiferous units of the main lens in the Maple-Hovey deposit are gray and gray-green slate, purple and red slate, red hematitic shale, and banded hematite ironstone.

The columnar sections of diamond-drill holes 12, 26, 28, 37, 38, 40, 41, and 42 from the Maple-Hovey deposit are shown on plate 3. (See pl. 2 for location of drill-hole collars.)[3] Various adjustments of thickness were made in constructing these sections. First, the drill holes are at an acute angle to the dip and strike of steeply dipping beds, so that in every drill hole the true thickness must be computed rather than measured. The measured angles between bedding and axes of the cores were used for calculating true thickness. Second, because differences in thickness owing to deformation cannot be readily separated here from those of original deposition, the thicknesses of the manganiferous units and their individual layers have been proportionately modified to provide the value shown on plate 3. This was done by increasing or decreasing the actual computed thickness in each drill hole to the arithmetic average thicknesses of each respective unit. These arbitrary modifications of thickness facilitate comparisons of lithology and metal content. The amounts by which the computed thicknesses of the manganiferous units have been so modified are expressed by the percentage of variation from a unit value of 100 percent for each assigned average unit thickness and are indicated in column Tc of plate 3. This figure is designed primarily to illustrate the lithologic variations in the three manganiferous units of the Maple-Hovey deposit and the tenor of manganese and iron found in channel samplings across the units. The sections on plate 3 are arbitrarily spaced at regular intervals, without regard to their positions within the deposit or the actual distances between them.

A generalized composite columnar section of the Maple-Hovey deposit, based on the drill holes shown on plate 3, has been prepared (see pl. 4); it provides a more precise indication of the iron and manganese tenor of specific lithologic types than do the analyses on plate 3, because the latter analyses normally are of samples which include more than one type of rock.

The gray and gray-green slate within these units is megascopically similar to that of the upper slate described above. The red and purple slate physically resembles the green and gray-green slate except for color. Layering in the purple and red slate, however, is generally more conspicuous than in the gray and green slate; commonly it is a color banding of less vivid or more vivid purple and red slate, and of some green slate.

The hematitic shale generally occurs as thin red layers a fraction of an inch to several inches thick. It lacks slaty cleavage and typically is finely lined by the traces of dark-red to black paper-thin layers; some of the black laminations are braunite bearing. Hematitic shale lacks the pronounced banding and thin carbonate-rich interlayers that are typical of the banded hematite ironstone.

Banded hematite ironstone typically is a light-red to dark-red rock with a high specific gravity and a blocky fracture. The thickness of individual layers is variable, but most of the layers average between ⅛ and 1 inch. Individual layers are commonly very finely laminated (fig. 16). They vary in color and composition. The rock consists of alternating very dark red to black layers rich in hematite or braunite, lighter colored red layers with less iron and manganese oxides, and pink and gray layers virtually free of opaque iron and manganese minerals. The lighter colored bands normally contain carbonate and are more readily leached than the ferruginous layers during weathering. Consequently, they stand in lower relief to the red and black bands, imparting a finely ribbed appearance to most outcrops of banded hematite ironstone. The laminations are either even bedded or wavy bedded. Some layers pinch and swell.

Internal contortion and folding is a minor but ubiquitous feature (fig. 17). The nearly perpendicular attitude of axial planes to the bedding in some of the

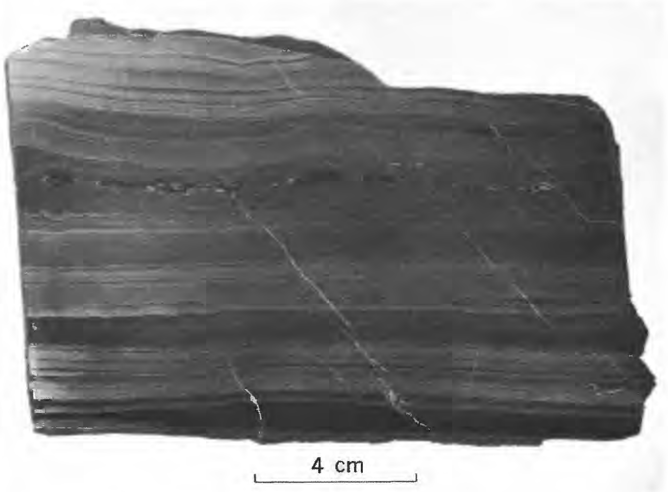


FIGURE 16.—Polished surface of a banded hematite ironstone, Maple-Hovey deposit. The dark-gray bands are mostly hematitic slate. The very fine laminae in the silvery-gray bands are chiefly specularite. Braunite-bearing blebs or podlike structures are present in one of the hematitic bands. The extremely thin fractures that cross the rock diagonally are carbonate-bearing.

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[3] The above drill-hole collars have the following approximate coordinates: drill-hole 12, 35,200 N., 16,600 E.; drill-hole 26, 33,350 N., 16,700 E.; drill-hole 28, 35,000 N., 16,300 E.; drill-hole 37, 31,900 N., 13,200 E.: drill-hole 38, 33,000 N., 15,500 E.; drill-hole 40, 32,750 N., 15,100 E.: drill-hole 41, 32,600 N., 14,100 E.; drill-hole 42, 33,300 N., 16,200 E.

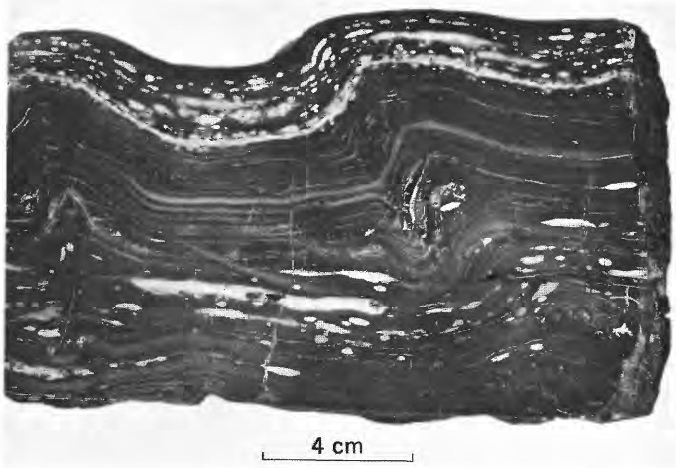

FIGURE 17.—Polished surface of a banded hematite ironstone showing folding, Maple-Hovey deposit. The white layer, pods, and lentils are carbonate bearing whereas the dark layers are hematitic.

internal folds, such as those in figure 17, suggests tectonic origin. Some of the microfaults in this specimen are mineralized, indicating that the rocks were competent when deformed. Displacements along small faults generally do not exceed a few inches and abruptly die out in the enclosing, undisturbed layers. Contortion and microfaulting are limited mainly to zones only several inches thick. Some of these structures may be preconsolidation sedimentary features. Similar microfaults in the iron-formations of Michigan have been attributed to a preconsolidation origin by James (1951, p. 256, and pl. 1, fig. 2).

Small elliptical pods of several colors and compositions are common throughout the ironstone (fig. 17). Black pods are braunite rich, whereas the white, tan, and cream-yellow ones are mineralogically more heterogeneous. These pods probably formed in several ways. Those that are isolated and have laminations of the ironstone wrapping around them probably originated as concretions; alternatively, they may be structures of accretion and concentration developed during diagenesis. Others are probably microboudinage structures formed by the attenuation and rupturing of laminae.

Rhodonite-bearing veinlets are conspicuous in the banded hematite ironstone. The localization of these veinlets and the paragenesis of the rhodonite are discussed elsewhere in this report.

Upper manganiferous unit.—The contact of the upper manganiferous unit with the overlying slate has been placed at the first appearance of a color change from grayish green to various shades of purple or red. In many places this contact is gradational, rather than sharp and distinct. The general lithologic features of the unit are illustrated in plate 4*A*. The slate in the upper part of the unit generally is a dull light purple and changes downward in the section to a brighter dark purple. In the lower half of the unit, the slate varies mainly from a dull earthy red to a bright brick red. Thin layers of purple slate enclosed by red slate occur within the lower part. Beds of green and grayish-green slate as much as 2 feet thick are present throughout the entire unit. More commonly, the green slate occurs in thinner layers intercalated with the red and purple slate. From one to several ½- to 1-inch-thick beds of altered volcanic ash or tuffs have been cut by 5 diamond-drill holes approximately 19 feet below the top of the unit.[4] Even where several ash beds are close to each other, it is not possible to determine whether they are separate beds or whether they represent one bed repeated by folding, faulting, or both. Megascopically, these layers are dark green to almost black, finely granular, and are enclosed by slate. Microscopically, they are all much alike, consisting of a highly sericitic groundmass enclosing sericitized feldspar and highly chloritized biotite. Apatite is an abundant, unaltered accessory, and granular leucoxene is the chief opaque mineral. White (1943) and Miller (1947) have noted the presence of similar layers of ash in the Dudley deposit of the northern manganese district.

Thin red hematitic layers are present throughout the upper manganiferous unit but are more common in its upper portion. (See pls. 3 and 4*A*.) Beds of banded hematite ironstone are generally restricted to the lower half of the unit, and commonly contain rhodonite-bearing veinlets.

The upper manganiferous unit has an average thickness of 57 feet. Wherever possible, the contact between the upper and the middle manganiferous units is placed at the base of a moderately persistent layer of green slate (see pl. 3) below which there is generally a continuous sequence of banded hematite ironstone. Where this green slate bed is absent, the contact normally is placed at the first appearance of well-developed thick beds of banded hematite ironstone. The irregular occurrence of the green slate at the base of the unit and its difference in thickness from place to place is probably a result mainly of folding, during which the bed

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[4] U.S. Bureau of Mines diamond-drill holes 24, 34, 35, 41, and 42.

was thickened, thinned, or totally eliminated by attenuation.

Middle manganiferous unit.—Although composed dominantly of banded hematite ironstone, the middle manganiferous unit also contains intercalated layers of green, purple, and red slate. (See pls. 3 and 4*A*.) The slate is generally thin laminae within layers of banded hematite, but in a few places there are beds of green slate several feet thick. Layers of interbedded green, purple, and red slate as much as several feet thick also occur in different parts of the unit, but not as commonly as those of the green slate alone.

The middle manganiferous unit, like the upper manganiferous unit, also has an average thickness of 57 feet. The contact between the lower and middle manganiferous units is placed where the lithology changes from banded hematite ironstone to a sequence of regularly interbedded green slate and red hematitic slate.

Lower manganiferous unit.—The lower manganiferous unit consists mostly of regularly interlayered green slate and hematitic slate. In many places, the slate is unevenly interlayered, the green slate being thicker and more abundant than the hematitic slate. Manganiferous banded hematitic ironstone is present in some places in the lower part of the unit. (See pl. 3.) Layers of this rock commonly are 1 to 5 feet thick, but may be as much as 14 feet thick. They also contain the rhodonite-bearing veinlets that are typically localized within this lithology. Layers of green laminated siliceous carbonate rock or ironstone also occur in the lower manganiferous unit. They are interlayered both with green slate and hematitic slate. The hardness of the hematitic layers of the lower manganiferous unit is markedly different from that of typical manganiferous banded hematite ironstone. They are readily scratched by a knife blade whereas the banded hematite ironstone is not. This feature proved useful in locating the contact between the middle and lower manganiferous units, particularly when logging diamond-drill cores.

The lower manganiferous unit has an average thickness of approximately 33 feet. The base of the lower manganiferous unit is placed beneath the last hematitic layer noted in the section.

Siliceous carbonate rock layers.—A thin and discontinuous zone from 0 to 23 feet thick, and with variable manganiferous tenor, of siliceous carbonate rocks, immediately underlies the lower manganiferous unit of the Maple-Hovey deposit. (See pl. 4*A*.) The siliceous carbonate rocks are mainly green, well-bedded ironstone composed of irregularly interlayered carbonate-rich and chlorite-rich beds and laminae. Locally these rocks contain conspicuous amounts of pyrite with pronounced stratiform distribution. (See fig. 29.) This differs markedly from the generally random distribution of pyrite metacrysts in the slate enclosing the deposits. The pyrite in this zone of siliceous carbonate rocks also forms massive microcrystalline pods or beads, ranging in size from those barely visible to those one-half an inch in greatest dimension. In some rocks, widely separated pyrite cubes are seen along bedding.

MAIN MANGANIFEROUS ZONE IN OUTLYING AREAS

The main manganiferous lens, in addition to cropping out in the Maple-Hovey deposit, also makes up the Central Hovey deposit. (See pl. 2) For the most part the three units of the lens in the Maple-Hovey deposit are also present in the Central Hovey deposit. The lens bounded by trenches 93 and 99 and designated by *E* on plate 2 is considerated to be separate from the main manganiferous lens, but to occupy the same stratigraphic horizon.

CENTRAL HOVEY DEPOSIT

For purposes of description the four fault blocks of the Central Hovey deposit are designated by the letters *A*, *B*, *C*, and *D*. (See pl. 2.) The deposit lies within a northeastward-trending belt, about 1,500 feet long and 500 feet wide in maximum dimensions (pl. 2). It contains the three manganiferous units described above, and is believed to be a faulted, more highly metamorphosed outlier of the main manganiferous lens. The physical and mineralogic differences between the Maple-Hovey and Central Hovey deposits may be due, in part, to differences in original sedimentary facies along strike as well as to modifications imposed by different degrees of metamorphism. The more thorough metamorphism that the Central Hovey deposit as a whole has undergone as compared to the more localized metamorphism in the Maple-Hovey deposit has impressed marked physical and mineralogic modifications on its rocks. These modifications also are present in the Maple-Hovey deposit wherever similarly metamorphosed (indicated by hachures on pl. 2). The purple and red colors of the slate in the upper manganiferous unit are pale and dull as compared to the hues of the typical slate of the upper unit in the Maple-Hovey deposit. Some of the interlayered green slate, on the other hand, is a deeper green than the normal slate in the Maple-Hovey deposit. In the middle manganiferous unit of the Central Hovey deposit the red banded hematite ironstone is a black banded magnetite-bearing ironstone or dull-red ironstone in which magnetite is disseminated in a hematitic groundmass. Laminations and banding in the ironstone, including features such as fluxion structure, are faithfully preserved. The lower manganiferous unit also has black iron-rich layers and interlayers of deep-green slate.

Because of the faults and changes of sedimentary and metamorphic facies, it is not everywhere possible to differentiate the three units within the Central Hovey deposit or to correlate them with the equivalent units in the Maple-Hovey deposit.

Segment *A* of the Central Hovey deposit is bounded by a fault at its northeast end and its manganiferous beds appear to lens out to the southwest at a point between trenches 61 and 105. (See pl. 2.) It is the only fault block in which the upper, middle, and lower manganiferous units all crop out. The middle manganiferous unit of segment *A* thins to the southwest and lenses out completely southwest of trench 106. A minor strike-slip fault separates the upper and lower units where the middle unit lenses out between them. The upper and lower manganiferous units also lens out abruptly to the southwest, somewhere in the interval between trench 61 and trench 105. The amount of each unit present in trenches 56 and 61 is not certain.

The rocks in fault block *A* are believed to occupy the northwest limb of a syncline; there, the middle manganiferous unit is lenticular, either because of lensing or because of attenuation during deformation. An alternate interpretation of the stratigraphy and structure is possible: the rocks in this fault block could represent a tight isoclinal southwestward-plunging anticline overturned approximately 25° NW. According to this interpretation, the rocks of the present lower unit would form the upper unit. The red and purple slate cut in diamond-drill hole 46 support this interpretation. Such an interpretation, however, would require the unlikely assumption that the lower unit has been completely squeezed out of the core of the anticline at the southwest end of the deposit, as rocks resembling it were not cut in diamond-drill hole 46.

Fault block *B* contains the remnant of a southwestward-plunging anticline (pl. 2). Diamond-drill holes 47 and 49 indicate that the bounding fault on the southeast, which strikes approximately N. 65° E., dips 65° NW. in the vicinity of trench 54. (See section *D–D′*, pl. 2.) It progressively cuts off the manganiferous rocks in block *B* at depth towards the north, until the vertical fault that terminates this deposit on its northern side is reached. The structure contour map (pl. 5) shows the curved nature of the trace of the intersection of the northwesterly dipping fault and the top of the middle manganiferous unit as it may appear below the surface. In this fault block, only the upper and middle manganiferous units have been recognized and were mapped at the surface in trenches 53 and 54. In trench 53, approximately between 100 and 180 feet northwest of the southeast end of the trench, the assay values of 5.56 percent manganese and 17.45 percent iron (Eilertsen, 1952, fig. 14) more closely resemble the tenors of the lower manganiferous unit than those of the upper or middle units. (Compare *A*, *B*, and *C* of table 12.) It is possible, therefore, that the lower manganiferous unit, greatly modified by metamorphism, is exposed in the core of this anticline.

Fault block *C* is the smallest block of the deposit. It is similar to fault block *B* in being a remnant of the nose of a southwestward-plunging anticline. Only the upper and middle manganiferous units are at the surface in this fold, as ascertained in trenches 51, 52, and 57 (pl. 2). The lower manganiferous unit was transected below the surface by diamond-drill hole 48. The deposit is cut off abruptly on its northwest side by a nearly vertical fault, adjacent to block *D*, and is separated from fault block *B* to the southeast by a northwestward-dipping fault.

Segment *D* of the Central Hovey deposit is also completely bounded by faults. It contains a thick section of the upper manganiferous unit, which appears to occupy the northwest part of the nose of a southwestward-plunging syncline. It is assumed that the absence of the middle and lower manganiferous units in this limb is believed to be primarily a result of original lensing. The manganiferous rocks of this segment are mostly pale-purple and red slate interlayered with green slate. Small lenses of magnetite-bearing banded ironstone are also present but are of irregular occurrence and could not be correlated between trenches, or from surface exposures, as in the northwest end of trench 52, to possible sub-surface extensions, as transected by diamond-drill hole 48.

The overlying and underlying slates are indistinguishable at the southwest end of the Central Hovey deposit where the manganese deposit lenses out. (See block *A*, pl. 2.)

LENS *E* BOUNDED BY TRENCHES 93 AND 99

Lens *E*, at about 30,000 N. and 10,500 E. on plate 2, occupies the same stratigraphic horizon as the main manganiferous lens (see explanation, pl. 2) but apparently does not have the three units of the main lens. Inasmuch as it consists of an irregularly interlayered sequence of hematitic shale and red and green slate, however, its lithology is generally similar to that in the main lens. A few beds of thin banded hematite ironstone are also interspersed in the sequence. Some of the hematitic rocks contain magnetite which probably formed during metamorphism. The rocks in lens *E* contain less magnetite, however, than the rocks of the main manganiferous lens in the Central Hovey deposit or some parts of the Maple-Hovey deposit, such as those in the syncline at the northwest end of the deposit.

The gray-green and green slate that encloses lens *E* is megascopically similar on both sides of the lens; however, the slate is subdivided into an upper and a lower slate (see pl. 2) in order that the terminology be consistent with that used in describing the main manganiferous lens.

Lens *E* is approximately 425 feet long and has a maximum width of about 50 feet.

LOWER SLATE

The gray-green and green slate underlying the main manganiferous lens and the small outlying lens *E* is termed the lower slate for purposes of description and has no set lower limit. It is not as well known as the upper slate, a considerable thickness of which was drilled in the vicinity of the Maple-Hovey deposit. (See pl. 2.) Rather widely spaced drill holes have penetrated only relatively short distances into the lower slate; hence, a continuous section is not available at any one place. The lower slate is megascopically similar and generally indistinguishable from the upper slate.

The lower slate encloses manganiferous lenses at four different horizons (see explanation, pl. 2), as well as a limestone breccia about 100 feet below the lowermost manganiferous lens (see pl. 4*C*).

SOUTHERN HOVEY LENS (DEPOSIT)

The lens of slate and ironstone that makes up the Southern Hovey deposit lies about 200 feet stratigraphically below the horizon of the main manganiferous lens.

The Southern Hovey deposit is the second largest in the area. The rocks do not crop out anywhere and float is sparse. The deposit has been explored by a series of trenches generally spaced about 200 feet apart, and by 8 diamond-drill holes.

Although the Southern Hovey lens is stratigraphically lower than the main manganiferous lens (Maple-Hovey and Central Hovey deposits) its manganese-bearing hematitic rocks are lithologically similar to those of the main manganiferous lens and are also subdivided into three units. These are manganiferous banded hematite ironstone, and both overlying and underlying interlayered manganiferous hematitic slate and green slate. The slates above and below the banded hematite ironstone are here called, respectively, the hanging-wall and footwall manganiferous slates. The general stratigraphic sequence in the Southern Hovey lens and its enclosing slate are summarized in plate 4*B*, which is a columnar section of the deposit as cut by diamond-drill hole 51.

The rocks of the Southern Hovey deposit appear to be lenticular, with varying thicknesses along strike, and probably downdip. The diamond-drill holes along the northwest side of the deposit provide that best evidence for the order of magnitude of strikewise variations in these thicknesses. The three units of the deposit have a combined average thickness of about 45 feet and a range of 26 to 64 feet in thickness along the northwest side of the deposit. (See table 6.) The hanging-wall slate averages about 13 feet in thickness, the footwall slate about 8 feet, and the banded hematite ironstone between the hanging-wall and footwall slates averages about 24 feet in thickness. Considerable local variations in thickness are characteristic of all these units.

TABLE 6.—*Calculated thicknesses, in feet, of the manganiferous units in the Southern Hovey deposit*

[Data from selected U.S. Bureau of Mines diamond-drill holes]

	Thickness of manganiferous units in diamond-drill holes—					Arithmetic average
	60	51	50	55	56	
Hanging-wall manganiferous hematitic slate	6	8	20	13	19	13
Manganiferous banded hematite	45	29	33	7	4	24
Footwall manganiferous hematitic slate	13	5	10	6	4	8
Total thickness of the deposit	64	42	63	26	27	45

Hanging-wall and footwall manganiferous units.—The hanging-wall and footwall slates of the Southern Hovey deposit generally resemble the upper and the lower manganiferous units, respectively, of the Maple-Hovey deposit. However, the units containing manganiferous banded hematitic ironstone in the two deposits are less similar in their physical resemblance.

The hanging-wall slate in the Southern Hovey deposit is composed mostly of red and purple slate of various shades interlayered with gray-green slate. A bed of volcanic ash one-half of an inch thick was cut by diamond-drill hole 51 in the lower part of the hanging-wall slate, and is very similar mineralogically to the volcanic rock in the upper manganiferous unit of the Maple-Hovey deposit described earlier. Similar beds of volcanic ash are also present in the gray-green slate stratigraphically overlying the hanging-wall slate (diamond-drill hole 61), and in the banded hematite ironstone within the deposit (trenches 71 and 74). The apparent sporadic distribution of these ash beds in and near the deposits of Maple and Hovey Mountains precludes their use as marker beds.

Manganiferous banded hematite ironstone sequence.—The manganiferous banded hematite ironstone sequence of the Southern Hovey deposit has a superficial physical resemblance to the middle manganiferous unit of the Maple-Hovey deposit. The ironstone-bearing units of these two deposits are similar in their light-to-dark red color, their high specific gravity, and their banding. The ironstone of the Southern Hovey deposit, however, is less brittle than that within the Maple-Hovey deposit and it has shaly partings; it also lacks a pronounced blocky fracture. In addition, it has a lower effective hardness and is more readily scratched by a knife. The banding of the ironstone in the Southern Hovey deposit is less pronounced than that of the other hematitic manganese-bearing rocks of the area. Nonetheless, this banding and the presence of light-colored layers in these rocks differentiates them from hematitic shale. Green slate beds are also contained in the manganiferous banded hematite ironstone sequence of the Southern Hovey deposit. A thin zone containing pyrite-bearing manganiferous siliceous carbonate ironstone layers is present immediately below the manganiferous hematitic rocks, in similar manner to the layers of siliceous carbonate rock underlying the Maple-Hovey deposit (pl. 4*B*). The manganese content of these rocks, in both deposits, decreases gradually with increasing stratigraphic depth until the tenor of less than 1 percent manganese, typical of the country rock slate near the deposits, is attained.

OUTLYING LENSES (DEPOSITS)

One small lens of the manganiferous hematitic variety and several lenses of magnetite-bearing siliceous carbonate rock are also interbedded in the lower slate. Most of these lenses are clustered in two areas on Hovey Mountain; one group is northwest of the Central Hovey deposit and the other group is at the southeast end of the Southern Hovey deposit. (See pl. 2.) Also, a deposit interpreted as a lens separate from the Maple-Hovey deposit was penetrated in diamond-drill holes 34 and 44 on the northwest side of Maple Mountain (See pl. 2.)

These small lenses are subdivided and described on the basis of their lithology and structural setting. Almost all of them were detected directly by magnetic surveying, or indirectly and fortuitously in the course of bulldozing while exploring other deposits in their immediate vicinity.

All of these lenses are enclosed by the lower slate as is the Southern Hovey lens. This slate is green to gray-green and megascopically similar to the slate enclosing the stratigraphically higher and larger, main hematitic lens of the area. The slate tends to change in aspect, however, in the vicinity of the manganiferous siliceous carbonate lenses *G* and *H* exposed in trenches 63, 64, and 65 and on Hovey Mountain, as will be described below.

HEMATITIC LENS *F*

The manganese-bearing hematitic lens designated by the letter *F* and centered approximately at the coordinates 32,500 N. and 11,500 E. on plate 2 is believed to occupy a separate horizon, below that of the Southern Hovey lens. (See explanation, pl. 2.) Although this horizon probably is some several hundred feet below that of the Southern Hovey lens, the exact amount of stratigraphic separation of these two horizons is uncertain because of faults. The stratigraphic succession between these two lenses described above and shown on plate 2 is favored because it requires fewer assumptions than alternate interpretations do. However, the possibility cannot be ruled out that the Southern Hovey lens and lens *F* are actually at the same stratigraphic horizon.

Lens *F* consists of thin manganiferous hematitic slate, green slate, and siliceous carbonate layers and laminae. In trench 104, a bed of volcanic ash one-quarter of an inch thick is present in the green slate overlying the lens 75 feet southeast of the upper contact of the manganiferous rocks. Lithologically, this lens is similar to the lower manganiferous unit of the Maple-Hovey deposit. The hematitic rocks at the northeast end of this lens, as seen in trench 62, contain magnetite. Magnetite was not observed, however, in other exposures of this lens, as in trenches 104, 69, and 121.

SILICEOUS CARBONATE LENSES

It appears that several other small lenses of siliceous carbonate in the area occur at two separate horizons below the Southern Hovey lens and lens *F*. This is mostly deduced from the relations as mapped on the northwest side of Hovey Mountain. Here, two siliceous carbonate lenses in trench 63, designated by the letters *G* and *H* on plate 2, apparently lie below the hematitic lens *F*. (See explanation, pl. 2.) The stratigraphic separation between lenses *F* and *G* is on the order of 180 feet.

The two lenses *G* and *H*, were discovered by a ground magnetic survey. A magnetic anomaly, north of the area trenched in lenses *G* and *H* (see pl. 2), was not further explored, but its size and shape suggest it may represent another distinct lens or possibly a faulted northwestward extension of lens *G* or *H*.

The gray-green slate that overlies lenses G and *H* is generally similar to the lower slate described above, except that sparse pyrrhotite forms films on cleavage planes in some of this slate.

Lenses *G* and *H*, as seen in trenches and drill core, are lithologically very similar; both are composed of irregularly interlayered green chloritic slate and banded siliceous carbonate rock. The stratigraphically lower lens *H*, contains more layers of siliceous carbonate than the upper lens *G*. Plate 4*C* is a generalized columnar section of these lenses.

Siliceous carbonate is the most manganiferous rock in lenses *G* and *H*. It is heavy, dark green, has a blocky fracture, and a pronounced banded structure. Commonly the individual bands are finely laminated. The banding tends to be wavy, and to resemble fluxion structure in some rocks. Small microfaults commonly offset laminae from 1 inch to microscopic distances. Small gray to gray-white pods, many with a dull purple cast, are common and are generally elongated subparallel with the laminations which typically bend around the pods. In a few places, the laminations pass through the pods without deflection. Magnetite commonly is abundant in the siliceous carbonate rocks.

The intercalated slate of the manganiferous lenses is green to dark green, and in places has color banding corresponding with bedding. The slate forms both laminations or partings between the layers of siliceous carbonate and beds several feet thick. The maximum thicknesses of lenses *G* and *H* are about 60 and 70 feet, respectively; the intervening slate is about 110 feet thick. If fault offsets are taken into account, the respective lengths of the lenses are probably on the order of 700 and 650 feet each.

The other lenses of siliceous carbonate in the area are believed to be at the horizon either of lens *G* or *H* or both. The suggested correlation favored in this report, between lenses *G* and *H* and the other lens of siliceous carbonate rocks on the northwest side of Hovey Mountain, is indicated by the inferred fold pattern shown on plate 2. Although the lenses of siliceous carbonate rocks on the southeast end of Hovey Mountain (see pl. 2) are believed to lie at the same two stratigraphic horizons, the relation of these lenses to one another is not clear.

The lithology of these small lenses of magnetite-bearing siliceous carbonate is generally comparable to that of lenses *G* and *H* with only minor differences of no apparent stratigraphic significance.

LIMESTONE BRECCIA

The gray-green slate cored by diamond-drill hole 52 is stratigraphically below the oldest manganiferous lens (*H*) and contains a few zones with elongate and round gray calcareous structures resembling stretched limestone pebbles. Parts of this slate have a banded appearance caused by the alternation of thin layers of light-green slate with dark-green to nearly black slate. A gray-blue limestone breccia, about 5 feet thick, was cut by the drill approximately 80 feet below the base of lens *H*. (See pl. 4*C*.) Some of the fragments of breccia contain a few deformed crinoid columnals. For at least 75 feet below the limestone breccia, the slate is gray blue and calcareous, and contains sporadically distributed pyrite.

AGE AND CORRELATION OF THE AROOSTOOK MANGANESE BEDS

A pyritized fragment of a branch of a graptolite was collected by the writer from about the middle portion of the lower manganiferous unit of the Maple-Hovey deposit. This fossil was originally studied by the late Josiah Bridge of the U.S. Geological Survey, who reported (written communication, 1950) that, although "* * * the identification of the specimen cannot be definite as several important parts that are needed for a positive determination are not preserved * * *," it agreed very closely with *Didymograptus sagitticaulus*, a form which is characteristic of the lower Middle Ordovician Normanskill shale (Black River) of New York and its equivalents elsewhere.

On the basis of this identification, the deposits of Maple and Hovey Mountains were tentatively assigned to the Ordovician(?) (Pavlides, 1952, p. 6). This graptolite was subsequently examined by several specialists and is now considered to be a Silurian rather than an Ordovician form. (See DDH 31, table 4.)

The only other fossils found near the deposits of Maple and Hovey Mountains are in the limestone breccia cut by diamond-drill hole 52 on Hovey Mountain. Some of the fragments of limestone breccia contain a few nondiagnostic pelmatazoan fragments which indicate a probable post-Early Ordovician age. Similar fragmentary fossils collected from elsewhere in the area (see table 4) probably are no older than post-Early Ordovician.

The age relations of many of the manganese deposits of the northern and southern manganese districts are, for the most part, uncertain. The northern manganese district, however, has been mapped in more detail (White, 1943, pl. 24) than the southern district (Miller, 1947, pl. 2), and more diagnostic fossils have been found in the northern district than elsewhere in the Aroostook manganese belt. The deposits of the northern manganese district are confined to the lower slate member of the Aroostook limestone and to the overlying shale and slate unit (the Ashland formation of former usage). Both the shale and slate unit and the Aroostook are assigned a Middle Silurian age by White. (See table 1.) The shale and slate unit is reliably dated as Silurian. At the Dudley manganese deposit, in Castleton Township, about 1.5 miles west of the town of Mapleton, a fossiliferous limestone breccia of the shale and slate unit is intercalated with slate and limestone that appear to overlie the Dudley deposit conformably (White, 1943, pl. 25). The faunule from this limestone breccia or conglomerate (Miller, 1947, p. 12) was studied by Twenhofel (1941, p. 172) who concluded that the Ashland (shale and slate unit of White, 1943) is of "very high Clinton or low Niagara," or Middle Silurian age.

The age of the manganese deposits that occur in what was assigned as the lower slate member of the Aroostook limestone by White (see table 1, and White, 1943, pl. 24) is less certain. In an earlier part of this report it was shown that the middle member of the Aroostook limestone as defined by White is of Middle Ordovician and not of Middle Silurian age. Such an age assignment necessitates inverting the stratigraphic order of some of White's units so as to fit the regional structure (White, 1943, pl. 24). Therefore the slate that contains the manganiferous lenses and which was thought by White to underlie the ribbon limestone that comprised the middle member of the Aroostook, actually overlies the ribbon limestone unit. It can be concluded therefore that this slate and its associated manganese deposits (which has been mapped as in conformable contact with the ribbon limestone unit) is of younger Ordovician age than the ribbon limestone unit and may even be of Silurian age. If it is of Silurian age it may correlate with the slate and shale unit of Silurian age that contains manganese deposits (such as the Dudley deposit) elsewhere in the district. This latter interpretation was used by Boucot and others (1960) in a recent compilation of the geology of northern Maine.

The age of many of the manganese deposits of the southern manganese district in Aroostook County, Maine, is uncertain. A reconnaissance geologic map of the southern manganese district was made by Miller (1947, pl. 4), but owing to the complexity of the geology only broad generalized stratigraphic subdivisions were made. He mapped the Ordovician and Silurian slates as an undifferentiated unit because of the difficulty of separating these rocks where fossils are lacking.

Both Silurian and Ordovician graptolites have been collected from rocks located close to manganiferous layers at Westford Hill (White, 1943, pl. 28). The rocks at Westford Hill are highly folded and faulted (White, 1943, pl. 28), but the Silurian graptolites there appear to be related definitely to the manganiferous unit and hence establish the age of the deposits at Westford Hill as Silurian.

The age of the Littleton Ridge deposit, approximately 5.3 miles northeast of Houlton, however, is of Early Devonian, New Scotland age. The writer found fossils at several localities on the southwest side of the deposit in buff-weathering calcareous slate with which the manganiferous rock appears to be conformably intercalated. Several large collections of material from one of these localities were prepared and studied by A. J. Boucot, of the U.S. Geological Survey (1960). The fauna obtained is as follows:

Coelospira? sp.
Eospirifer cf. *E. macropleura*
Unidentified rhynchonellid
Levenea? sp.
pelmatozoan columnals
Leptaena "rhomboidalis"
Kozlowskiellina cf. *K. perlamellosus*
Platyostoma? sp.
Orthoceroid
Tetracoral
Rhipidomellid
Schizophorid
Atrypa "reticularis"

The information concerning the relative age of the Aroostook manganese belt can be summarized as follows: (a) In the northern manganese district, the hematitic Dudley deposit, enclosed within the slates of the shale and slate unit of White, 1943 (Ashland formation of former usage) is of Silurian age, whereas the two manganiferous horizons of the lower member of what White considered to be the Aroostook limestone may be Middle Ordovician or younger; (b) the deposits of Maple and Hovey Mountains are probably of Silurian age and most likely Early Silurian rather than Late Silurian; (c) the manganese deposits of the southern manganese district may be of two or more ages. The Littleton Ridge deposit is Early Devonian and the deposits south of Houlton are of post-Early Ordovician age and those on Westford Hill are Silurian.

STRUCTURE OF THE DEPOSITS

The deposits of Maple and Hovey Mountains are highly deformed and only exceptionally good natural exposures would normally have enabled the structure to be mapped in detail. Such exposures are sparse and poor—a few at or near the crests of both Maple and Hovey Mountains—as the area is covered by a mantle of glacial till and is heavily wooded. The extensive trenching and diamond drilling by the U.S. Bureau of Mines provided many artificial exposures and subsurface cross sections from which the structure of the deposits was worked out.

Large folds are readily recognized by stratigraphic relation. In some places folds can be recognized by the attitudes of the bedding and its relation to axial plane cleavage. Faults, however, are more difficult to recognize and direct evidence for locating them closely, such as zones of brecciation and gouge, is sparse. Most of the faults were mapped by indirect evidence such as omission or repetition of beds, or anomalous attitudes caused by drag near faults.

Detailed geologic mapping of the deposits (1 inch equals 40 feet), supplemented by a vertical ground magnetometer survey, and by diamond-drill data supplied considerable information useful in understanding the structural and deformational history of the deposits and of the area in general.

FOLDS

The manganiferous lenses on Maple and Hovey Mountains (see explanation, pl. 2) occur in several large northeastward-trending folds or parts of folds. These lenses may outline such major folds in considerable detail as does the main manganiferous lens in the Maple-Hovey deposit (pl. 2), where the main lens is contained in a large doubly plunging syncline extending between Maple and Hovey Mountains. Different parts of the Maple-Hovey deposit have previously been designated as the Hovey Mountain prospects, the Lower Maple Mountain prospect, and the Upper Maple Mountain deposit. Miller (1947, p. 61–66) suggested that the deposits on Maple Mountain, at least, were continuous.

A large fold, such as the one which contains the Maple-Hovey deposit, is considered to be a first-order fold, comparable in size to the major folds of the area. The Southern Hovey lens (deposit) probably is on the limb of another first-order fold. Subsidiary northeastward-trending folds are also present along the limbs and ends of such first-order folds. The larger of these subsidiary folds are classed as second-order folds, and are defined more specifically as anticlinal or synclinal. The northeast end of the Maple-Hovey deposit on Maple Mountain contains several such second-order folds. Such folds are synclines I, III, and V, and the intervening anticlines II and IV. (See pl. 2.) Some of these second-order folds, such as syncline III on Maple Mountain, in turn contain subsidiary folds, here called third-order folds. These third-order folds appear as circled numerals ① through ⑭ on plate 2. Second-order syncline III, for example, has three third-order synclines separated by two third-order anticlines. They are designated by circled numerals ① to ⑤. (See pl. 2.) The end of the deposit on Hovey Mountain is considered to be a part of second-order fold VI, which contains third-order folds ⑫, ⑬, and ⑭.

In addition to first-, second-, and third-order folds, there are also smaller northeastward-trending folds, shown on the geologic map (pl. 2) as minor anticlines and synclines. In general, these folds have a "wavelength" of 1 to 3 feet and are classed as fourth-order folds. The distribution of the fourth-order folds in the deposits of the area is directly related to the degree of recrystallization (described later in the section on metamorphism) the rocks in different parts of the deposits have undergone. Thus, the fourth-order folds are in the more highly metamorphosed parts of the deposits such as in trench 23 of second-order syncline I on Maple Mountain, in trench 57 of block C in the Central Hovey deposit, and in trenches 84 and 112 in the syncline at the southeast end of the Southern Hovey deposit (see pl. 2).

The lineations (symbols shown in pl. 2) in the manganiferous rocks of second-order syncline V on Maple Mountain (trenches 4 and 9) are the fold axes of fifth-order folds. Fifth-order folds, shown in plate 2 as lineation, characteristically are the fold axes of corrugations with a "wavelength" on the order of a few inches to a fraction of an inch.

Besides the major and minor northwestward-trending folds, there are also subsidiary third order folds whose axes lie at a fairly large angle to the axes of the northeastward-trending folds. Such folds are classed as cross folds. Two subsidiary cross folds ⑥ and ⑦, are on the northwest limb of second-order syncline V on Maple Mountain. (See pl. 2.)

The folds on Maple and Hovey Mountains are mainly flexure folds. The relative competence of the different rock units of the deposits during deformation can generally be evaluated by their thicknesses in different parts of the folds. These differences in thickness have been measured in trenches and in drill holes. The cross sections cut by the drill holes have been published elsewhere by the writer (*in* Eilertsen, 1952, figs. 16–28) and only a selected few have been included in this report. (See pl. 2.)

The upper manganiferous unit in the Maple-Hovey deposit, which contains mostly slate, has undergone the most flowage towards the axial region of folds. The thickening that this unit has undergone, however, is relatively little. The upper manganiferous unit in second-order syncline V on Maple Mountain has not been thickened as much as the map pattern (pl. 2) suggests. Much of the apparent thickness of the unit here is due to repetition of beds as a result of the shallow double plunge of the second-order syncline (which has an inlier of upper slate along its axial region), as well as to the bulging effect induced by the cross folds along the northwest limb of the syncline. The upper manganiferous unit is about 100 feet thick on the nose of second-order anticline II, approximately along the axis of which diamond-drill holes 27 and 29 were drilled. This is somewhat less than twice the average arithmetic thickness of 57 feet assigned to this unit.

The middle manganiferous unit of the Maple-Hovey deposit, composed chiefly of banded hematite ironstone, has generally folded without appreciable thickening at the crests and troughs of folds, suggesting that it was competent during deformation. Wherever present minor changes in thickness due to folding in the middle manganiferous unit are mostly characteristic of the second-order folds that do not have third-order folds. Thus second-order syncline V on Maple Mountain has a rather uniform thickness along the southeast limb, around the nose, and in part, along the northwest limb except for the carinate cross fold ⑦ (in fold ⑦ the rocks may not actually have been thickened but only appear so through being repeated by doming). In second-order syncline III, which is corrugated by five third-order folds (see pl. 2), the middle manganiferous unit is normally thinner on the limbs of the third-order folds and maintains about the same general thickness on the noses of these folds, as it has in the less deformed second-order folds, such as V described above. Apparently the middle manganiferous unit, in such more highly deformed places as in syncline III, was attenuated along the limbs of the third-order folds but not noticeably thickened or thinned at the crests. For example, in third-order anticlinal fold ② (see pl. 2) thickening of the middle manganiferous unit has not taken place at the crest insofar as could be detected in (vertical) diamond-drill hole 18, which is located on the fold axis. The northwest limb of the fold, however, is thinned by about 50 percent as measured in trench 20. In a general way, therefore, the banded hematite ironstone of the middle manganiferous unit apparently had the competency to deform by bending, down to a critical stress value, namely, approximately that stress which prevailed when first- and second-order folds formed. If these rocks were stressed beyond this critical value through further folding, they then yielded by stretching along the limbs of the third-order folds.

In a few places, the banded ironstone such as that in the middle manganiferous unit evidently was thickened in the noses of folds as well as attenuated along the limbs. One such place is along the southeast limb of the Maple-Hovey deposit in the general area between trenches 26 and 31 on Hovey Mountain. (See pl. 2.)

With the exception of the section contained in trench 25, the small measured thicknesses of the middle manganiferous unit in these folds actually may be a result of inconclusive stratigraphic identification. For example, the rocks shown as belonging to the main manganiferous units in the northern part of trench 24 and in trench 59 may only be banded ironstone interlayers in the upper manganiferous unit; the rocks mapped as the middle and lower manganiferous units may actually be only relatively thin interbeds of banded ironstone and hematitic shale which elsewhere characterize these units as a whole. Irrespective of these uncertainties, the mapping has shown that rocks in this part of the deposit have been closely folded and faulted, and the middle manganiferous unit is thicker in trench 25 and thinner in trench 31 than in less complexly deformed parts of the deposit elsewhere. The thickening of the middle manganiferous unit in places such as trench 25 probably is mostly a result of faulting, whereby slices of rocks are wedged together and repeated (the detailed map of this trench—1 inch equals 40 feet—suggests faulting in a few places).

Thickening of individual beds of banded hematite ironstone in the crests and troughs of folds by flowage from the limbs was apparently of minor magnitude at most. The outcrop pattern of more highly recrystallized magnetite-bearing ironstone in syncline I on Maple Mountain and in the syncline at the southwest end of the Southern Hovey deposit suggests that solid flow may have taken place in these folds. The thickness of the ironstone here is greater than its average thickness in the deposits and thickening due to faulting is not apparent.

The doubly plunging syncline outlined by the main manganiferous lens (Maple-Hovey deposit) is the dominant first-order fold on Maple and Hovey Mountains. (See pl. 2.) The main manganiferous lens on the ends of the syncline crops out on and near the crests of Maple and Hovey Mountains. The synclinal axis trends approximately N. 55° E., although near the crest of Hovey Mountain its trend has been shifted slightly northward by faulting. The plunge of the major fold axis and of the axes of second- and third-order folds on Maple Mountain is to the southwest, towards Hovey Mountain, whereas on Hovey Mountain the axes of the major and minor folds plunge to the northeast, towards Maple Mountain. Diamond drilling along the southeast limb of the syncline, between Maple and Hovey Mountains, indicates that this limb is locally overturned to the northwest (pl. 5). Second-order anticline II on Maple Mountain, cut along its axis by diamond-drill holes 27 and 29 (pl. 2), has both its northwest and southeast limbs overturned, and in cross section is fan shaped (section *A–A′*, pl. 2 and pl. 5).

Overturning of most of the second-order anticlines in the direction of their plunge characterizes both ends of the Maple-Hovey syncline (pl. 2, diamond-drill holes 24, 25, and 43). This overturning and the resulting opposing plunges of the ends of the Maple-Hovey syncline over such a short distance are believed to be a result of local "cross folding" (described later), transverse to the regional, northeastward-trending folds. The small carinate fold ⑦ outlined by the middle manganiferous unit on Maple Mountain (cut by trenches *E*, *F*, and *G* of the Manganese Ore Company) is a near-surface example of another type of cross fold.

Two small doubly plunging anticlines, related to local faults, are present in the Maple-Hovey syncline. One of these is between trenches 29 and 45 (pl. 2) on Hovey Mountain; the other is in the vicinity of the northwest end of trench 12 on Maple Mountain.

In addition to the nearly complete fold on Maple and Hovey Mountains, parts of other folds are outlined by the manganiferous lenses of the area. The Central Hovey deposit is exposed in the faulted remnants of two anticlines (see pl. 2, fault blocks *B* and *C*), part of the northwest limb of a syncline (fault block *D*), and at the end of a lens (fault block *A*). These folds plunge to the southwest.

The Southern Hovey lens is less deformed than the main manganiferous lens in either the Maple-Hovey or Central Hovey deposits. It evidently lies along the limb of a first-order fold which was broken by the faults northwest and southeast of the Southern Hovey deposit (pl. 2). The southwest end of the deposit is folded into a northeastward-plunging syncline (pl. 2). The southeast limb of this syncline lenses out within a relatively short distance from the nose of the fold. This syncline may be a third-order fold similar to those in the Maple-Hovey deposit. The length and relative staightness of the limb of the fold along which most of the Southern Hovey deposit lies make it unique when contrasted with the faulted and crumpled character of the rocks throughout most of the area. The northeast extremity of the Southern Hovey deposit terminates against a fault; southwest of the fault the deposit is in a sigmoidal flexure and locally the bedding is slightly overturned to the northwest.

Small manganiferous lenses on Hovey Mountain have undergone different degrees of deformation. The amount of deformation is believed to be a function of position on the limbs or the noses of large folds. Such large folds, however, were not recognized in the field. The slate that encloses the lenses is poorly exposed, lacks marker beds, and could not be mapped in sufficient detail to outline accurately such possible major folds. The fold involving the possible horizons between the lenticular deposits on the northwest side of Hovey Mountain (pl. 2) is therefore conjectural. It is based partly on the relative position of the lenses to each other and assumed stratigraphic correlation between the different siliceous carbonate lenses, and in part, on the pattern of folding known to exist in the district, such as that at the southwest end of the Maple-Hovey deposit. For example, the small anticline that is outlined by siliceous carbonate rocks near coordinates

32,000 N. and 11,500 E. has its axial plane inclined to the southeast in similar manner to that of third-order fold ⑬ of the Maple-Hovey deposit on Hovey Mountain.

CLEAVAGES

Slaty cleavage is well developed in the argillaceous rocks enclosing, and contained within, the manganese deposits of the area; the banded ironstone of hematite or magnetite and the banded siliceous carbonate rocks of the deposits, however, lack cleavage. The regional strike of the slaty cleavage is generally from N. 50°–70° E. and its range from vertical to 60° NW. or SE. Most commonly, however, its dips are vertical or nearly vertical (85° or more).

The regional slaty cleavage is generally parallel to the axial planes of some of the northeastward-trending folds, although it deviates from rigid parallelism in many places. It also clearly lacks even rough parallelism to axial planes in some folds. For example, the trend of the cleavage in the Central Hovey deposit cuts across the trend of the axes of the folds in blocks *B*, *C*, and *D* at a small angle, although it maintains an overall regional trend (pl. 2). Such deviations may be the result of the cleavage having formed as a late-stage structure after folding. Some faulting evidently also occurred before cleavage developed.

Bedding-plane cleavage is also present at a few places, particularly in some of the green slate interlayered with the hematitic rocks of the different manganiferous units. Such bedding-plane cleavage was seen in trench 36, which exposes the lower manganiferous unit in third-order fold thirteen on Hovey Mountain. Bedding-plane cleavage also parallels the east limb of fold ⑦ which crosses second-order fold V in the upper manganiferous unit on Maple Mountain.

Regional slaty cleavage that is more or less parallel to the axial planes of the folds proved very useful as a clue to local structure during the exploration of the Maple-Hovey and Southern Hovey deposits. It was particularly helpful in interpreting structural relations in the deep vertical drill holes within the Maple-Hovey deposit. These holes deviated progressively both in azimuth and inclination with increasing depth. The azimuth and the inclination of the holes were measured at intervals ranging from one to several hundred feet (Eilertsen, 1952, table 3, p. 53). By using cleavage and lineation produced by the axes of minor corrugations it was possible to orient this core completely. These structures were usable because the strike of cleavage and the general strike and plunge of the lineation were known from surface geologic mapping. Thus, drill core could be oriented in two possible positions, by using cleavage alone. Generally, on the basis of stratigraphy, or by projecting the axes of known folds mapped at the surface, the correct orientation of these two possible orientations could be deduced. If crenulations are also present, then the orientation of the core was determined immediately, as one of the two positions obtainable from cleavage alone would indicate a plunge opposite to that known from surface evidence. These criteria could not be used in parts of folds overturned by cross folding. At such places, the structure was interpreted from the repetition of stratigraphic units and the relation of bedding to the axes of the drill cores. (See pl. 2, sections of diamond-drill holes 24, 25, and 43.)

LINEATIONS

Only two types of lineation are widely enough developed in the deposits to be readily recognizable and of practical use. These are: (a) axes of minor crenulations or corrugations (fifth-order folds), and (b) a lineation resulting from the intersection of bedding and cleavage. On the geologic map (pl. 2) only the former is shown. Lineation plunging conformably with the major folds was useful in orienting drill core, as mentioned above. The microcorrugations in the Maple-Hovey deposit strike N. 57°–85° E. and plunge 70°–78° on Hovey Mountain, wheras on Maple Mountain they strike S. 56°–85° W. and plunge 35°–65°. The bedding-cleavage intersections, especially the trace of bedding on vertical cleavage partings at the noses of folds, was useful in directly determining the amount and direction of plunge of the folds where the clevage parallels the axial planes. Lineation formed by cleavage-bedding intersections has not been shown on the geologic map (pl. 2), but it can be determined readily from the attitudes of bedding and cleavage recorded on the map.

The lineations described above are restricted to specific types of rock. Lineation caused by the intersection of bedding and slaty cleavage is well developed in the argillaceous slate that contains primary laminations, whereas microcorrugations are confined mostly to thin-bedded hematitic slate that is interbedded with the argillaceous slate. The fourth-order folds also show localization based on lithology. For example, those in trench 23 within second-order syncline I of the Maple-Hovey deposit on Maple Mountain, and in trench 84 in the syncline at the southwest end of the Southern Hovey deposit on Hovey Mountain (pl. 2) are developed in the more heavily bedded and competent banded ironstone.

JOINTS

Joints were not mapped in detail and few are shown on the geologic map (pl. 2). A conspicuous set of fractures in the deposits dips steeply or is vertical. For the most part, these are cross joints, perpendicular or nearly perpendicular to fold axes. Poorly developed, gently inclined joints are also present. Joints are especially conspicuous in the brittle, banded hematite and banded magnetite-chlorite ironstone and in siliceous carbonate rocks, and consequently these rocks fracture into blocks. A rhombic fracture pattern occurs in some places, such as in trench 14, along the northwest limb of second-order syncline III on Maple Mountain. There, well-developed oppositely dipping cross joints cut steeply dipping banded hematite ironstone. Rhombic blocks of banded ironstone are common in many parts of the deposits.

Well-developed intersecting conjugate fractures in trench 44 near fold ⑪ on Hovey Mountain are probably shear fractures related to the small folds in this area. These folds, in turn, are considered to be wrinkles related to local faulting. The average strikes of these conjugate fractures is N. 62° E. and N. 71° E., so that they intersect at an acute angle of about 47°. The fractures dip southward, 82° to 87°. The trace of the acute bisectrix of the intersecting fractures is not parallel with the trend of the axis of the small doubly plunging anticline, although these fractures are developed in the axial region of this fold. (See pl. 2.) Nonetheless, the acute bisectrix is alined in the general direction of the axes of wrinkles in this area.

FAULTS

Faults are recognized with difficulty in the deposits of Maple and Hovey Mountains, and most are shown as inferred.

Strike-slip faults are probably the most important faults in the district. Most of these faults also had a vertical component of movement, but as the net slip commonly cannot be determined the order of magnitude of this component is not readily assessed. The apparent displacement on some of these faults suggests that the vertical component is smaller than the strike-slip component in most places.

The largest and most important inferred strike-slip fault cutting the deposits bounds the Maple-Hovey deposit on its northwest flank. Diamond-drill holes 34 and 44 on Maple Mountain and diamond-drill hole 45 on Hovey Mountain intersect this fault. (See pl. 2.) From this and the fact that the position of the fault at the surface is known in the immediate vicinity of diamond-drill hole 45 (see pl. 2), a steep southeast dip of the fault at both ends of the deposit is evident.

The map pattern suggests the likelihood that the rocks of the Central Hovey deposit have been displaced southwestward relatively, from an original position much closer to rocks now exposed at the northwest end of Maple Mountain. Minor fold axes in both places plunge southwestward, as would be expected near the northeasterly nose of a doubly plunging syncline. The rocks in the Central Hovey deposit, furthermore, are more similar in lithology to the highly metamorphosed rocks at the northwest end of Maple Mountain (fold I) than to those elsewhere in the Maple-Hovey deposit. The northwest block of this fault, therefore, probably moved to the southeast toward Hovey Mountain, in order to have displaced the Central Hovey deposit from its original position on the southwestward-plunging, northeast end of the Maple-Hovey deposit, to its present position on Hovey Mountain. The inferred fault that bounds the Central Hovey deposit on its northwest side may also be a strike-slip fault with horizontal displacement of the northwest block to the southwest.

The fault blocks in which the Central Hovey deposit lies need not necessarily have been offset from the exact end (present erosion surface) of the large fold on the northwest side of Maple Mountain (pl. 2), but may have been displaced from some position down plunge along the northwest flank of the Maple-Hovey fold. Thus, the movements along the fault would have had an appreciable vertical component and the rocks northwest of the fault would have been displaced relatively upward. The possible relative horizontal displacement of the northwest block to the southwest along the major fault bounding the Maple-Hovey deposit is estimated to range from 2,500 to 4,500 feet. The maximum value is based on measurements from the geologic map (pl. 2); the minimum value is deduced from a consideration of the structure contour map (pl. 5) whereby allowance is made for the minimum reasonable displacement that would affect rocks from the southwestward-plunging end of the Maple-Hovey syncline.

The southeast flank of the Maple-Hovey deposit has also been locally faulted. A part of the deposit on Hovey Mountain, between trenches 27 and 38 in the area of folds ⑩ and ⑪ (see pl. 2), has been displaced along two major faults. These faults occurred at different times and caused displacement in different directions. Apparently, a large anticlinal flexure was initially broken, approximately along its axis, by the northeastward-trending fault bounding the west side of fold ⑩, and later by the fault between folds ⑩ and ⑪. The present northwest limb of fold ⑩ was the east limb of the original anticlinal flexure. The west block here was horizontally displaced southward relative to the east block. Folds ⑩ and ⑪ are separated by the later eastward-trending fault south of which the west limb of the original anticlinal flexure, previously displaced to the south, moved relatively eastward. A change in strike of the strata from northeast to north in fold ⑩ is probably a consequence of drag. Apparently this drag caused a rotation in strike of nearly 90° and possibly an appreciable rotation of the dip of the strata, as the beds exposed in trench 43 were structurally the west limb of the earlier anticlinal flexure. The nose of the original anticlinal flexure is missing in fold ⑪ and suggests that either or both faults had an appreciable vertical component rather than simply horizontal movement.

The wrinkling in the upper manganiferous unit near fold ⑪, expressed, for example, by the small northeastward-trending, doubly plunging anticline intersected by trench 38, is believed to be related to the fault separating folds ⑩ and ⑪.

The small faults separating blocks *A*, *B*, *C*, and *D* of the Central Hovey deposit are believed to be complex strike-slip faults developed during the displacement of this deposit by faulting. Movement along the smaller faults may have been confined mostly to the zone included between the principal strike-slip faults bounding the Central Hovey deposit. Unequal horizontal movement within this zone contemporaneous with the major faulting could have fragmented the rocks into the four fault blocks, before the major movements along the large bounding faults ceased. The assumed intersection of these faults with the top of the middle manganiferous unit in the fault blocks is shown in the structure contour map (pl. 5).

Each of the fault blocks of the Central Hovey deposit has rather unique lithologic and structural features, even though the rocks within these blocks are presumed to have been structurally continuous at one time. One feature common to all of the blocks, however, is the discordance of cleavage with the axial planes of the major folds. The cleavage generally strikes from about N. 60° E. to east and dips steeply southeast or is vertical, whereas the axial planes of the folds strike N. 30°–55° E. and dip steeply northwest or are vertical.

Differential movements along cleavage in fault block *A* developed large, deformed pyrite cubes, in whose pressure shadows quartz and calcite have crystallized.

Faults involving smaller displacements have been recognized elsewhere both in the Maple-Hovey and other deposits. These include the northeastward-trending faults between trenches 24 and 31 on Hovey Mountain where an attenuated part of the southeast limb of the Maple-Hovey deposit was deformed by folding and faulting. (See pl. 2.) The faults on Maple Mountain, such as those along the southeast limb of third-order folds ② and ⑤ in trench 1 and in trenches 10 and 11, strike in the same direction as the local slaty cleavage. They may have formed by slip along cleavage. The inferred fault cutting the two siliceous carbonate lenses *G* and *H* between trenches 63 and 64 on Hovey Mountain is probably a strike-slip fault along which the northwest block moved southeastward relative to the northeast block, but possibly is a normal fault downthrown to the northeast.

Actually, however, only two faults that cut the deposits are believed to be of the gravity or normal type. These are on Maple Mountain. The sliver of the lower manganiferous unit exposed in trench 5 appears to have been down dropped between two intersecting arcuate normal faults. (See pl. 2.) The large arcuate fault extending through trenches 12, 15, and 21 is believed to be a hinge fault; the axis of the hinge lies between trenches 6 and 12 with the northwest block of the fault having scissored downwards towards the southeast (pls. 2 and 5). The small doubly plunging anticline at the northwest end of trench 12 may be a wrinkle caused by this hinge fault.

DEFORMATIONAL HISTORY

The structural features of the deposits on Maple and Hovey Mountains are believed to have formed during one of two periods of deformation and in a continuous episode. This deformation, which affected all of the rocks of the area, produced folds with northeastward-trending axes. Irrespective of the ultimate nature of the forces that imposed the deformation, the net resultant of the stresses involved was compression essentially perpendicular to the axes of the folds.

Although compression adequately explains the gross fold patterns, the rather pronounced overturning of second-order folds at the opposite ends of the doubly plunging syncline outlined by the Maple-Hovey deposit cannot have formed from compression alone. Actually, this overturning is considered to be a special modification of compression, imposed on this particular fold by the nature or degree of competence of the rocks that surround and enclose it on Maple and Hovey Mountains.

As described earlier, the deposits are enclosed by a thick sequence of slate of the upper part of the Hovey formation and the slate is underlain by lenticular but rather extensive volcanic rocks. (See fig. 3.) Furthermore, the structural setting around the deposits is such that they are nearly enclosed on three sides by these and other volcanic rocks as well as by the Spruce Top greenstone on Meduxnekeag Mountain. (See pl. 1.) The deposits, or at least parts of them, such as the middle manganiferous unit (banded hematite ironstone) of the Maple-Hovey deposit, may be visualized as having been prior to folding, generally thin, competent, flat lenses enclosed in incompetent argillaceous rocks underlain by competent layered extrusive and intrusive rocks. (See fig. 3.) When this section of rocks was folded, the ultimate distribution of the competent igneous rocks was such that the slate and its associated manganiferous deposits were enclosed in a syncline that was bounded almost continuously on three sides by the competent igneous rocks (pl. 1). The manganese deposits and slates of the Hovey formation probably were folded directly by compression until complimentary elongation parallel to the fold axes resulted in a significant space problem. Elongation parallel to major fold axes by lateral movement in the incompetent slates of the Hovey formation eventually must have been restricted by the resistance of the competent masses of Dunn Brook volcanic rocks northeast and southwest of the deposits. Thus, such elongation became directed upward near the ends of such folds as the one containing the Maple-Hovey deposit, and especially in the slate immediately underlying it, resulting in an inwardly directed compression from the northeast and southwest.

The second-order folds on the ends of the Maple-Hovey deposit had probably developed initially as subsidiary folds on the larger Maple-Hovey syncline during original compression. The upward flow of slate near the ends of the Maple-Hovey deposit probably resulted in accentuating as well as overturning these second-order folds. The small cross folds, such as those along the northwest flank of second-order syncline V on Maple Mountain (see pl. 2), probably were also formed as wrinkles in response to the compression induced by the masses of Dunn Brook volcanic rocks northeast of the Maple-Hovey deposit. The distribution of such cross folds probably was uneven and subject to irregularities in the relief of stress in different parts of the deposit during the sharp upturning of the ends of the syncline. The more competent ironstone layers of the middle manganiferous unit of the deposit probably determined the ultimate shapes of the second- and third-order folds.

The banded hematite ironstone layers of the middle manganiferous unit preserved a fairly uniform thickness during most of the folding and principally underwent stretching along the limbs of third-order folds as described earlier. When the rocks of this unit were stretched beyond their elastic limit they ruptured. The slate in the upper manganiferous unit of the Maple-Hovey deposit, however, underwent plastic deformation and was somewhat thickened at the crests and troughs of folds.

At places where conformable layers of igneous rocks are not present as competent rock barriers, such as to the southwest of the deposits, the faults produced within the deposits had an appreciable strike-slip component and reflect a further compensation by stretching in the trend direction of fold axes. Where faulting due to stretching could not take place, the rocks fractured across the strike of the regional fold axes in faults such as those described along the southeast flank of the Maple-Hovey deposit near folds ⑩ and ⑪.

Cleavage probably developed as a late feature, after the major folds and faults had formed in the deposits. It strikes at a small angle to the axes of some folds, such as those in the Central Hovey deposit (see pl. 2) and maintains the same general trend throughout the area irrespective of the large offset and rotation undergone by different fault blocks of the deposits. Cleavage must have formed, however, during a compressive phase of deformation. Judging from its regional strike, such compression was generally or nearly perpendicular to the major fold axes of the region, as some of the slaty cleavage has approximate axial plane symmetry to several of the folds in the deposits. Later, some normal faulting, such as on Maple Mountain, terminated the deformational history of these deposits.

The age of the deformation in the Maple and Hovey Mountains area is not known. At least three periods of deformation, however, have affected the rocks of the northern manganese district, where angular unconformities separate Middle Ordovician from Middle Silurian rocks, Middle Silurian from Lower Devonian rocks, and probably Lower Devonian from Upper Devonian rocks. Probably at least the last two orogenies also affected the rocks in the Maple and Hovey Mountains area. The intense deformation of the deposits of Maple and Hovey Mountains predates the post-Mapleton (Upper Devonian) deformation of the northern manganese district, as the disturbance involving the Mapleton sandstone there developed broad open folds, whereas the rocks underlying the Mapleton sandstone were affected by an earlier deformation and are closely folded comparable in degree to the rocks of the Maple and Hovey Mountains area.

PETROLOGY OF THE MANGANESE DEPOSITS

LITHOLOGY AND MINERALOGY OF THE DEPOSITS

By Louis Pavlides and Charles Milton

The manganese deposits of Aroostook County are of two principal rock-types: (a) red hematitic shale, slate, and banded ironstone; and (b) green siliceous carbonate rocks. These will be referred to respectively as the oxide and carbonate facies. Hematitic and siliceous carbonate rocks occur together within many deposits but commonly one type of lithology is dominant. Rocks formed by metamorphism of the hematitic and siliceous carbonate types are characterized by abundant magnetite and chlorite; these rocks, which vary in color from dark green to black, are present only on Maple and Hovey Mountains and in the southern manganese district. The colors of the rocks, in all the deposits throughout the Aroostook manganese belt, may be locally obscured by black oxides of manganese which stain and replace both the manganiferous rocks and the enclosing country rock.

The lithology and mineralogy of the northern and southern manganese districts have been described by White (1943, p. 132–137 and 139–142) and by Miller (1947, p. 21–25), who also gave a brief description of the manganiferous rocks on Maple and Hovey Mountains (Miller, 1947, p. 24). The present report is concerned mainly with the deposits on Maple and Hovey Mountains and the reader is referred to the reports of White and Miller for details of the lithology and mineralogy of the northern and southern manganese district deposits not discussed herein.

The deposits on Maple and Hovey Mountains, namely, the Maple-Hovey and Southern Hovey deposits of this report, are chiefly of the hematitic type (oxide facies). The more highly metamorphosed magnetite-bearing equivalent of the hematitic type is chiefly exemplified by the Central Hovey deposit. The siliceous carbonate type (carbonate facies), except where it occurs without magnetite in the thin zones below the manganiferous units of the Maple-Hovey and Southern Hovey deposits, is magnetite-bearing throughout the area. The magnetite-bearing siliceous carbonate deposits of this area occur mainly as small lenses on Hovey Mountain (pl. 2).

The mineralogy of the manganiferous rocks in the Aroostook belt is difficult to decipher because of the extreme fineness of grain, the intimate admixture of manganese minerals and gangue, the masking effect of the oxides, and because of the complex and variable composition of many of the manganese minerals. Nevertheless, even though it is difficult if not impossible to isolate the minerals of these rocks, it has been possible through optical study, X-ray diffraction, and chemical analysis to determine the essential minerals with reasonable certainty.

The layered manganese-bearing rocks of Maple and Hovey Mountains are cut by thin veinlets, which normally have a different characteristic mineral suite within each of the three types of deposits. The mineral suites of the veinlets also appear indirectly to reflect the mineral and chemical composition of the enclosing wallrock. The mineralogy and origin of these veinlets will be discussed separately, following the description of the lithology and mineralogy of the bedded oxide and carbonate facies rocks, and their magnetite-bearing equivalents.

OXIDE FACIES

HEMATITIC SLATE, SHALE, AND IRONSTONE

The manganese-bearing hematitic rocks of Maple and Hovey Mountains are chiefly slate and banded ironstone. Some reddish hematitic layers (1 to 2 inches thick) are interbedded with green slate, as in the lower manganiferous unit of the Maple-Hovey deposit. These lack the cleavage that cuts the interbedded argillaceous layers; hence, they resemble shale rather than slate.

The most abundant manganese minerals of the hematitic manganese deposits commonly are braunite and ferroan rhodochrosite. Spessartite and bementite are generally present in relatively small amounts; a minute quantity of hausmannite was identified at only one place.

PRINCIPAL MINERALS

Braunite.—Braunite ($3Mn_2O_3 \cdot MnSiO_3$) is an important manganese mineral in the hematitic manganese deposits. It is found both in hematitic shale and slate and in banded hematite ironstone, mixed with other minerals in laminae of paper thinness to an eighth of an inch thick. It occurs also in pods as much as an inch across which are in places connected by thin layers. Such pods are more common in the hematitic shale and slate than in the banded hematite ironstone. At a few places, the pods have a concentric structure in which the black outer shell contains more braunite than the lighter colored core. Several concentric braunite-rich layers are present in some of the pods.

Pods with such concentric zoning are more characteristic of the Dudley deposit of the northern manganese district, where this structure is apparently best developed. The geologic section of the Dudley deposit, compiled by Miller (1947, between p. 56–57) illustrates the stratigraphic distribution of the pods in this deposit. Figure 18 is a polished surface of two specimens of diamond-drill core from the Dudley deposit of the northern manganese district illustrating the shapes and structures of braunite pods. Figure 19 shows the microstructure of braunite in a pod from the Dudley deposit. The braunite there consists of discrete rounded poikilitic grains approximately 0.0002 of an inch in diameter.

Chemical analyses (table 7) were made of the richest

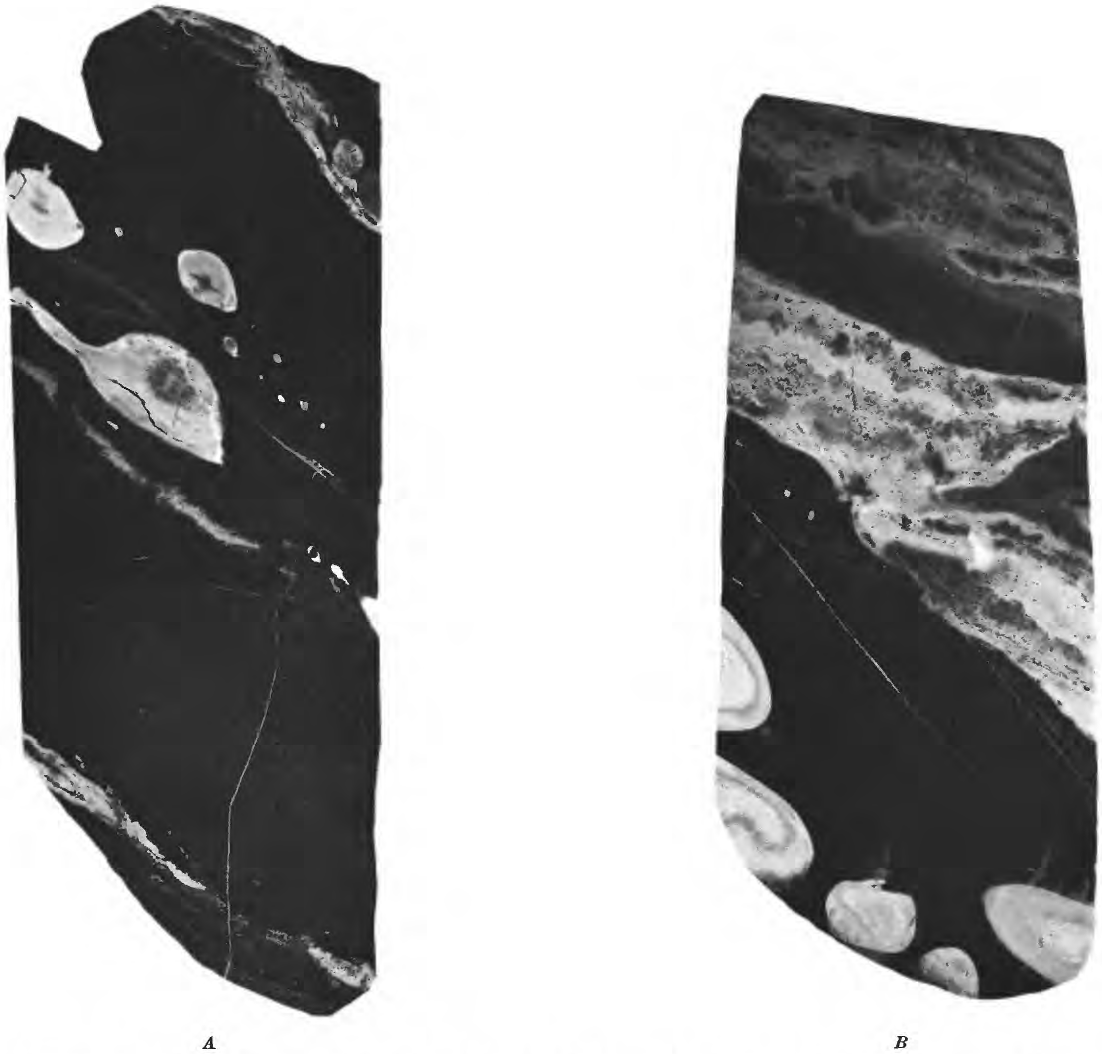


FIGURE 18.—Polished surfaces (under reflected light) of two pieces of diamond-drill core, Manganese Ore Co., Dudley deposit, northern manganese district. *A*, Braunite-rich ovoids (white) embedded in hematitic shale (dark). The actual color of the braunite masses seen by the naked eye is black and the enclosing hematitic shale is reddish brown. The braunite-rich layer leading off to the left from the large pod connects with another pod in dumbbell fashion. The other pod is partly visible on the side of the drill core but not in the plane of the photograph. *B*, Braunite-rich ovoids and contorted braunite-rich laminae (white) embedded in hematitic shale. Note the concentric structure of some of the pods. Approximately × 1.7.

braunite available from the Dudley deposit, as far as could be judged by its blackish color and apparent low gangue content, and of the barren red shale associated with this braunite. X-ray diffraction patterns were also made of the braunite and the red shale. These indicate that the black braunite pods also contain a little quartz and feldspar, with perhaps bementite and some unidentified minerals. The enclosing red shale showed the lines of quartz, mica, a little braunite, perhaps bementite, feldspar, and unidentified minerals.

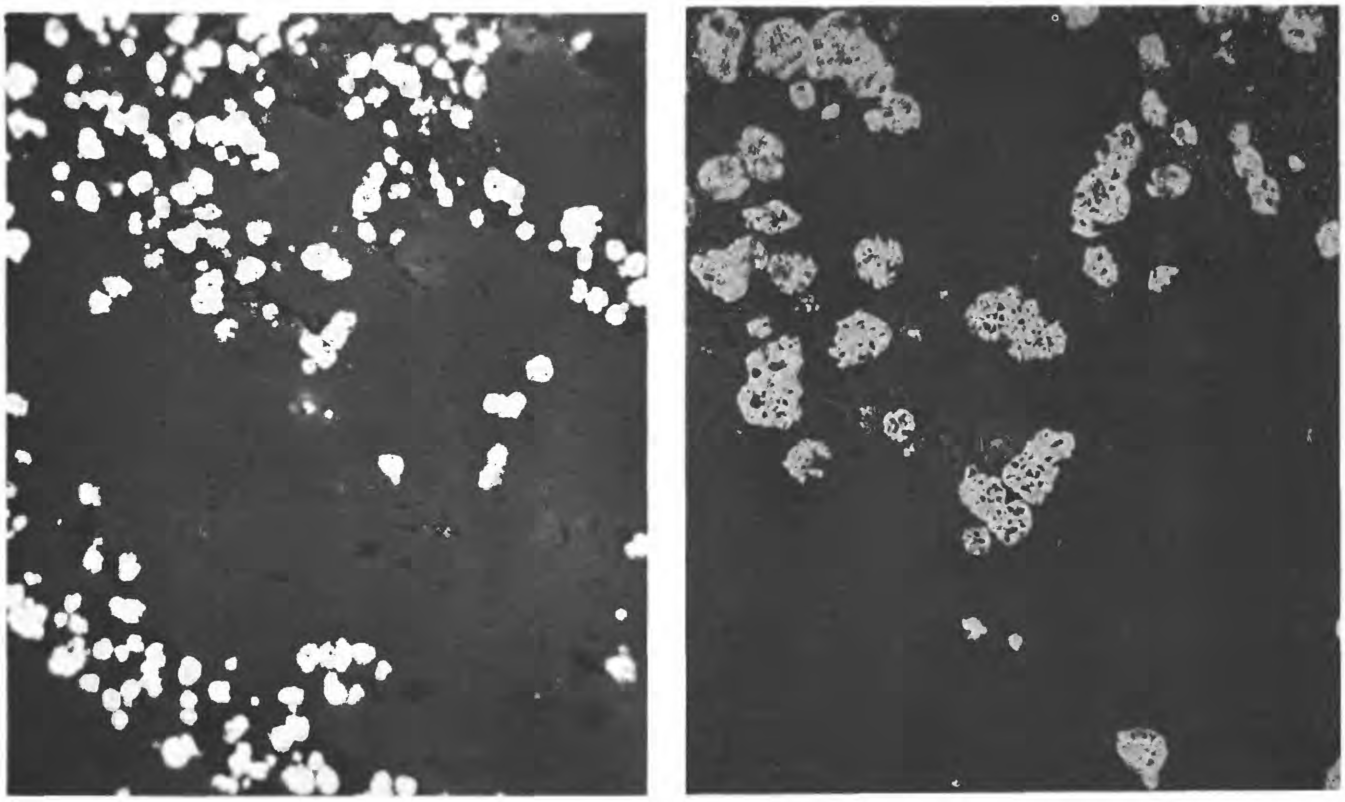
Assuming that all of the oxygen (4.70 percent) of the analysis (table 7) is present in braunite ($3Mn_2O_3 \cdot MnSiO_3$), the corresponding MnO would be 48.18 percent and the SiO_2 5.85 percent, making 58.69 percent braunite. There is, however, a slight excess of MnO (5.70 percent) which may be present as silicate or carbonate. The X-ray analyses suggest that bementite ($8MnO \cdot 7SiO_2 \cdot 5H_2O$) may be the manganese mineral that contains much or all of the divalent manganese.

TABLE 7.—*Chemical analyses of braunite and its enclosing hematitic shale, Dudley deposit, northern manganese district*

[Chemical analyses by C. M. Warshaw]

Laboratory No.	50-947SC	50-948SC
Field No.	Dudley 6F-1	Dudley 6F-2
Description	Braunite	Hematitic shale
SiO_2	23.36	51.58
Al_2O_3	3.75	15.97
Fe_2O_3	2.58	9.75
CaO	1.58	.60
MgO	.82	3.56
Na_2O*	.69	2.30
K_2O*	.39	3.91
TiO_2	.28	1.04
MnO	53.88	6.18
H_2O+	4.74	4.27
H_2O-	2.07	.63
P_2O_5	None	.04
CO_2	.47	.40
O	4.70	.04
BaO	.66	.06
B_2O_3**	.12	.02
Total	100.09	100.35

*Flame photometer determination by S. M. Berthold.
**Spectrographic determination by K. J. Murata.



A. × 500

B. × 1000

FIGURE 19.—Photomicrographs of a polished section of braunite in a pod, Dudley deposit, northern manganese district. *A*, Braunite crystals (white) in gangue. *B*, Part of same field shown in *A* at higher magnification. The actual size of these braunite particles is about 0.0002 inch across. Note the inclusions of gangue within the braunite crystals. Plane light.

White (1943, p. 133) also has reported well-crystallized bementite from the cores of some masses of braunite.

The chemical analysis of the braunite-rich pellet is of further interest in that it shows about ten-fold and six-fold concentrations of BaO and B_2O_3 respectively, over the amounts in the red shale enclosing the pellet. Although boron is undoubtedly concentrated in the braunite-rich pellets of the Aroostook hematitic ores, there is much less than found by Wasserstein (1943, p. 395) in his study of braunite specimens from Postmasburg, South Africa, and from India, Sweden, Brazil, and Germany. His spectrographic analyses show a range from 0.3 to 1.2 percent B_2O_3, whereas the Aroostook braunite-rich pods only show 0.12 percent B_2O_3. However, two Swedish braunites whose boron content was determined as 0.008 percent (0.03 percent B_2O_3) and 0.004 percent (0.01 percent B_2O_3) respectively (Ödman, 1950, p. 7), indicate that boron may not be as essential, nor as diagnostic a constituent of braunite as suggested by Wasserstein (1943, p. 396).

Wherever braunite occurs in thin laminae rather than in pods, it is intimately mixed with gangue (see fig. 20).

The braunite-rich lamina from part of the specimen illustrated in figure 20 contained 21.7 percent SiO_2, 45.6 percent MnO, and 3.4 percent Fe_2O_3.[5] A similar sample from another specimen contained 27.1 percent SiO_2, 44.5 percent MnO, and 3.6 percent Fe_2O_3. Theoretical braunite ($3\ Mn_2O_3 \cdot MnSiO_3$) has approximately 10 percent SiO_2, 8 percent O, and 82 percent MnO; therefore, even though all of the manganese were present as braunite (which it is certainly not) the maximum braunite content of these laminae is only slightly over 50 percent. X-ray determinations indicate that the chemically analyzed samples contain rhodochrosite, feldspar, and one or more unidentified minerals, in addition to braunite. Some of the reported manganese is therefore contained, in part, as carbonate as well as braunite. The Fe_2O_3 of the analyses may be in the form of hematite, or chemically bonded to an unidentified gangue mineral or contained in the braunite, probably by ionic substitution of iron for manganese. Braunite also occurs intimately mixed with hematite from which it may be distinguished with difficulty by microscopic methods if the subequant habit of braunite is not discernible.

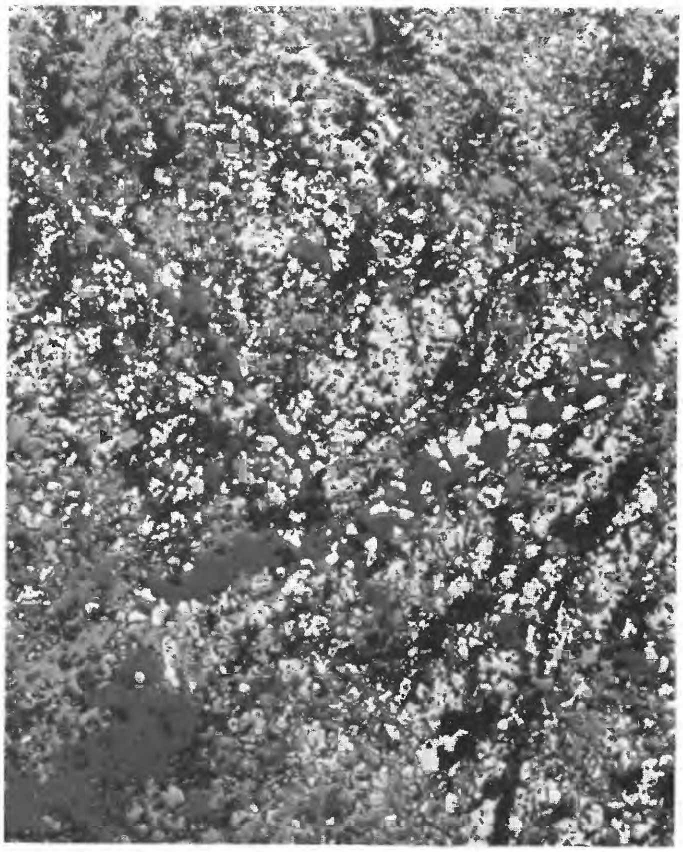


FIGURE 20.—Photomicrograph of braunite (white) occurring as irregular to subequant grains within a lamina of banded hematite ironstone, Maple-Hovey deposit. Plane light; × 200.

Ferroan rhodochrosite.—Ferroan rhodochrosite, with No (index of refraction of the ordinary ray) commonly greater than 1.790, is relatively abundant in the hematitic manganese deposits of Maple and Hovey Mountains. Minor amounts of magnesium and calcium in varying ratio are also present in the carbonate. Commonly, two or more carbonates may be intimately associated in one specimen, as can be discerned from their relative differences in indices of refraction in thin sections. The carbonate occurs as more or less impure concentrations either in laminae or pods. (See fig. 21.) It is also intimately disseminated in hematite- and braunite-rich laminae. Carbonate-rich laminae in the banded hematite ironstone are more readily leached at the bedrock surface than in the other laminae, and banded hematite ironstone with such laminae hence tend to have a finely ribbed appearance in outcrop.

Hematite.—Hematite is normally the most abundant mineral of the hematitic manganese deposits. It is concentrated almost exclusively in layers (see fig. 22), in contrast to braunite and carbonate which occur both in layers and pods. Small amounts of hematite, however, are sometimes disseminated within carbonate-rich pods.

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[5] Rapid-method analysis by Leonard Shapiro.

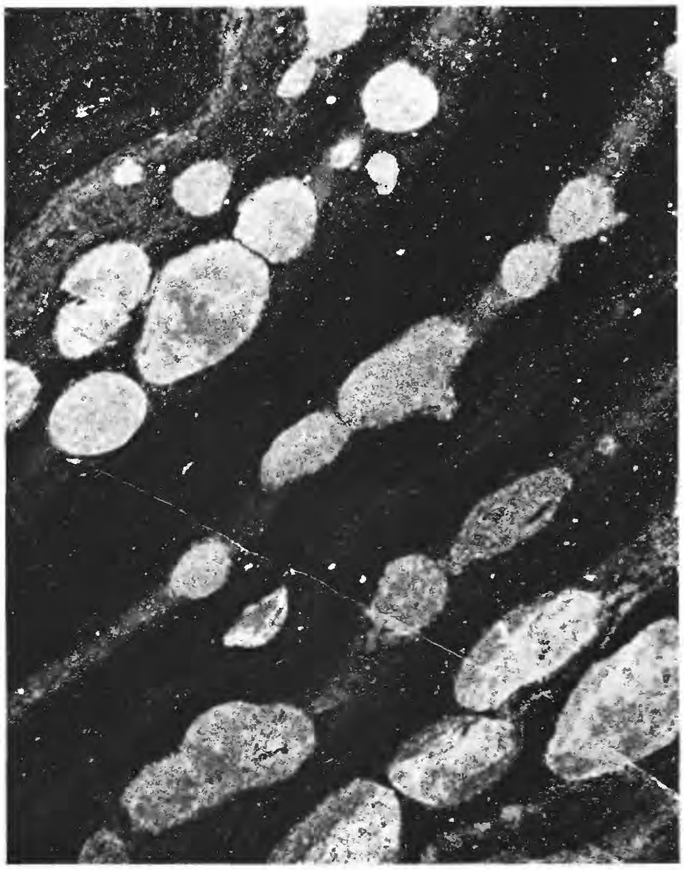


FIGURE 21.—Photomicrograph of carbonate-rich pods in laminated hematitic ironstone. Manganiferous carbonate is present in some of the lighter colored laminae as well as in the hematitic (dark) layers. Maple-Hovey deposit. Plane light; × 15.

ACCESSORY MINERALS

Spessartite.—Spessartite garnet in some of the deposits on Maple and Hovey Mountains occurs in laminae containing light-colored minerals and opaque oxides, and in the light-colored pods in hematitic slate and banded hematite ironstone. Spessartite may make up 50 percent of some laminae and pods. Figure 23 shows this garnet.

Bementite.—Bementite is not as abundant in the deposits on Maple and Hovey Mountains as it reportedly is in the northern district. It has been identified optically in light-colored laminae or pods.

Cryptocrystalline apatite.—Cryptocrystalline apatite is an important accessory in the manganiferous rocks of the Maple and Hovey Mountains deposits. In the banded hematite ironstone of the Maple-Hovey deposit, it is concentrated in the light-colored laminae. It also occurs as tiny irregular patches or blebs embedded in the carbonate-rich laminae of the ironstone. It is recognizable by the yellow precipitate it produces when tested chemically with ammonium molybdate, and in thin section by its low birefringence and high relief.

Hausmannite.—Hausmannite, which appears to be quite rare, is the only other opaque crystalline oxide besides braunite and hematite identified in the Aroostook hematitic manganese deposits. In the deposits of Maple and Hovey Mountains it has been identified only in small amounts within a cream-yellow carbonate-rich pod in one specimen of brick-red hematitic ironstone. (For chemical analysis see T–43–A, table 8.) This rock contains numerous pods, beads, and laminae of various light-colored minerals, which include carbonate, feldspar, barite, spessartite, and possibly bementite. Some of the nodules are partly darkened by black manganese oxides. The hausmannite in this specimen is readily recognizable in polished section by its moderate reflectivity (less than that of hematite, but somewhat greater than that of braunite), its strong anisotropy, with

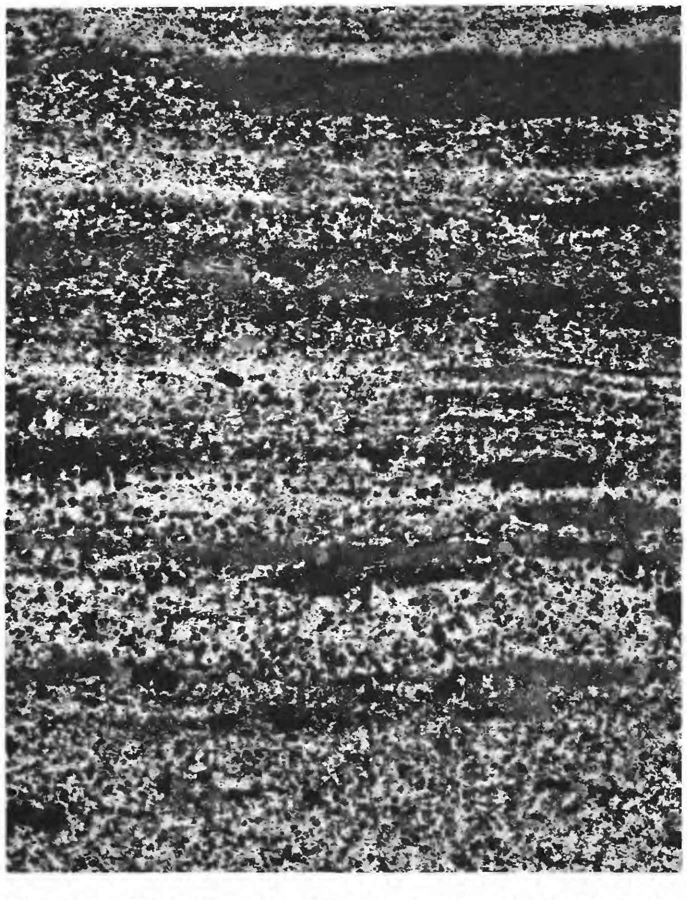


FIGURE 22.—Photomicrograph of a polished section of banded hematite ironstone, Maple-Hovey deposit. Note the intimate association of gangue which occurs in different proportions in the various sedimentary layers of hematite (white). Plane light; × 105.

Figure 23.—Photomicrograph showing spessartite in part of a carbonate-rich lamina with irregular constrictions. Spessartite-bearing laminae are separated by a hematitic layer (black in the illustration), cut by gash veinlets of carbonate. Maple-Hovey deposit. Plane light; × 40.

marked reflection-pleochroism, and the diagnostic lamellar twinning. (See fig. 24.)

White (1943, p. 139), in describing the mineralogy of the deposits of the southern manganese district, thought that "possibly some manganese is present also in an opaque mineral such as braunite or hausmannite," but the metallic minerals were never studied in sufficient detail for hausmannite to be identified. At present the only known occurrence of hausmannite in the Aroostook manganese deposits is the minute amount discovered in the ironstone from the Maple-Hovey deposit described above.

Other accessory minerals. Alkalic feldspars are additional accessory minerals of these deposits but they are generally difficult to recognize because of the nature of the manganiferous rocks. They are normally untwinned and their refractive indices are below that of canada balsam. Fine-grained quartz is also present in most of these rocks. Muscovite and chlorite are ubiquitous constituents. Irregular chertlike blebs are sparsely present in some of the layers of the manganiferous rocks. Barite and phlogopite have been noted in a few pods.

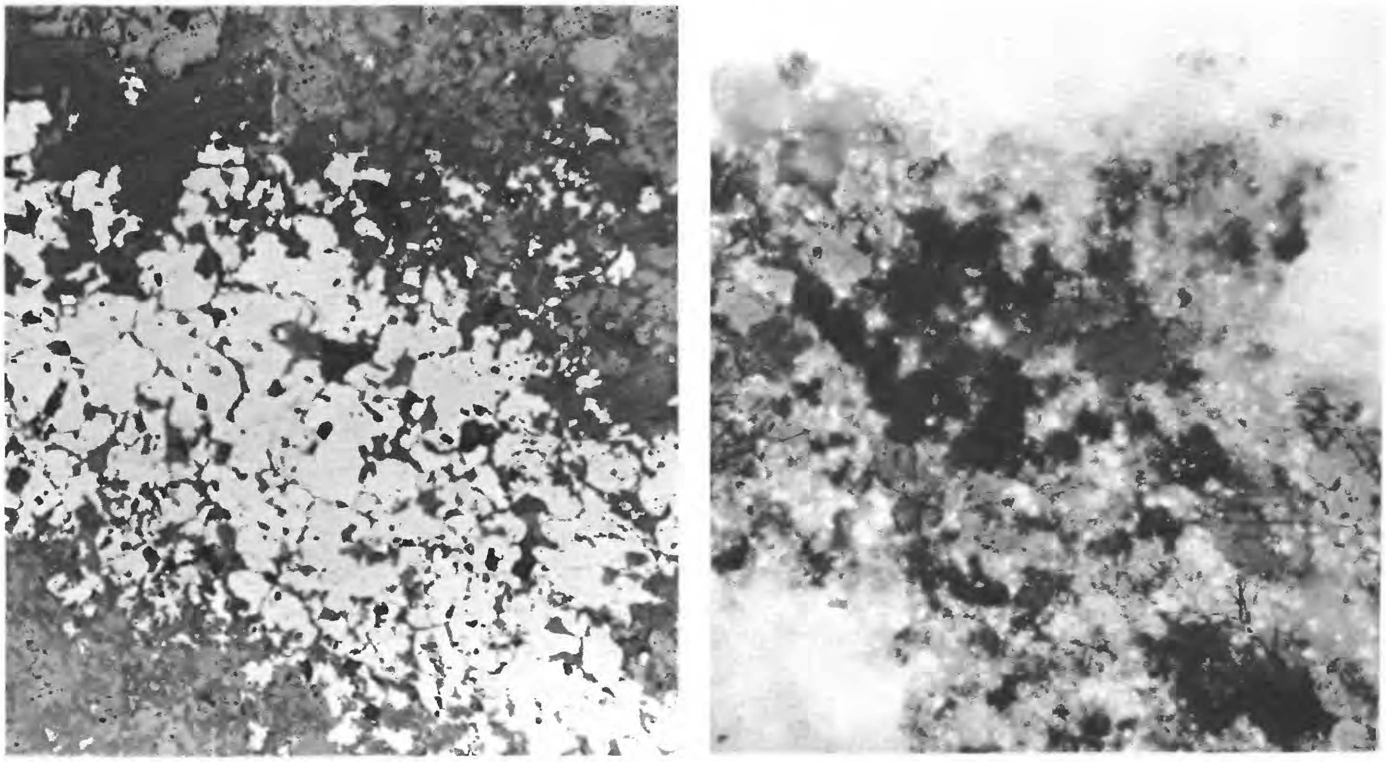
ESTIMATES OF MINERAL PERCENTAGES

The physical nature of the manganiferous rocks of Aroostook County precludes precise quantitative determinations of their mineral constituents by standard microscopic techniques.

White (1943, p. 133–134) has made a visual, partial quantitative estimate of the mineral composition of the Dudley deposit of the northern manganese district as follows: braunite, 10 to 11 percent; bementite, 1 to 2 percent; carbonate (of variable composition), about 25 percent; and hematite, about 27 percent. The remaining minerals are chlorite, sericite, detrital quartz, collophane, biotite, and barite. White's estimates for the Dudley deposit are in the same order of magnitude as the present writers' estimates for the hematitic deposits of Maple and Hovey Mountain, where comparisons are based on rocks with similar chemical and mineral features.

The banded hematite ironstone of the middle manganiferous unit of the Maple-Hovey deposit, however, is a lithologic type not abundant in the Dudley deposit of the northern manganese district. The ironstone of the Maple-Hovey deposit is more brittle and has a higher effective hardness than the ironstone common in the Dudley deposit. All these rocks, however, resemble those generally referred to as iron-formation, although the banded hematite ironstone of the Maple-Hovey deposit contains only negligible amounts of chert. However, according to James' definition of iron-formation (1954, p. 239–240), "a chemical sediment, typically thin-bedded or laminated, containing 15 percent or more iron of sedimentary origin, commonly but not necessarily containing layers of chert," much of the manganiferous banded ironstone of Aroostook County, Maine, would be classed as iron-formation.

Although the complex and diverse lithologic types constituting the banded hematite ironstone of the middle manganiferous unit in the Maple-Hovey deposit and the difficulty in identifying the fine-grained minerals microscopically make visual estimates of mineral percentages very uncertain, an attempt has been made



A. Plane light; × 470 *B.* Crossed nicols; × 500

FIGURE 24.—Photomicrographs of hausmannite in a polished section of a carbonate-rich pod from a hematitic ironstone, Maple-Hovey deposit. Figure *B* illustrates the diagnostic lamellar twinning forming random straight lines across the grains.

to obtain rough semiquantitative estimates of the mineral percentages of some of the ironstones by recasting their chemical analyses (see table 8*A*) into mineralogic terms. The analyses in table 8 are of hand specimens a few inches in size, collected from several trenches on Maple and Hovey Mountains, and chosen as representative of the common varieties of ironstone within the middle manganiferous unit of the Maple-Hovey deposit. The procedure followed is somewhat similar to that used in calculating norms in igneous rocks, except that the "normative" minerals in this instance are those which are known to be generally present in the rocks under consideration. Of necessity, generalized and ideal formulas were used for the minerals constructed. These formulas are listed in table 9, along with the calculated mineral percentages. In general the mineral percentages were calculated as follows:

1. Apatite is calculated as tricalcium phosphate, with the amount of P_2O_5 determining the amount of apatite formed.
2. Sphene is formed with the TiO_2 present.
3. Albite is formed with the Na_2O present.
4. Form either muscovite or orthoclase, using all of the K_2O in only one of these minerals.
   - a. Muscovite is formed if sufficient residual Al_2O_3 is present after albite is formed.
   - b. Orthoclase is formed, if the residual Al_2O_3 present after albite is formed is insufficient to construct muscovite.
5. If a sufficient amount of Al_2O_3 is left after step 4, chlorite is formed with the MgO present. If enough Al_2O_3 is not left to form chlorite, magnesite is formed with the MgO.
6. If Al_2O_3 remains after step 4 or 5, spessartite is formed with it.
7. Calcite is formed with the residual CaO present.
8. Rhodochrosite is formed with the residual CO_2.
9. Bementite is formed with the residual H_2O. If in so doing the amount of MnO needed exceeds the amount remaining, then:
   - a. Bementite is constructed with the amount of MnO remaining after step 8.
   - b. Limonite is formed with the residual H_2O after step 9a.

TABLE 8.—*Chemical analyses of manganese-bearing hematitic ironstone and manganiferous magnetite-bearing ironstone from the Maple-Hovey deposit*

[Samples 51-55SC and 51-54SC analyzed by Charlotte M. Warshaw; other samples analyzed by Robert N. Eccher]

A. **Hematitic ironstone**

Laboratory No. Field No.	51-1626CD [1] [2] T-5-A	51-1627CD [1] T-12-A	51-1628CD [1] T-12-B	51-1629CD [1] [2] T-42-A	51-1630CD [1] [2] T-43-A	51-55SC [2] T-12+142E	Arithmetic average
SiO_2	19. 19	19. 77	14. 64	13. 30	37. 14	21. 02	20. 84
Al_2O_3	3. 53	3. 31	2. 53	3. 20	9. 67	2. 53	4. 13
Fe_2O_3	38. 65	27. 10	55. 16	56. 67	5. 66	57. 10	40. 06
FeO	. 00	. 00	. 00	. 00	. 00	. 00	. 00
MgO	1. 49	1. 59	1. 08	1. 29	2. 36	1. 15	1. 49
CaO	5. 91	5. 04	5. 99	5. 31	2. 54	5. 02	4. 97
Na_2O	. 76	. 02	. 97	1. 32	1. 42	[3]. 18	. 78
K_2O	. 76	. 50	. 44	. 57	2. 74	[3]. 24	. 88
H_2O-	. 06	. 09	. 30	. 16	. 06	. 14	. 14
H_2O+	. 57	1. 05	. 94	. 71	. 70	1. 08	. 84
TiO_2	. 16	. 13	. 11	. 14	. 39	[3]. 16	. 18
CO_2	4. 78	4. 50	2. 96	4. 49	6. 85	1. 62	4. 20
P_2O_5	4. 02	3. 17	4. 15	3. 25	. 15	3. 70	3. 07
MnO	19. 87	33. 67	10. 37	9. 47	29. 93	6. 31	18. 27
S [4]	. 01	. 01	----------	----------	----------	----------	----------
O	----------	----------	----------	----------	----------	. 18	----------
Total	99. 76	99. 95	99. 64	99. 88	99. 61	100. 43	99. 85

B. **Magnetite-bearing ironstone**

Laboratory No. Field No.	51-1631CD [1] T-19-C	51-1632CD [1] T-23-B	51-1633CD [1] T-23-A	51-1634CD [1] [2] T-23-C	51-1635CD [1] [2] T-23-D	51-54SC [2] T—11+270W	Arithmetic average
SiO_2	8. 96	18. 62	19. 90	16. 63	13. 57	26. 41	17. 35
Al_2O_3	3. 59	3. 60	2. 25	3. 40	3. 73	4. 59	3. 53
Fe_2O_3	45. 52	40. 51	20. 09	42. 21	40. 21	39. 21	37. 96
FeO	17. 71	20. 86	3. 45	17. 24	1. 47	15. 53	12. 71
MgO	1. 35	2. 33	1. 54	1. 14	. 92	1. 78	1. 51
CaO	5. 98	4. 00	8. 09	4. 18	6. 56	4. 11	5. 49
Na_2O	. 03	. 04	. 02	. 03	. 10	[3]. 07	. 05
K_2O	. 26	. 23	. 63	1. 30	. 88	[3]. 45	. 63
H_2O-	. 08	. 58	. 57	. 57	1. 00	. 14	. 49
H_2O+	2. 07	2. 78	1. 88	1. 64	1. 95	2. 12	2. 07
TiO_2	. 14	. 14	. 10	. 09	. 03	[3]. 22	. 12
CO_2	2. 17	. 28	13. 26	3. 06	7. 22	. 00	4. 33
P_2O_5	4. 80	3. 13	5. 52	2. 94	4. 62	3. 16	4. 03
MnO	6. 98	2. 66	21. 99	5. 75	17. 27	1. 78	9. 41
S [4]	. 03	. 02	. 06	. 007	. 01	. 05	. 03
Total	99. 67	99. 78	99. 35	100. 187	99. 54	99. 63	99. 71

[1] Polished-section study made.
[2] Thin-section study made.
[3] Determined by S. M. Berthold.
[4] Determined by M. K. Carron.

10. Braunite is formed with the residual MnO, converting the oxide to metal and then recalculating as MnO and Mn_2O_3 in order to satisfy the 3:1 ratio of these oxides in the mineral.
11. Hematite is formed with the residual Fe_2O_3.
12. Quartz is formed with the residual SiO_2.

This procedure was modified where thin section and polished section studies indicated that one of these minerals is probably absent.

Table 9 also lists some measured specific gravities and the specific gravities of the rocks calculated in terms of these mineral percentages. The results listed in table 9 are of value only in expressing the general mineral percentages of the ironstone.

MAGNETITE-BEARING SLATE AND IRONSTONE

PRINCIPAL MINERALS

Magnetite.—The magnetite in the more metamorphosed oxide facies manganese-bearing rocks is believed to have been formed, chiefly, if not entirely, from original hematite. Magnetite and hematite are present in all proportions to one another in the manganese-

TABLE 9.—*Calculated mineral content (weight percent) of manganese-bearing hematitic ironstone from the Maple-Hovey deposit*

[n.d.=not determined]

Mineral	Sp gr	Field No.					
		T-5-A	T-12-A	T-12-B	T-42-A	T-43-A	T-12+142E
Braunite ($3Mn_2O_3 \cdot MnSiO_3$)	4.8	16.3	29.6	7.3	2.7	14.7	0.8
Bementite ($8MnO \cdot 7SiO_2 \cdot 5H_2O$)	3.0	3.5	3.7	-----	-----	8.4	1.5
Spessartite ($3MnO \cdot Al_2O_3 \cdot 3SiO_2$)	4.2	-----	3.1	.5	2.0	21.3	3.6
Rhodochrosite ($MnO \cdot CO_2$)	3.5	7.1	10.0	6.7	7.8	6.9	4.1
Hematite (Fe_2O_3)	5.2	38.7	27.2	50.9	52.5	5.6	50.1
Quartz (SiO_2)	2.7	8.9	10.1	5.6	1.9	5.6	15.7
Albite ($Na_2OAl_2O_3 \cdot 6SiO_2$)	2.6	6.3	1.6	8.4	11.0	12.1	1.6
Orthoclase ($K_2O \cdot Al_2O_3 \cdot 6SiO_2$)	2.6	-----	-----	2.8	3.3	16.1	-----
Muscovite ($2H_2O \cdot K_2O \cdot 3Al_2O_3 \cdot 6SiO_2$)	2.9	6.4	4.0	-----	-----	-----	2.4
Chlorite ($4H_2O \cdot 5MgO \cdot Al_2O_3 \cdot 3SiO_2$)	2.7	-----	4.3	1.7	-----	-----	3.2
Magnesite ($MgO \cdot CO_2$)	3.1	3.1	-----	-----	1.5	5.0	-----
Calcite ($CaO \cdot CO_2$)	2.7	1.0	1.5	.9	1.6	3.7	.1
Sphene ($CaO \cdot TiO_2 \cdot SiO_2$)	3.4	.4	.4	.2	.4	1.0	.4
Apatite ($3CaO \cdot P_2O_5$)	3.2	8.7	6.8	9.0	7.1	.3	8.1
Limonite ($2Fe_2O_3 \cdot 3H_2O$)	3.8	-----	-----	5.0	4.9	-----	4.5
Total mineral content	-----	100.4	102.3	99.0	96.7	100.7	96.1
Calculated sp gr	-----	4.1	4.1	4.3	4.3	3.5	4.2
Measured sp gr	-----	3.8	n.d.	n.d.	4.1	3.4	n.d.

bearing rocks. Some rocks contain sparse, disseminated magnetite octahedra embedded in hematitic laminae and some contain magnetite but no hematite.

Carbonate.—The chief manganese mineral in the magnetite-bearing ironstone is a carbonate near rhodochrosite in composition. It typically occurs in the same manner as in the banded hematite ironstone, namely, in layers and in pods, but in a few places it is coarser grained than carbonate in the banded hematite ironstone.

Chlorite.—Several varieties of chlorite are present, most of which are iron-chlorites whose indices of refraction are close to those of thuringite or daphnite. Some of the chlorite, characterized by low birefringence and a relatively low mean refractive index, may be a variety of penninite or clinochlore. Chlorite commonly borders magnetite on two sides in pressure-shadowlike growths. (See fig 25.) Peripheral martitization of the magnetite is common in the ironstone. (See fig. 26.)

ACCESSORY MINERALS

Other common but less abundant minerals in these rocks are original hematite, cryptocrystalline apatite, quartz, and alkalic feldspars. Biotite, muscovite, spessartite, stilpnomelane(?), and bementite(?) are present in small amounts.

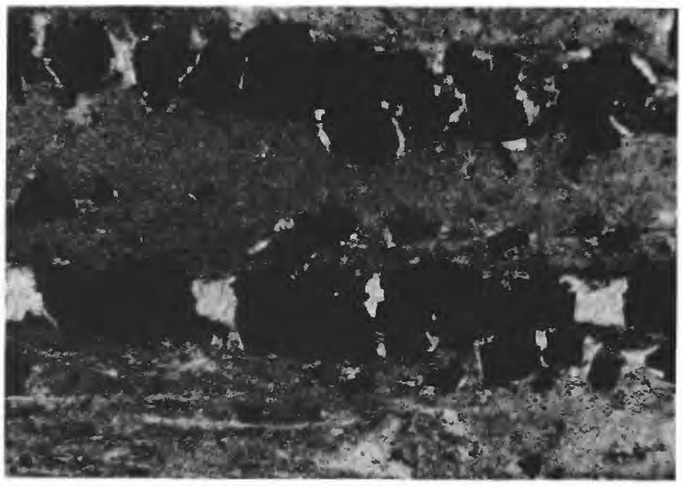


FIGURE 25.—Photomicrograph of magnetite-bearing banded ironstone. Magnetite-rich laminae (black) are bounded by pressure shadow growths of two varieties of chlorite; green pleochroic chlorite and a colorless chlorite (light gray). The other layers in the section (dark gray) consist of a mat of cryptocrystalline transparent material which may be both chloritic and apatite rich. Magnetite and some chlorite are disseminated in the nonopaque layers. The thin black streaks in the nonopaque layers are hematitic dust. Plane light; × 80.

ESTIMATES OF MINERAL PERCENTAGES

The manganiferous banded magnetite-bearing ironstone is not amenable to mechanical quantitative measurements of mineral percentages. The presence of

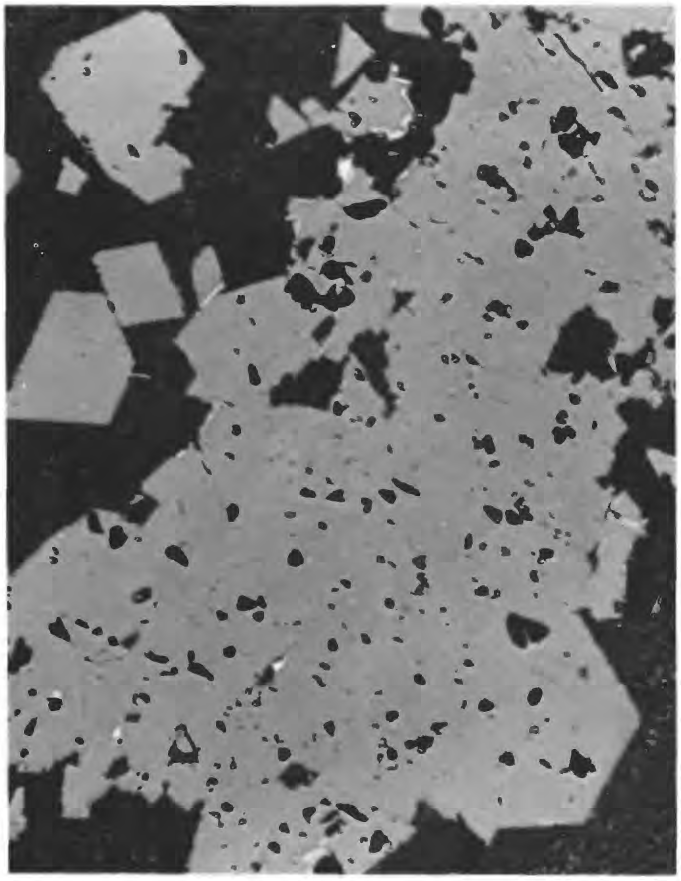


FIGURE 26.—Photomicrograph of a polished section of part of the magnetite-bearing ironstone in figure 25, showing minor peripheral alteration of magnetite (gray) to hematite (white). Interstitial dark material is gangue. Plane light; × 200.

chemically complex minerals such as biotite and iron-bearing chlorite in these rocks precludes attempts at calculating mineral percentages from chemical analyses of individual rocks, because the precise chemical formulas of these minerals, necessary to determine the distribution of K_2O, MgO and FeO in them, as well as their $MgO:FeO$ ratios, is not available. Visual mineral estimates supplemented by selective partial mineral calculation from the chemical analyses in table 8*B*, however, indicate the following modal range for these rocks:

Mineral	*Percent*
Rhodochrosite	5–30
Magnetite	2–55
Iron-bearing chlorite	4–15
Hematite	1–30
Apatite	6–12
Quartz	1–20
Biotite	2–7
Muscovite	2–15
Bementite	0–5
Spessartite	0–13
Other minerals	Trace to several percent

CARBONATE FACIES—SILICEOUS CARBONATE ROCKS

Deposits of manganiferous siliceous carbonate occurs in all three districts of the Aroostook manganese belt, but only in the northern manganese district are these deposits consistently free of magnetite. Magnetite-free manganiferous siliceous carbonate rocks on Maple and Hovey Mountains occurs only in a thin zone immediately below the lower manganiferous units of the Maple-Hovey and Southern Hovey deposits. Magnetite-bearing siliceous carbonate layers, however, are also present within the lower manganiferous unit of these deposits at various places, and their distribution, at least in the Maple-Hovey deposit, is related to localized, structurally controlled metamorphism. These rocks and their probable mechanism of formation are described in a later section of this report. In the southern manganese district, the northern part of the Littleton Ridge siliceous carbonate deposit apparently has no magnetite (Pavlides, 1955, p. 6). The southern part of the Littleton Ridge deposit contains magnetite. Magnetite has not been reported in several beds of the manganese-bearing siliceous carbonate facies in the southern district, such as the Atherton-Sloat prospect or the Gardner prospect (Miller, 1947, pp. 70–74), but is evidently present in other such deposits in the district.

The term "siliceous carbonate rock" as used in this report is equivalent to White's "chlorite-carbonate rock" of the northern manganese district (1943, p. 135), and to Miller's "siliceous limestone" and "calcareous quartzite" (1947, p. 23 and 25.) White recognized siliceous carbonate rock only in the northern district and according to him (1943, p. 136) the ironstone typically is a hard, heavy, laminated rock consisting of alternating light-green layers mainly of fine-grained "calcitic" manganese- and iron-bearing carbonate, and dark-green layers mostly of chlorite and with small quantities of carbonate and 5 to 10 percent of quartz. He estimates that "the carbonate apparently makes up 15 to 30 percent of the individual manganiferous zones." White also believes that the siliceous carbonate rocks differ primarily from other manganiferous rocks in Aroostook County in that they are "almost free of hematite." White does not classify the deposits of the southern manganese district as hematitic and siliceous carbonate types as he did in the northern manganese district. Miller (1947, p. 23–25, pl 4), on the other hand, who studied the Littleton Ridge deposit, northwest of Houlton in the southern manganese district, recognized siliceous carbonate rocks in the southern district. (The

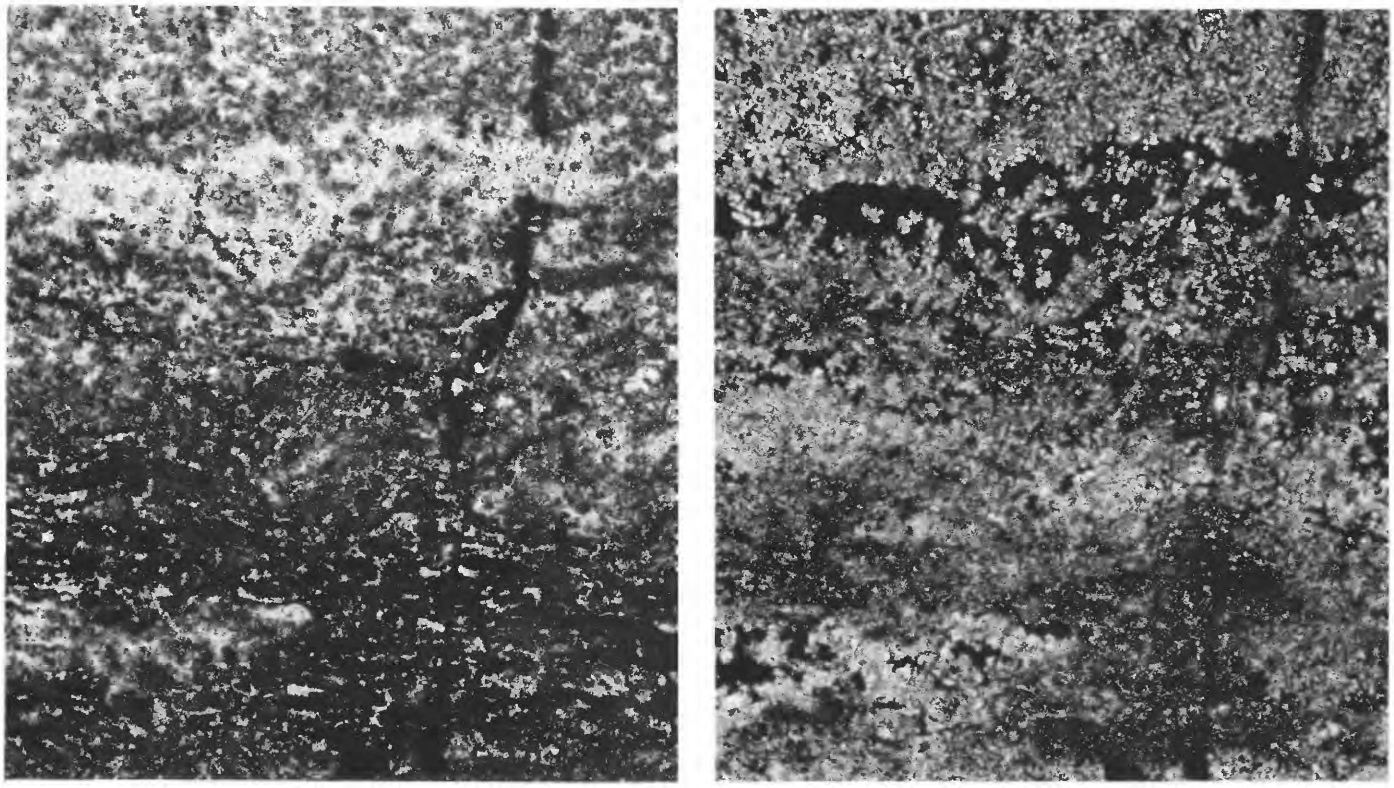
Littleton Ridge deposit had not been discovered when White worked in the area.) According to Miller's general description of the siliceous carbonate rocks of the Aroostook manganese belt, the chlorite in these rocks is iron rich, and the chlorite examined and analyzed by the writers from the Littleton Ridge deposit confirms this. Miller further states that braunite is the most abundant type of manganese mineral in both the hematitic and siliceous carbonate types of "ores" in the Aroostook deposits. The writers, however, have not observed braunite in the siliceous carbonate rocks of any of the deposits in the Aroostook manganese belt, nor does White report it in his description of this lithologic type in the northern manganese district. The absence of braunite in these siliceous carbonate rocks is thought to be a primary depositional feature.

The manganiferous siliceous carbonate rocks underlying the hematitic Maple-Hovey and Southern Hovey deposits on Maple and Hovey Mountains consist typically of beds of siliceous carbonate from 1 inch to several feet thick, unevenly interlayered with green sericite-chlorite slate. The magnetite-free siliceous carbonate rocks below the hematitic Maple-Hovey deposit are considered to be typical of this lithology.

MAGNETITE-FREE SILICEOUS CARBONATE ROCKS

Fresh, unweathered specimens of the magnetite-free manganiferous siliceous carbonate rocks are dense, have a blocky fracture, and are finely layered with alternating green and buff to tan laminae. In gross aspect, however, these rocks have a greenish color. Pyrite is always present and commonly is very abundant. It ranges from a fraction of a percent to 30 percent.

Under the microscope, the green laminae of a typical siliceous carbonate rock consist chiefly of a green, pleochroic chlorite mat in which carbonate is disseminated as the principal nonopaque accessory mineral. The buff to tan laminae and generally the green laminae contain carbonate, much of which has spherulitic texture (see fig. 27), and generally varying amounts of interstitial green chlorite. Figure 28 illustrates the general mineral composition and textures of these laminae in thin section.



A. Plane light

B. Crossed nicols

FIGURE 27.—Photomicrographs of siliceous carbonate rock showing an area of intimately associated green pleochroic chlorite and spherulitic carbonate (some of which is iron stained). *A,* Carbonate (gray) and chlorite (white). *B,* Carbonate (gray—note spherulitic extinction) and chlorite (black). × 50.

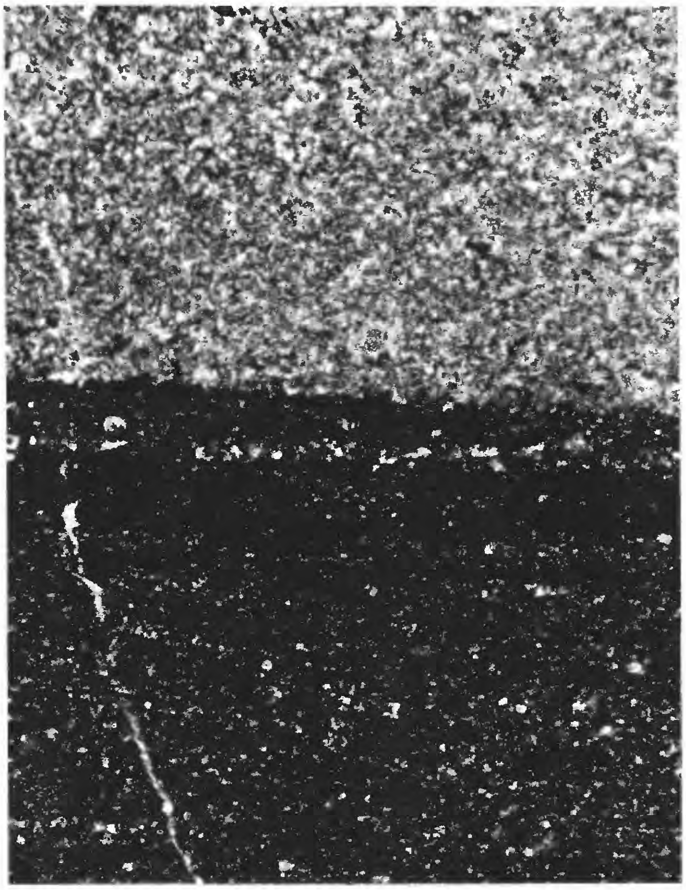


FIGURE 28.—Photomicrograph of a siliceous carbonate rock showing a chloritic lamina in contact with a typical carbonate-rich lamina. Carbonate-rich lamina (gray); chlorite-rich lamina (black). Crossed nicols. × 50.

PRINCIPAL MINERALS

Carbonate.—In general, the magnetite-free siliceous carbonate rocks from the Maple and Hovey Mountains area do not yield suitable mineral concentrates for precise chemical and X-ray determinations. A few layers of magnetite-free siliceous carbonate rock from the Littleton Ridge deposit of the southern manganese district, which contains carbonate and chlorite optically similar to that in the corresponding rocks on Maple and Hovey Mountains, furnished some specimens from which a substantially pure concentrate of carbonate and chloritelike mineral were obtained by hand picking under a microscope. The chemical analysis[6] of the carbonate indicates it is a ferroan rhodochrosite containing about 24 percent $FeCO_3$, 6 percent $CaCO_3$, and 62 percent $MnCO_3$, which totals to 92 percent (MgO was analyzed for but not found). The measured No of this carbonate is 1.810; if computed from the general formula of carbonate components, No is 1.800, a reasonably good agreement with the measured value for this type of material.

Chlorite.—The chlorite found in the siliceous carbonate rocks commonly has indices of refraction, optic sign, color, and birefringence close to those of the iron chlorites, such as thuringite and daphnite (Larsen and Berman, 1934, p. 231).

Other types of carbonate and chlorite.—Ferroan rhodochrosite and an iron-rich chlorite close to daphnite in composition are the principal carbonate and chlorite in the manganese-bearing siliceous carbonate rock. Thin-section study indicates, however, that several varieties of carbonate and chlorite are present in any one specimen. Although calcic and dolomitic carbonate is found in some rocks it is nonetheless rare. The carbonate of the siliceous carbonate deposits of Maple and Hovey Mountains and of the Littleton Ridge deposit of the southern manganese district may differ appreciably from that in the siliceous carbonate rock of the northern district, which was reported as manganese- and iron-bearing calcic carbonate by White (1943, p. 136). Besides strongly pleochroic chlorite, the siliceous carbonate rock also has green, weakly pleochroic to nonpleochroic chlorite and more rarely, colorless chlorite. These chlorites commonly have low birefringence or anomalous blue or purple interference colors. Chemical analyses of specimens of magnetite-free manganiferous siliceous carbonate rock from Littleton Ridge (see table 10) further indicate that MgO is a relatively minor constituent of such rocks (average is 2.0 percent) so that their carbonate can contain only a small proportion of $MgCO_3$ and the chlorite too must be low in MgO.

Pyrite.—The pyrite in these rocks is chiefly associated with the chlorite in chloritic layers. The pyrite occurs as single crystals, in clusters, or in layers. Pyrite clustered into elongate knots is typically enclosed or mantled by fairly coarse-grained optically negative and strongly pleochroic (green to pale yellow) chlorite, optically suggesting daphnite. A minor amount of carbonate is present in the pyritic knots, and in some places it resembles inclusions of carbonate-rich laminae, whereas in other places it bounds the pyrite in pressure-shadow recrystallization growths. The pyritic laminae that are conformable to the primary sedimentary banding of the associated chloritic and carbonate-rich laminae have similar mineral associations. (See fig. 29.) An unique occurrence of pyrite is as balls in a layer composed chiefly of fragments of cryptocrystalline apatite(?) (fig. 30).

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[6] Rapid-method analysis by Leonard Shapiro.

TABLE 10.—*Chemical analyses of manganiferous magnetite-free and magnetite-bearing siliceous carbonate rocks from the Littleton Ridge deposits southern manganese district, Aroostook County, Maine*

[Chemical analyses by H. F. Phillips and K. E. White by rapid method (Shapiro and Brannock, 1952)]

	Magnetite-free specimens				Magnetite-bearing specimens	
Laboratory No	53-1113C	53-1114C	53-1115C	53-1116C	53-1117C	53-1118C
Field No	L-DDH62-1	L-DDH62-2	L-DDH62-4	L-DDH65-7	L-DDH66-1	L-DDH66-6
SiO_2	18. 2	36. 0	19. 4	20. 2	20. 0	14. 5
Al_2O_3	4. 3	5. 8	3. 6	5. 9	3. 0	5. 4
Fe_2O_3	4. 7	10. 4	8. 1	1. 7	16. 7	27. 4
FeO	17. 9	21. 9	20. 4	15. 5	27. 8	23. 0
MgO	1. 6	2. 3	1. 6	2. 6	. 94	. 95
CaO	7. 3	3. 8	3. 9	7. 1	3. 5	4. 6
Na_2O	. 19	. 22	. 23	. 14	. 20	. 76
K_2O	. 59	1. 2	. 58	. 12	. 88	. 86
TiO_2	. 19	. 18	. 16	. 18	. 09	. 26
P_2O_5	4. 4	2. 1	1. 6	2. 4	1. 6	2. 8
MnO	18. 4	4. 9	18. 2	21. 2	6. 8	6. 8
H_2O+	2. 7	5. 7	3. 1	2. 9	. 54	1. 4
H_2O-	. 26	1. 6	. 72	. 08	. 08	. 07
CO_2	19. 4	4. 8	19. 7	20. 1	18. 8	12. 4
Total	100. 13	100. 90	101. 29	100. 12	100. 93	101. 20

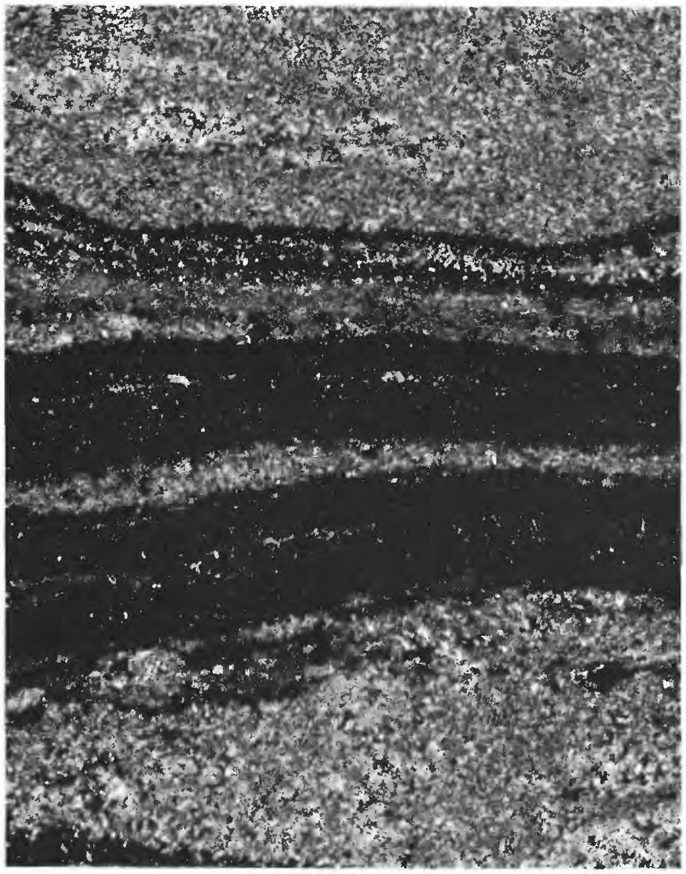

FIGURE 29.—Photomicrograph of pyrite-rich laminae (black) interlayered with carbonate-rich laminae (gray). Crossed nicols; × 25.

The optical properties of much of the carbonate in this rock are close to those of siderite and ferroan rhodochrosite.

ACCESSORY MINERALS

Quartz and, in some places, blebs of cryptocrystalline apatite, are among the recognizable accessory nonopaque minerals in the siliceous carbonate rocks. Alkalic feldspar and a little white mica are also present in small quantities.

A chloritelike mineral concentrate from the rock that also provided the sample of ferroan rhodochrosite (p. 61) was partly analyzed, as follows:[7]

	Percent
SiO_2	27
Total Fe as Fe_2O_3	28
MgO	Not found
CaO	5
MnO	10
Total	70

The absence of detectable MgO both in the chlorite and the carbonate fractions is noteworthy. The iron-manganese ratio in the carbonate analysis indicates that no more than 4 percent of the iron in the above silicate analysis can be present as carbonate impurity; accordingly the chloritelike mineral is high in iron, is free of magnesium, and is low in manganese. The

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[7] Rapid-method analysis by Leonard Shapiro.

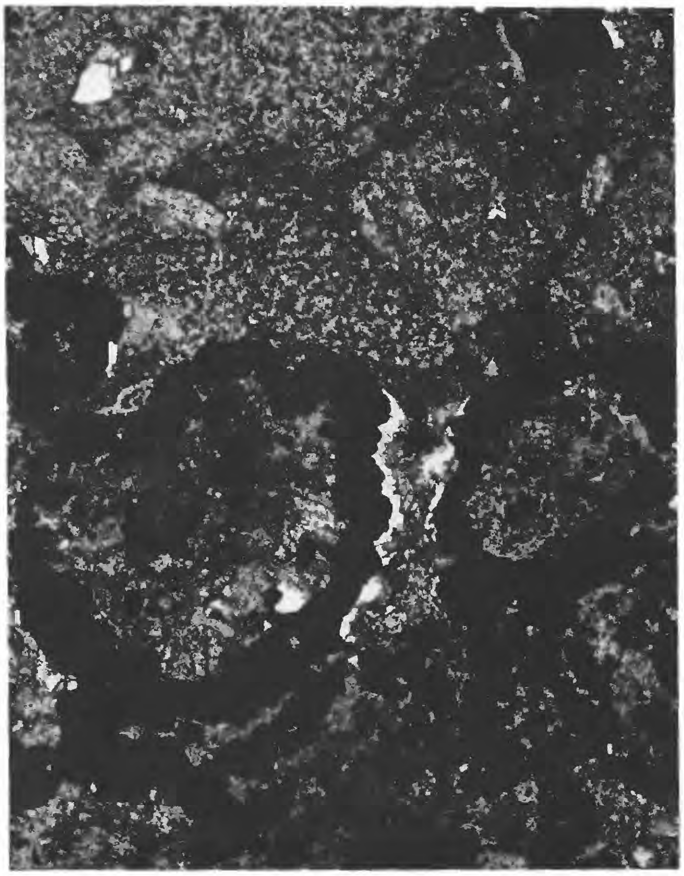

FIGURE 30.—Photomicrograph of rounded pyrite ovoids and balls in a layer composed mainly of fragments of cryptocrystalline apatite (?). Note chlorite bounding pyrite. Outline of rounded (?) fragments of cryptocrystalline apatite (?) vaguely visible in upper left of photograph. Crossed nicols; × 50.

above anlaysis and the optical properties are insufficient for precise referral of the mineral to any particular mineral species. X-ray examination did not give a precise pattern that could be identified, but suggested a stilpnomelanelike structure.[8]

ESTIMATES OF MINERAL PERCENTAGES

The siliceous carbonate rocks, like the magnetite-bearing ironstone, and not amenable to mechanical quantitative measurements of mineral percentages, such as Rosiwal analyses, or to calculated mineral percentages as described above for the hematitic ironstone. The chief reason for this is that the chloritic and stilpnomelanelike minerals in these rocks are chemically too variable and complex to permit the use of a generalized species formula for use in normative mineral construction. However, visual microscopic estimates supplemented by normative estimates of the carbonate and apatite of the magnetite-free rocks in table 10 indicate the following modal range for these rocks:

	Percent
Carbonate	10–50
Apatite	3–10
Chlorite and stilpnomelane	10–50
Pyrite	Trace–30
Quartz	Trace–10

MAGNETITE-BEARING SILICEOUS CARBONATE ROCKS

The manganese-bearing siliceous carbonate rocks on Maple and Hovey Mountains, exclusive of most of those associated with the Maple-Hovey and Southern Hovey deposits, contain magnetite. In some places, these siliceous carbonate rocks are somewhat similar both in their megascopic features and mineralogy to the banded magnetite-bearing ironstone believed to have developed by metamorphism of primary banded hematite rock.

The distribution of the nonopaque and opaque minerals in the magnetite-bearing siliceous carbonate rocks is highly variable. The light-colored laminae consist principally of carbonate with different amounts of chlorite, cryptocrystalline apatite, quartz, and ferrostilpnomelane(?). In places, a pale pink to red color is imparted to these layers by limonite and red oxides associated with the carbonate. The dark-green layers are composed chiefly of chlorite and also contain minor amounts of the above-mentioned minerals. The carbonate in some of the chloritic layers occurs as rhombohedrons embedded in a chloritic groundmass. Some laminae of these rocks are nearly monomineralic in carbonate, chlorite, or any of the other constituents. Wherever present, magnetite, pyrite, and pyrrhotite are associated with these laminae.

PRINCIPAL MINERALS

Magnetite.—Magnetite in siliceous carbonate rocks is chiefly of octahedral habit and occurs either concentrated in laminae or dispersed, often as alined crystals, conformable with the bedding.

Carbonate.—Carbonate, chiefly in the range between siderite and rhodochrosite, contains nearly all the manganese in the magnetite-bearing siliceous carbonate rocks. Minor amounts of carbonate with indices of refraction lower than rhodochrosite are also present.

Chlorite.—Chlorite, in several varieties, is one of the chief constituents of these rocks. The varieties of chlorite suggested by optical properties are penninite, clinochlore, and daphnite. The chemical analyses of magnetite-bearing siliceous carbonate rocks from Littleton Ridge (see table 10) and the partial chemical

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[8] X-ray analysis by F. A. Hildebrand.

analyses of composite samples from diamond-drill holes through a siliceous carbonate deposit on Hovey Mountain (see table 16) indicate low MgO, 0.94 and 0.95 percent from Littleton Ridge, and 2.21 and 2.62 percent from Hovey Mountain (which contain beds of chloritic slate in addition to siliceous carbonate layers). The relatively small amount of MgO in these samples also suggests that the bulk of the chlorite in these rocks is iron rich rather than magnesian.

ACCESSORY MINERALS

Pyrite and pyrrhotite are also present in these rocks. Pyrrhotite of possible metamorphic origin in the magnetite-bearing siliceous carbonate rocks occurs either as semitabular crystals or elongate aggregates. On the other hand, the pyrite commonly occurs as distorted cubic metacrysts, normally alined along bedding.

Quartz is a minor constituent, chiefly of detrital habit and generally occurs embedded in chlorite. Cryptocrystalline apatite is an important accessory. It forms small blebs embedded in carbonate- or chlorite-rich laminae, or is concentrated in separate laminae. Normally, it is difficult to distinguish the apatite-rich laminae from those composed of fine-grained chlorite with low birefringence. Cryptocrystalline apatite in hand-picked material from such laminae can be recognized, however, by the ammonium molybdate test. A very fine grained micaceous mineral has been noted in several thin sections of the magnetite-bearing siliceous carbonate rocks. It resembles biotite, but its strong pleochroism suggests ferrostilpnomelane.

ESTIMATES OF MINERAL PERCENTAGES

The percentages of different minerals in the magnetite-bearing siliceous carbonate rocks cannot be closely estimated, for reasons similar to those given above for the magnetite-free siliceous carbonate rocks. Through visual estimates and partial normative analyses for the magnetite-bearing rocks in table 10, the mineral percentages are estimated as follows:

	Percent
Carbonate	10–40
Apatite	2–5
Chlorite and stilpnomelane	10–50
Magnetite	Trace–35
Quartz	Trace–10

In general, the mineralogy of these rocks is similar to that of the magnetite-free types described earlier, except for magnetite and very minor and local pyrrhotite. Where magnetite is abundant, apparently there is proportionately less carbonate.

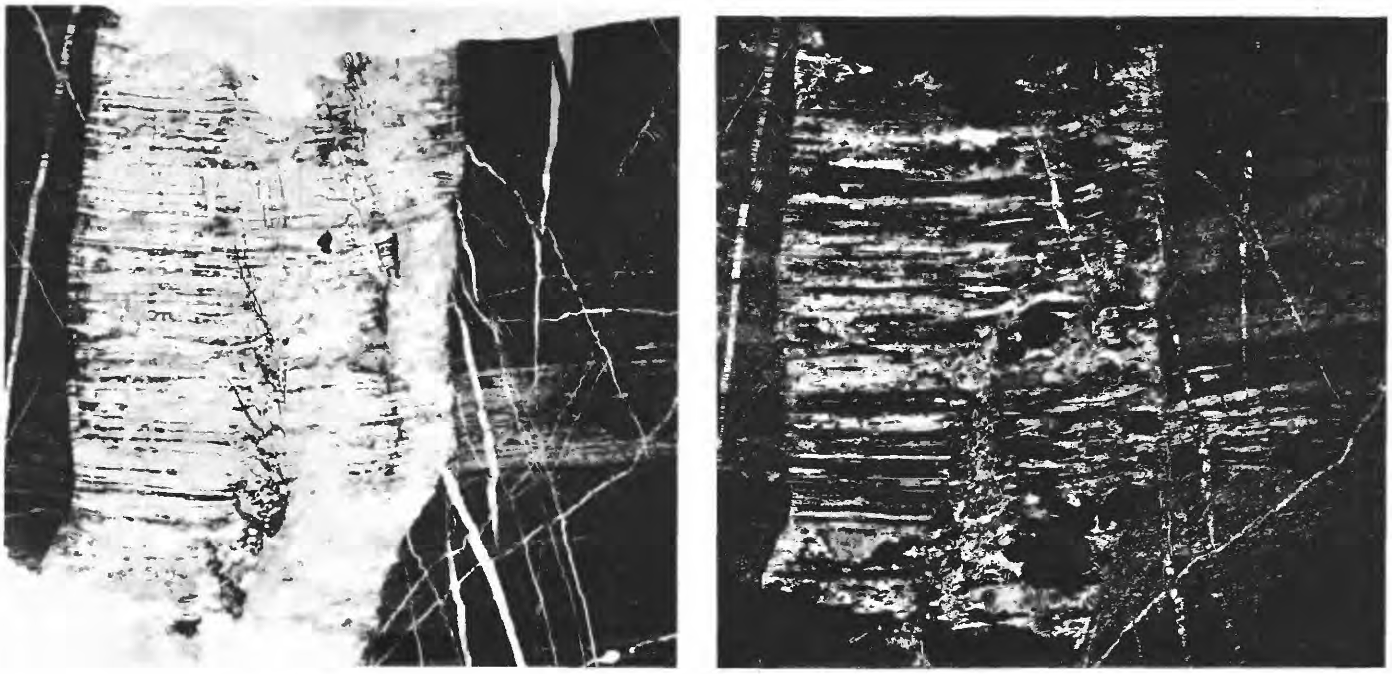
VEINLETS ASSOCIATED WITH THE MANGANESE DEPOSITS

LOCALIZATION AND STRUCTURE

The manganiferous rocks and the enclosing wallrock slate of the deposits on Maple and Hovey Mountains are cut by numerous veinlets of differing compositions. The brittle, banded ironstone is the most highly veined of all the rocks in the deposits, whereas the less brittle enclosing slate has fewer fractures and fewer veins. The veinlets may be several inches wide or microscopic in width. One quartz vein, several feet thick, was uncovered in trenches 60 and 61 in the slate enclosing the southwest end of the Central Hovey deposit (pl. 2), but veins of this thickness are exceptional. None of the veins or veinlets completely transects the deposits. They are small and localized and reflect the physical and chemical features of their respective host rocks. The manganiferous banded hematite ironstone, for example, encloses veinlets containing manganese minerals whereas the relatively nonmanganiferous slate, within the deposits as well as enclosing them, is cut by veinlets free of manganese minerals.

Manganese-bearing veins in manganiferous wallrocks have also been reported in manganese deposits in the Ultevis district of northern Sweden. There, pegmatitic veins in places "pass over into veins carrying a variety of manganese oxide and silicate minerals * * *. The pegmatitic veins preferably carry manganese minerals in those cases where the surrounding rocks are enriched in manganese" (Ödman, 1947, p. 44–45).

Many of the veinlets in the deposits on Maple and Hovey Mountains are clearly replacements of the host rock. Bedding laminations of the wallrock can be followed across such veinlets and retain structural continuity with laminations in the enclosing wallrock. (See fig. 31.) The replacement veinlets typically have clean-cut, sharp contacts with the wallrock and in places have small stringerlike offshoots (fig. 38). The cores of some of the veinlets have a thin seam parallel with the veinlet. The seam typically is marked by oxides alined along with it, and probably represents the crack along which the replacing solutions gained access to the wallrocks. Near the walls these veinlets contain opaque oxides and finely crystalline minerals commonly alined in surfaces more or less parallel to the walls. Such layering is believed to represent remnants of successive interfaces between the solutions which formed the veinlets and the wallrock. (See fig. 32.) Apparently, the solutions effected replacement of wallrock in a lateral direction from the fracture in which they were intro-



A. Plane light

B. Crossed nicols

FIGURE 31.—Photomicrographs of a replacement veinlet in manganiferous laminated ironstone from the Maple-Hovey deposit. Bedding laminae in the quartz-feldspar veinlets are continuous with those in the wallrock. × 8.

duced. Laminations in wallrock inclusions in many of the veinlets are parallel with laminations of the wallrock. These inclusions represent incomplete replacement, or fragments isolated within the veinlet by becoming mantled with vein minerals and thereby isolated from the replacing solutions. (See fig. 33.)

Satellitic stringers emanating from some rhodonite-bearing veinlets have apparently not only pried slivers away from the wallrock but have rotated them by wedging due to growth of minerals within the veinlet. If this were an important process the resultant structure might resemble tectonic breccia. There are no criteria for distinguishing true breccia fillings from such replacement pseudobreccias. Breccia fragments and vein material with irregular shapes and not enclosed within tabular veinlets, however, are most probably cemented true tectonic microbreccia.

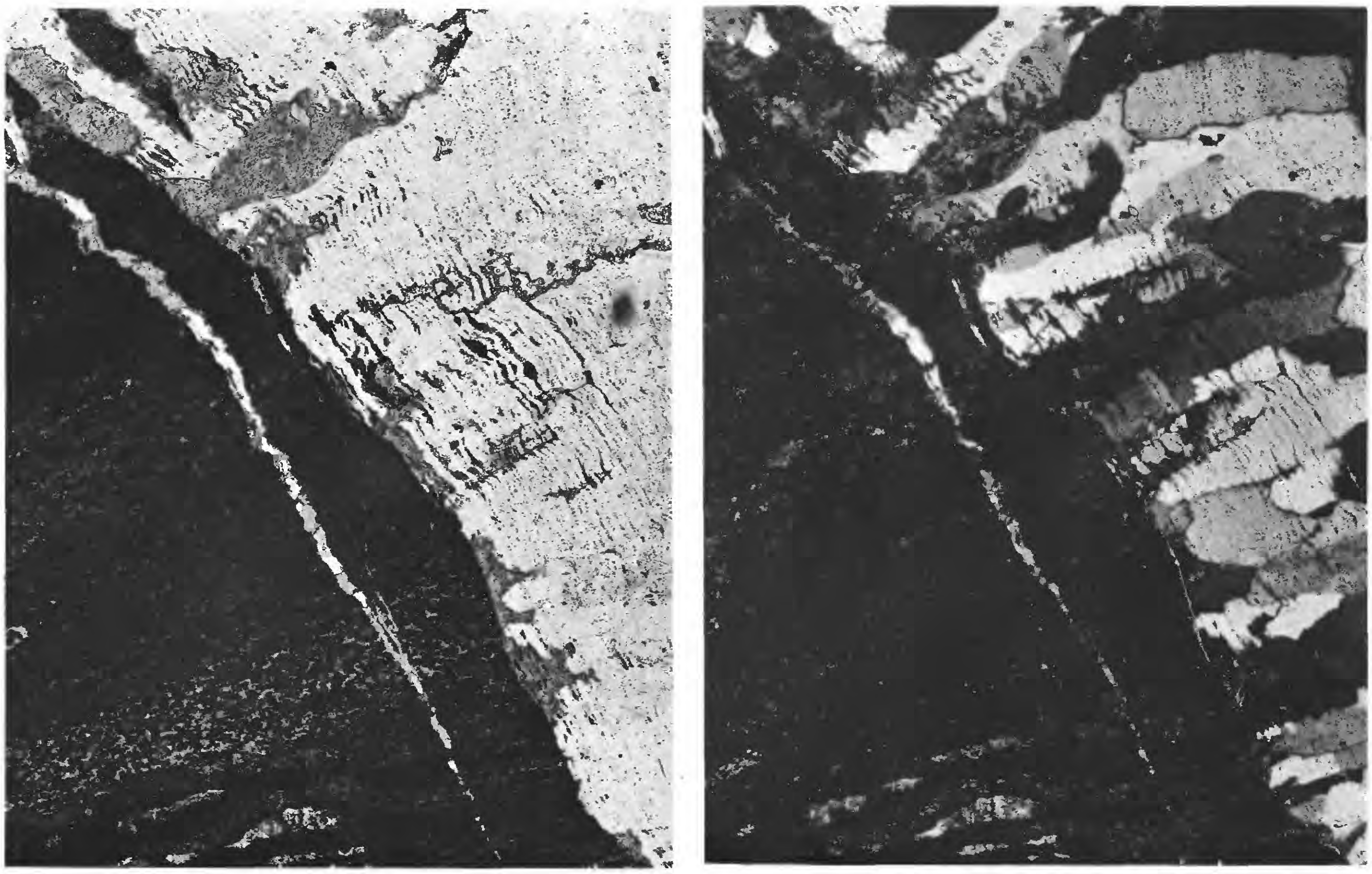
Gash veinlets are present in both the manganiferous rocks and their enclosing slates in addition to the tabular replacement veinlets and breccia fillings discussed above. The gash veinlets are commonly very small, more readily visible under the microscope than by the unaided eye in hand specimens. They are strikingly lens shaped and few show mineral zoning. Their mineralogy closely reflects that of the enclosing wallrock; the veinlets are typically composed of slightly coarser grained minerals of the wallrock. The gash veinlets generally are confined to specific layers, with their long dimensions normal to bedding.

RHODONITE-BEARING VEINLETS

It was stated earlier that the veinlets with manganese minerals are strictly confined to the manganiferous units of the deposits. As a further refinement of this principle, certain manganese minerals are contained almost exclusively in veinlets enclosed by distinct rock types. Rhodonite-bearing veinlets, some of which resemble breccia, as discussed above, are confined almost exclusively to the manganiferous banded hematite ironstone of the Maple-Hovey deposit.

RHODONITE

The rhodonite in veinlets is readily recognized by its distinct rose-pink color and its hardness. In thin sections it shows a well-developed cleavage and high bire-



A. Plane light

B. Crossed nicols

FIGURE 32.—Photomicrographs of remnant wallrock interfaces. *A*, Banded carbonate-rich hematitic ironstone wallrock at left of photograph. Veinlet at right of photograph contains quartz (colorless) and green chlorite (dark gray) and carbonate (light gray). Many of the remnant wallrock and solution interfaces preserved in the veinlet are outlined by the chlorite which crystallized along them. The wedge-shaped dark material in the veinlet near the wallrock in the upper part of the photograph is part of wallrock inclusion. *B*, Note platy crystallization of the quartz perpendicular to the wall of the vein. Compare with figure 31*B*. × 40.

fringence. Optical properties of rhodonite from two veinlets in the Maple-Hovey deposit are:[9]

	Drill-hole 1-1	*Drill-hole 4-1*
α	1. 721	1. 721
β	1. 725	1. 725 or 1. 726
γ	1. 734	1. 734
Optic sign	+	+
$2V$	68°–70°	70°
Maximum extinction	26°	26°

X-ray analyses of rhodonite from various veinlets in the Maple-Hovey deposit indicate, however, that some of it may be "intermediate between rhodonite and pyroxmangite."[10] Figure 34 shows a rhodonite-bearing veinlet containing wallrock inclusions with layering parallel to that of the wallrock.

OTHER MINERALS

Although rhodonite is the characteristic mineral of these veinlets, they contain other manganese minerals as well as gangue. Carbonate, varying from manganoan calcite to rhodochrosite, is one of the principal manganese minerals in these veinlets and breccialike fillings. Dolomite and rarely ankerite are minor gangue minerals. A fibrous bementite-type (hydrous manganese silicate) mineral is also present in the rhodonite-bearing veinlets but is generally more abundant in stringerlike offshoots from these veinlets; under the microscope it is usually pale yellow or pale brown, weakly pleochroic, and uniaxial negative. X-ray patterns are referable to the bementite group.[11] Ganophyllite, a hydrous manganese aluminum silicate (optically

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[9] Determined by J. J. Glass.

[10] X-ray analysis and interpretation by J. M. Axelrod.

[11] X-ray analysis by J. M. Axelrod.

FIGURE 33.—Photomicrograph of a replacement veinlet containing an inclusion whose laminations are essentially parallel with those in the wallrock (left). The remnant wallrock and solution interfaces in the center of this photograph are illustrated under higher magnification in figure 32. A stringer from the veinlet is wedged into the wallrock in the center of the photograph and illustrates the way in which inclusions with laminations parallel to the wallrock (such as the one in the upper part of the photograph) may become enclosed in the veinlet. The mineralogy of the wallrock and veinlet is as described in figure 32. Plane light; × 15.

resembling bementite), has been identified by X-ray. A substance amorphous to X-rays, and with an index of refraction slightly greater than 1.57, has been noted in at least one thin veinlet. This material may be neotocite, although the range of refractive index of neotocite cited by Larsen and Berman (1934, p. 48–51) is 1.47± to 1.54±. Pyrophanite was found in one veinlet and was identified by optical, spectrographic, and X-ray methods.

Albite-oligoclase is the most abundant gangue (nonmanganiferous) mineral of the rhodonite-bearing veinlets and microbreccias. It commonly is broadly twinned, with some of the twinning bands irregularly interfingering into one another. (See fig. 35.)

Quartz is also present in some of the veinlets but veinlets with considerable rhodonite generally have no quartz. Euhedral to subhedral apatite is generally present in minor amounts in these veinlets. (See fig. 36.) Barite locally may be moderately abundant, although generally it is a sparse constituent. Phlogopite has also been noted in a few places. It occurs as amber yellow, pleochroic flakes that are optically negative and have a characteristically small $2V$ which approaches zero. Absorption, however, seems to be reversed from that of normal phlogopite. Stilpnomelane, identified by X-ray pattern,[12] has also been found in rhodonite-bearing veinlets. In one place it occurs in fibrous growth, perpendicular to the wall of a stringer.

The rhodonite-bearing veinlets are generally free of opaque minerals except for specularite, which in places occurs in tabular crystals generally perpendicular to the enclosing wallrock.

OTHER TYPES OF VEINLETS

In addition to the localization of rhodonite-bearing veinlets within the manganiferous banded hematite ironstone, many of the other types of veinlets also are selectively localized within certain rock types. Among these are chloritic veinlets, which are generally restricted to magnetite-bearing rocks that contain much chlorite. Veinlets in these rocks consist principally of chlorite, alkalic feldspar (orthoclase and albite-oligoclase), carbonate of several varieties, quartz, apatite, and in a few veinlets, fibrous and micaceous minerals with optical properties close to the bementite group and ganophyllite. Both the chlorite and carbonate of these veinlets appear to be similar to those of the host rocks.

The veinlets cutting the manganese-bearing hematitic slate and shale are similar in mineralogy to the chloritic veinlets, except that they contain only moderate amounts of chlorite. The veinlets cutting the green sericite-chlorite slate that encloses the manganese deposits have the simplest mineral assemblage. It consists essentially of quartz, alkalic feldspar, and carbonate, most of which is calcite; rhodochrosite or siderite is absent. The tiny gash veinlets mentioned earlier also are mineralogically relatively simple, and contain only the minerals found in their enclosing layers. One other type of veinlet, although of limited distribution and rare occurrence, is contained in the Maple-Hovey deposit. It consists almost entirely of dense, extremely fine grained blue-black hematite (determined by X-ray). These hematite-rich

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[12] X-ray analysis by J. M. Axelrod.

FIGURE 34.—Photomicrograph of a rhodonite-bearing veinlet in manganiferous banded hematite. The vein material is dominantly rhodonite (dark gray). Black areas are holes in the slide. Note the diamond-shaped inclusion that can be matched with the wall of the vein on the right. Plane light; × 15.

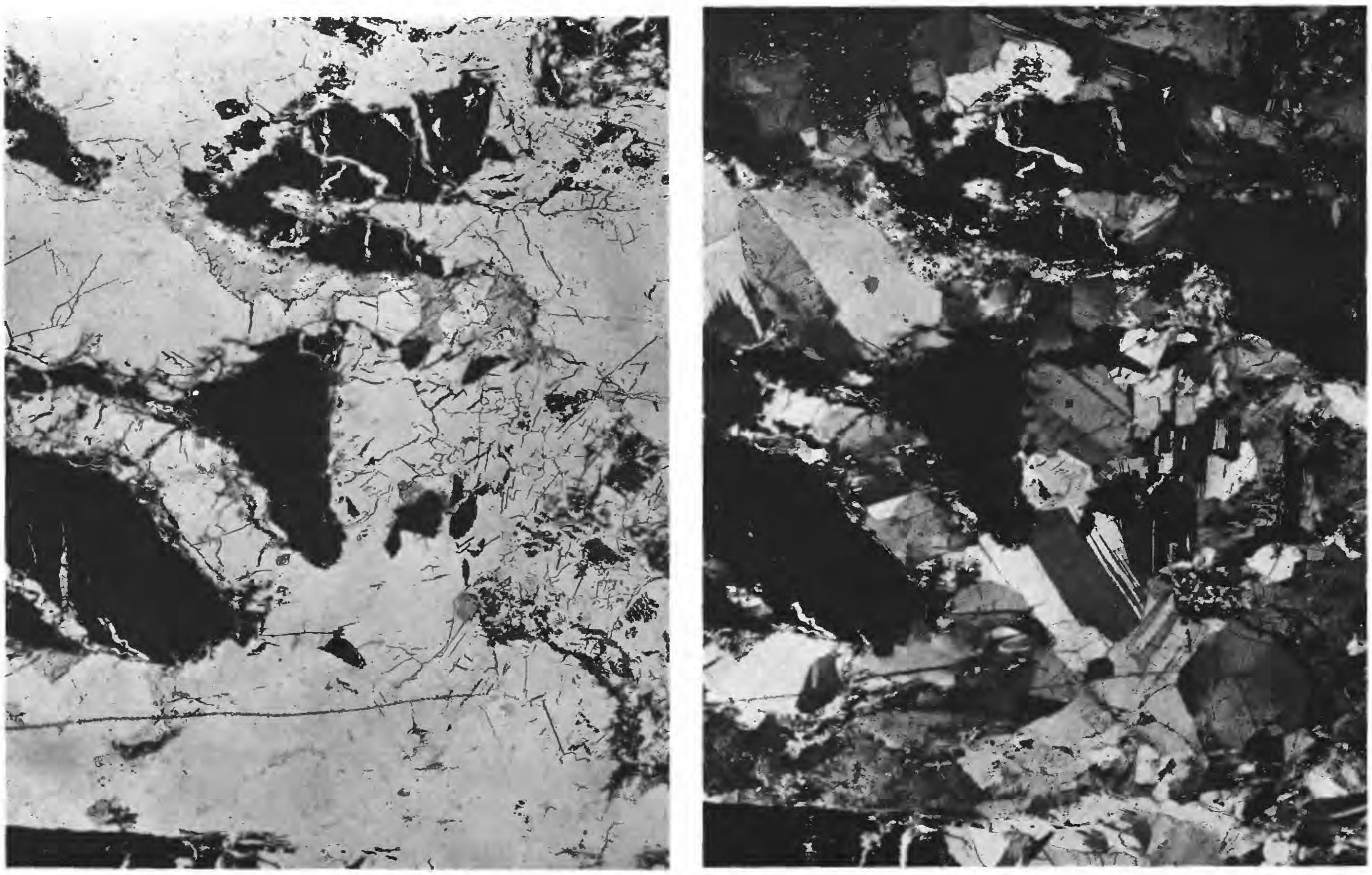
veinlets occur in rocks structurally above the rhodonite-bearing veinlets. They have been noted in the red and purple slate of the upper manganiferous unit of the Maple-Hovey deposit as well as in the gray-green slate immediately overlying this unit. The relation between the types of wallrock within and enclosing the Maple-Hovey deposit and the mineralogy and shape of the veinlets localized in these rocks is summarized in table 11.

ORIGIN OF THE VEINLETS

The veinlets of the Maple and Hovey Mountains area and elsewhere in the Aroostook manganese belt are minor features of the deposits, probably constituting only a few percent of the volume of any of them. Nonetheless, they are of interest because of their paragenesis and the marked control exerted on their mineralogy by the enclosing rocks. The localization of veinlets with different mineral suites in rocks of characteristic mineral assemblages and chemical character is critical in understanding the paragenesis of these veinlets.

It has been shown, in the deposits of Maple and Hovey Mountains, that the internal features of many veinlets indicate replacement of wallrock. Some veinlets formed by the replacement of wallrock by solutions moving out from hairline fractures such as tight joints or microfaults. Such veinlets have sharp wallrock contacts. (See fig. 31.) Veinlets also formed along small zones of tectonic breccia that probably developed as crush breccia during the folding of some of the relatively brittle banded ironstone. Replacement also took place where cemented breccia formed as it commonly contained partly digested wallrock fragments. (See fig. 35.)

The invading solutions probably had a simple, manganese-free composition which gave rise to the quartz-carbonate-alkalic feldspar veinlets cutting the sericite-chlorite slate that encloses the manganese deposits.



A. Plane light *B.* Crossed nicols

FIGURE 35.—Photomicrographs of a breccia with abundant wallrock inclusions of banded hematite. *A,* Some of the inclusions of hematitic wallrock (black), such as the triangular fragment in the center of the photograph, are bordered by apatite (light gray and high relief). The irregular concentration of material immediately above and to the right of the triangular inclusion consists of a fibrous aggregate of bementite(?) or ganophyllite(?). The black patchy material in the lower right of the photograph is residuum of incompletely replaced wallrock inclusions. The white matrix is plagioclase. *B,* Note the broad twinning of the feldspar and the irregular interfingering between twins. Dark areas, such as in the upper left corner of the photograph, are holes in the slide. × 15.

These solutions could have originated from igneous bodies that may underlie the Maple and Hovey Mountains area. On the other hand, it is possible that the solutions originated through deformation in the sediments that underlay the deposits. Rubey (1930, p. 34–38, also fig. 2, p. 35) has shown that there is a decrease in the porosity of argillaceous rocks that have undergone a steepening in dip from their original horizontal position. Interstitial connate water, trapped in the argillaceous sediments underlying the deposits on Maple and Hovey Mountains, could have been warmed and expelled from these rocks during the regional folding and metamorphism that has affected the district. Other water may have been derived from the water of crystallization of clay minerals in the argillites, which was liberated from them in their conversion to less hydrous minerals during the reconstitution of the argillaceous rocks to slate. The term "sweat solutions" aptly describes solutions generated under such conditions of regional deformation and metamorphism. The solutions penetrated the deposits after these had been metamorphosed, however, because veinlets cut and have reacted with magnetite-bearing wallrock.

The replacement of wallrock in both veinlets and cemented breccia, therefore, is believed to have been accomplished by reactions between aqueous solutions of uncertain origin and the constituents of the replaced wallrock. Reactions between manganiferous wallrock and invading solutions were particularly important in forming the rhodonite-bearing veinlets. Inasmuch as rhodonite is almost exclusively confined to veinlets and, with but two minor exceptions has not been found elsewhere in the manganiferous rocks, it cannot have recrystallized from primary rhodonite. Some accessory

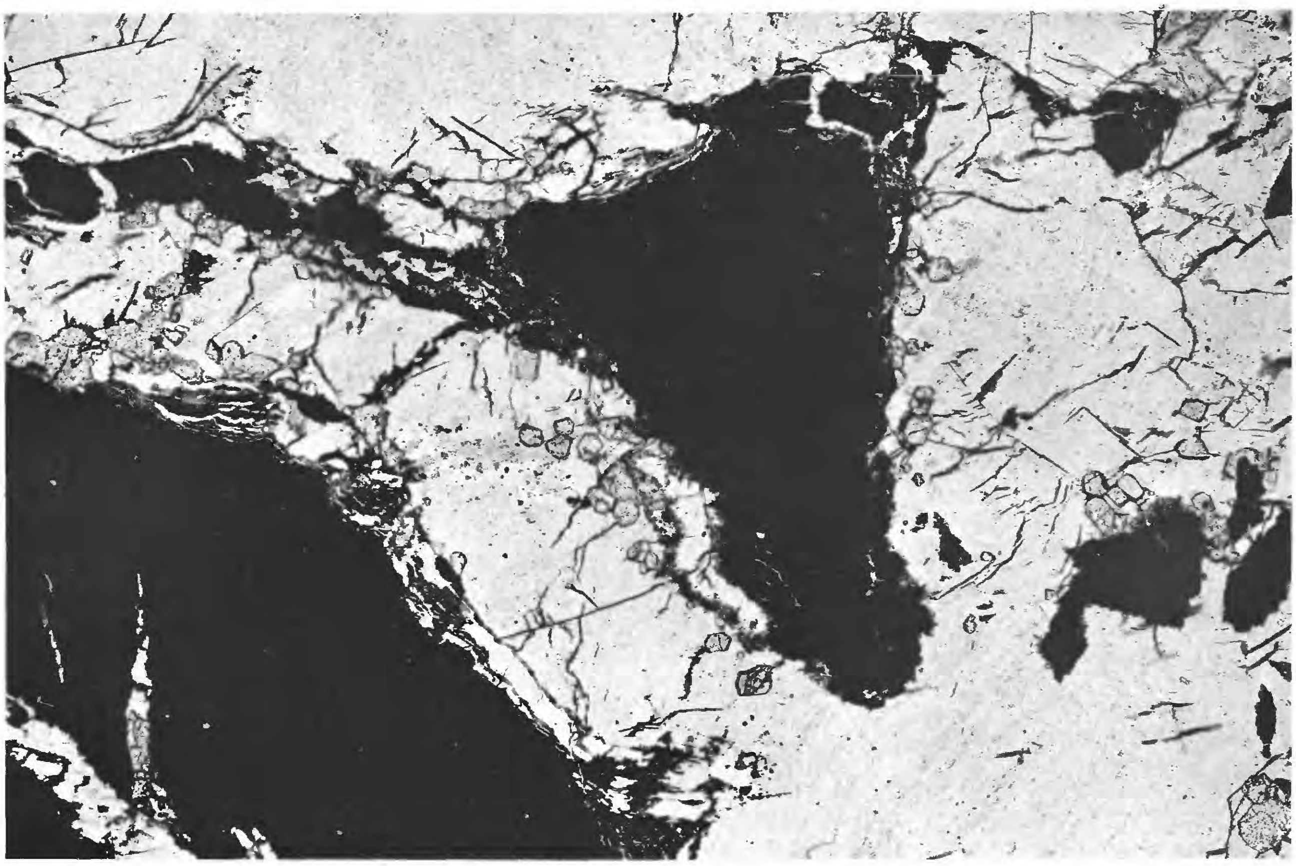


FIGURE 36.—Photomicrograph of euhedral and subhedral apatite (dark gray) bordering a partially replaced wallrock fragment (black). Photograph is a more highly magnified portion of figure 35. Plane light; × 40.

minerals in these veinlets, however, probably represent recrystallized wallrock constituents.

Quartz is generally scarce or absent wherever rhodonite is abundant (see fig. 34) in veinlets cutting manganiferous banded hematite (table 11). Conversely, rhodonite is sparse or missing in quartz-rich veinlets. It is believed, therefore, that the rhodonite formed in part, if not entirely, by the reaction of silica in the introduced solutions with manganese oxide obtained by replacement and digestion of manganese-rich wallrock in the general manner indicated by equation 1:

$$MnO + SiO_2 \longrightarrow MnSiO_3$$

The reaction of SiO_2 with MnO to form rhodonite may have been a function of the amount of MnO made available to the solutions by the wallrock and digested inclusions. There is a close correlation between tenor of manganese in the wallrock and the manganese minerals in veinlets. For example, the manganiferous banded hematite ironstone, within which the rhodonite-bearing veinlets are localized (see table 11), are among the most highly manganiferous rocks of the deposits. The way in which the manganese was bonded in the host rocks was also probably of great importance in forming rhodonite veinlets. The tenor of manganese in the manganiferous banded hematite in the Southern Hovey deposit is comparable to that of the middle manganiferous unit of the Maple-Hovey deposit (compare table 12*B* and table 13*B*), but rhodonite-bearing veinlets within this manganiferous unit of the Southern Hovey deposit are scarce. This is believed to be caused by the sparseness of braunite in the banded hematite ironstone of the Southern Hovey deposit (manganoan carbonate is more abundant), whereas in the Maple-Hovey deposit, braunite is an important manganese mineral in comparable ironstone. Rhodonite of the rhodonite-bearing veinlets and breccia fillings, therefore, probably formed mostly through the destruction of braunite by the replacing solutions. The absence of recrystallized braunite in the veinlets supports this

TABLE 11.—*The relation of wallrock to mineralogy and shape of veinlets localized within it, Maple-Hovey deposit*

Wallrock[1]		Mineralogy of the veinlets		Vein forms
		Major minerals	Minor minerals	
Upper slate		Quartz Carbonate (chiefly calcite) Plagioclase (alkalic)	Chlorite	1. Sharp wallrock boundaries 2. Lens shaped (gash veinlet)
		Hematite (rare)		Irregular stringers
Upper manganiferous unit	(Exclusive of manganiferous banded hematite ironstone)	Quartz Carbonate: Calcite Dolomite Manganiferous calcite Plagioclase (alkalic)	Chlorite	1. Sharp wallrock boundaries 2. Lens shaped (gash veinlets)
		Hematite (rare)		Irregular stringers
Middle manganiferous unit	Manganiferous banded hematite ironstone	Rhodonite Carbonate (manganiferous calcite-rhodochrosite) Plagioclase (alkalic)	Apatite Specularite Barite Carbonate: Dolomite Ankerite Bementite-type minerals Stilpnomelane (rare) Phlogopite (rare) Quartz (rare) Pyrophanite (rare)	1. Sharp wallrock boundaries (a) with wallrock inclusions (breccia fillings) (b) without wallrock inclusions (replacement veinlets) 2. Irregular wallrock boundaries—commonly with wallrock inclusions (breccia fillings) 3. Lens shaped (gash veinlets)
		Bementite- and ganophyllite-type minerals	Carbonate Quartz	Thin stringers (commonly satellitic to rhodonite-bearing veinlets)
		Neotocite		Thin stringers or along joints
	Manganiferous banded magnetite- and chlorite-bearing ironstone	Chlorite Carbonate Quartz Plagioclase Rhodonite (rare)	Apatite Bementite-type minerals and ganophyllite	1. Sharp wallrock boundaries (a) with wallrock inclusions (breccia fillings) (b) without wallrock inclusions (replacement veinlets) 2. Irregular wallrock boundaries—commonly with wallrock inclusions (breccia fillings) 3. Lens shaped (gash veinlets)
Lower manganiferous unit	(Exclusive of manganiferous banded hematite ironstone)	Carbonate Calcite Rhodochrosite (rare) Plagioclase Quartz	Chlorite	1. Sharp wallrock boundaries (a) with wallrock inclusions (breccia fillings) (b) without wallrock inclusions (replacement veinlets) 2. Irregular wallrock boundaries—commonly with wallrock inclusions (breccia fillings) 3. Lens shaped (gash veinlets)
Lower slate		Quartz Carbonate (mostly calcite) Plagioclase	Chlorite	1. Sharp wallrock boundaries 2. Lens shaped (gash veins)

[1] Lithology of the wallrock units is described on pages 34–39.

hypothesis. Assuming that the invading solutions contained $CaHCO_3$ and SiO_2, the conversion of braunite to rhodonite may have been as follows (equation 2):

$$3Mn_2O_3 \cdot MnSiO_3 + 6HCO_3 + NSiO_2 \longrightarrow 7MnSiO_3 + 6CaCO_3 + 3H_2O.$$

Equations 1 and 2 are suggested only as indicating the possible reactions that may have produced rhodonite, as inferred from petrographic relations and the lithologic localization as well as field distribution of the rhodonite-bearing veinlets and breccia fillings. Limited ionic substitution of Fe^{++} for Mn^{++} probably produced the ferroan rhodonite intermediate between rhodonite and pyroxmangite. Chemical reactions between wallrock and invading solutions may also have produced some of the other minerals in the veinlets associated with these manganese deposits, such as the ganophyllite- and bementite-type minerals, pyrophanite, stilpnomelane, and manganiferous carbonates.

Some of the minerals in the various replacement veinlets, such as apatite, probably formed by recrystallization of wallrock residuum containing cryptocrystalline apatite. Apatite is absent in quartz-carbonate-feldspar veinlets contained in the slate enclosing the deposits, but it is present as euhedral or subhedral grains (fig. 36) in almost all veinlets cutting the manganiferous rocks, in most of which phosphorus is abundant (see table 8).

Chlorite, particularly in chlorite-rich veinlets emplaced in chloritic rocks, is also considered to be mostly a recrystallized original constituent of the replaced wallrock, rather than of introduced origin or a reaction product of replacement, as in the case of rhodonite. Likewise, specularite in the rhodonite-bearing veinlets is also regarded as recrystallized iron oxide derived from the immediately replaced wallrock.

The hematitic veinlets (described earlier), in the enclosing relatively iron- and manganese-poor slate, however, are believed to represent iron taken into solution and deposited elsewhere during the emplacement of the manganese-bearing veinlets by replacement in the structurally underlying manganese- and iron-rich rocks. The iron-rich solutions moved up into an environment of iron-poor rocks before precipitating out their iron as hematite.

Some of the minerals in the veinlets and cemented breccia may have been formed partly by solution and redeposition of selected chemical components of the rocks immediately enclosing the veinlets during metamorphism, rather than by replacement reactions involving introduced solutions. Presumably, rhodonite, apatite, and numerous of the other minerals could have formed in this manner, when pore solutions, mobilized during metamorphism, dissolved and redeposited their constituents in fissures of various types. At two different places within manganiferous banded hematite ironstone, small (1/16 to 1/8 inch long) irregular knots containing rhodonite and some barite have been seen in thin sections. These structures may have formed by metamorphic differentiation on a small scale. It is possible that some cemented breccia may have formed this way, but the veinlets with clear-cut replacement structures such as the one in figure 31 are undoubtedly replacement veins as described earlier. The mineral constituents of the very small gash veinlets, which are strictly confined to laminae whose competence favored the development of gash fractures, and which closely reflect the mineralogy of their enclosing layers, might also be extremely local and small-scale products of metamorphic differentiation. On the whole, metamorphic differentiation probably affected the rocks of the district in a very limited and minor fashion.

Miller (1947, p. 35) briefly mentions the presence of "veins and replacements of manganiferous carbonate and bementite" in his general description of the Aroostook manganese deposits and believes they were formed by "migration and redeposition of manganese" during regional metamorphism. He does not report rhodonite in any of the veinlets, and rhodonite has not been found anywhere outside of the deposits on Maple and Hovey Mountains. The Dudley deposit in the northern manganese district, however, has braunite and might be expected to carry rhodonite-bearing veinlets. It is possible that such veinlets are absent in this deposit because it was not invaded by silica-rich solutions so that reactions such as indicated by equation 1 could not take place. Also, the solutions affecting the Dudley may have been of more local origin and, representing small-scale solution and redeposition of manganese (Miller, 1947, p. 35), were not as highly charged with constituents capable of breaking down the braunite as were the solutions in equation 2.

CHEMICAL CHARACTER AND MINERALOGY OF THE DEPOSITS

The manganese- and iron-bearing deposits of Maple and Hovey Mountains are distinctive for the persistence of relatively uniform amounts of manganese, iron, phosphorus, CaO, MgO, SiO_2, Al_2O_3, and sulfur through specific units of the deposits. These characteristics are brought out by partial chemical analyses that have been compiled mainly from the analyses of composite samples made by Lerch Brothers of Hibbing, Minnesota, for the U.S. Bureau of Mines and reported by Eilertsen (1952, p. 52, 117–118). Some of the composite samples overlap stratigraphic boundaries as mapped by the writer. The part of the unit generally represented by these analyses is given by footnote on all the tables in this report. The coincidence is generally good between the composite samples determined by Eilertsen (combined on the basis of assay cutoffs), and the map units such as the upper, middle, and lower manganiferous units of the Maple-Hovey deposit established by the writer in the field on the basis of lithology. Composite samples with considerable overlap into adjacent stratigraphic units have been omitted in compiling the tables for this report; those with only slight overlap have been used at the discretion of the writer. The metallic iron and manganese and elemental phosphorus of the analyses as given by Eilertsen have been recast here into the oxide form. Although the analyses are only partial, the chemical character of the unanalyzed fraction is generally deducible from petrographic information and by comparison with some of the complete rock analyses of selected specimens, as well as from the qualitative spectrographic analyses (tables 20–24) made available to the writer by the U.S. Bureau of Mines.

CHEMISTRY AND MINERALOGY

OXIDE FACIES

Among the manganese deposits on Maple and Hovey Mountains, by far the largest part of the rock is of the oxide facies, and only small segments contain magnetite. The Central Hovey deposit is also of the oxide facies type but it has apparently been more thoroughly reconstituted by metamorphism and most of its original hematite has been converted to magnetite.

Numerous partial chemical analyses both for trenches and diamond-drill cores are available from which the chemical character of the Maple-Hovey deposit can be evaluated. The three units into which the deposit has been subdivided on the basis of lithology have persistent chemical features along strike and downdip. Table 12 contains the partial chemical analyses of the upper, middle, and lower manganiferous units of this deposit. Similar analyses of composite samples from trenches directly overlying, or nearly overlying diamond-drill holes, are placed in the same column in table 12 for comparative purposes. The column of arithmetical averages in table 12 summarizes the chemical character of each manganiferous unit. The difference between the total oxides listed and 100 percent probably represents mostly H_2O and CO_2 (see tables 8 and 18) with variable amounts of Na_2O and K_2O (see table 21). Some of the unanalyzed residuum also represents oxygen, since an appreciable amount of the manganese is present in a higher valence state than that of the MnO assumed in recalculating these analyses. Unless otherwise stated, only the chemical analyses of diamond-drill core cited in these tables will be used in the following discussion.

As described earlier, the Maple-Hovey deposit consists of three mappable manganese-bearing hematitic units. A discontinuous layer of pyritic, manganese-bearing siliceous carbonate rock underlies the lower manganiferous unit. Otherwise the deposit is enclosed by green slate. (See pl. 4*A*.)

The columnar section of the deposit (pl. 4*A*) has been generalized from selected diamond-drill holes; the listed assay values of manganese and iron and the thicknesses of beds are weighted averages; the thicknesses of the units are arithmetic averages of sections cut by diamond-drill holes and trenches.

As can be seen from plate 4*A*, the manganese content in the different beds of the upper manganiferous unit varies with the iron content, but not in a rigorous and systematic manner. The manganese content generally increases progressively with the amount of hematite. The green slate beds are the least manganiferous, commonly containing less than 1 percent of manganese. In order of increasing manganese content, the manganiferous beds vary in color and lithology from various shades of purple slate (1–4 percent), through various hues of red slate (2–8 percent), and red hematitic slate (8–12 percent), to red banded hematite ironstone (10–14 percent). The manganese tenors cited for these beds indicate the range of contained manganese that can be expected within a particular rock and color type. The variation in iron content within the manganiferous beds is greater, but the order of abundance and distribution of the iron can be visualized from the composite assays listed in plate 4*A*. Partial chemical analyses of samples representing the entire upper unit are listed in table 12*A*.

The generalized section of the middle manganiferous unit in plate 4*A* indicates the approximate position of the thicker layers of slate interbedded with the banded hematite ironstone of this unit. The green slate beds generally contain less than 2 percent of manganese, the layers composed of interbeds of green, red, and purple slate contain about 3 to 5 percent of manganese, and the intervals of banded hematite average between 9 and 14 percent of manganese (pl. 4*A*). The iron tenor of

TABLE 12.—*Partial chemical analyses of the upper, middle, and lower manganiferous units from composite samples of diamond-drill cores and trenches, Maple-Hovey deposit.*

[Trenches overlying drill holes are listed in the same column as the drill hole. Compiled from Eilertsen, 1952, table 2, p. 52, and table 6, p. 117. See plate 2 for location of drill holes and trenches]

A. UPPER MANGANIFEROUS UNIT

Diamond-drill holes

	1[1,2]	2[2]	12[2]	27[2]	37[3]	39[2]	40[2]	41[1,2]	45[3]		Arithmetic average
Mn	4.66	6.48	6.56	6.80	7.56	6.51	8.88	8.49	5.83	---	6.86
Fe	9.57	12.10	15.84	15.07	14.03	13.30	13.98	15.78	10.10	---	13.31
P	.222	.345	.486	.465	.468	.384	.459	.551	.315	---	.411
MnO	6.02	8.37	8.47	8.78	9.76	8.41	11.47	10.96	7.53	---	8.86
Fe_2O_3	13.68	17.30	22.65	21.55	20.06	19.02	19.99	22.56	14.44	---	19.03
P_2O_5	.509	.790	1.114	1.065	1.072	.880	1.052	1.262	.722	---	.830
SiO_2	49.44	45.23	40.54	41.51	39.23	40.87	38.02	35.14	43.81	---	41.53
CaO	.48	1.10	1.70	1.88	3.12	1.94	2.40	3.09	2.03	---	1.97
MgO	2.43	2.27	1.43	2.35	.93	1.15	2.11	2.07	2.54	---	1.92
Al_2O_3	16.25	14.58	14.14	9.69	13.28	13.93	12.93	12.17	16.25	---	13.69
S	.070	.050	.012	.015	.064	.037	.054	.025	.110	---	.049
Total	88.88	89.69	90.06	86.84	87.52	86.24	88.03	87.28	87.43		87.88

Trenches

			14[2]				31[2]		47[2]	7[3]	Arithmetic average
Mn	---	---	6.48	---	---	---	7.40	---	4.92	6.31	6.28
Fe	---	---	12.10	---	---	---	12.78	---	9.54	13.23	11.91
P	---	---	.336	---	---	---	.780	---	.186	.372	.419
MnO	---	---	8.37	---	---	---	9.56	---	6.35	8.15	8.11
Fe_2O_3	---	---	17.30	---	---	---	18.27	---	13.64	18.92	17.03
P_2O_5	---	---	.770	---	---	---	1.787	---	.426	.852	.959
SiO_2	---	---	44.62	---	---	---	42.11	---	46.99	41.80	43.88
CaO	---	---	.76	---	---	---	1.34	---	.73	1.41	1.06
MgO	---	---	1.31	---	---	---	1.14	---	2.06	2.51	1.76
Al_2O_3	---	---	12.22	---	---	---	13.49	---	18.03	14.15	14.47
S	---	---	.006	---	---	---	.037	---	.013	.009	.016
Total			85.36				87.73		88.24	87.80	87.29

B. MIDDLE MANGANIFEROUS UNIT

Diamond-drill holes

	1 and 2[4,5]	12	24	27[4]	35[6,7]	37	40	41	45			Arithmetic average
Mn	12.04	11.46	12.04	11.36	9.98	9.90	11.00	11.22	11.12	---	---	11.12
Fe	27.27	26.05	26.62	24.38	21.22	22.32	25.47	24.74	18.76	---	---	24.09
P	1.059	1.110	1.062	1.116	.803	.852	1.098	1.038	.684	---	---	.980
MnO	15.55	14.80	15.55	14.67	12.89	12.78	14.20	14.49	14.36	---	---	14.37
Fe_2O_3	38.99	37.24	38.06	34.86	30.34	31.91	36.41	35.37	26.82	---	---	34.44
P_2O_5	2.426	2.543	2.433	2.557	1.840	1.952	2.516	2.378	1.567	---	---	2.246
SiO_2	22.60	23.64	19.61	24.67	27.85	28.80	20.43	23.67	31.05	---	---	24.70
CaO	3.37	3.43	4.14	4.07	3.21	5.69	4.48	4.07	4.13	---	---	4.07
MgO	1.17	1.53	1.15	1.73	1.66	1.41	1.73	.76	1.48	---	---	1.40
Al_2O_3	5.27	6.78	6.64	5.01	9.34	9.28	6.56	7.22	10.06	---	---	7.35
S	.010	.014	.052	.016	.028	.032	.053	.063	.029	---	---	.033
Total	89.39	89.98	87.64	87.58	87.16	91.85	86.38	88.02	89.50			88.61

Trenches

	4[5]	14[5]				29	31[5]		47[8]	7[5]	19[5,7]	Arithmetic average
Mn	14.92	12.38	---	---	---	13.67	10.56	---	10.96	13.95	11.68	12.59
Fe	25.32	28.27	---	---	---	23.12	24.19	---	18.27	24.32	21.87	23.62
P	1.032	1.266	---	---	---	1.098	1.062	---	.678	.912	1.080	1.018
MnO	19.27	15.99	---	---	---	17.65	13.64	---	14.15	18.01	15.08	16.26
Fe_2O_3	36.20	4.042	---	---	---	33.06	34.58	---	26.12	34.77	31.27	33.77
P_2O_5	2.364	2.901	---	---	---	2.516	2.433	---	1.553	2.090	2.474	2.333
SiO_2	22.13	20.48	---	---	---	23.20	26.72	---	31.45	23.63	29.20	25.26
CaO	3.12	3.30	---	---	---	6.17	2.91	---	2.79	3.30	3.01	3.51
MgO	.94	1.08	---	---	---	.69	.57	---	1.18	.92	1.35	.96
Al_2O_3	5.61	5.56	---	---	---	7.32	8.08	---	10.86	6.45	5.07	6.99
S	.011	.005	---	---	---	.011	.017	---	.026	.009	.016	.014
Total	89.65	89.74				90.62	88.95		88.13	89.18	87.47	89.10

See footnotes at end of table.

TABLE 12.—*Partial chemical analyses of the upper, middle, and lower manganiferous units from composite samples of diamond-drill cores and trenches, Maple-Hovey deposit*—Continued

C. LOWER MANGANIFEROUS UNIT

Diamond-drill hole

	1 and 2[4,5]	12[5]	27[5]	31[5,7]	35[5,7]	41				Arithmetic average
Mn	6.80	6.57	6.46	6.69	5.39	7.21	----------	----------	----------	6.52
Fe	22.54	18.04	16.78	17.00	26.79	20.27	----------	----------	----------	20.24
P	.891	.600	.578	.654	.960	.798	----------	----------	----------	.747
MnO	8.78	8.48	8.34	8.64	6.96	9.31	----------	----------	----------	8.42
Fe_2O_3	32.23	25.79	23.99	24.31	38.30	28.98	----------	----------	----------	28.93
P_2O_5	2.041	1.375	1.324	1.498	2.200	1.828	----------	----------	----------	1.711
SiO_2	31.60	36.41	36.86	32.71	28.95	33.04	----------	----------	----------	33.26
CaO	2.51	1.78	2.20	2.54	2.90	3.97	----------	----------	----------	2.65
MgO	1.83	1.15	2.73	3.33	1.98	2.16	----------	----------	----------	2 20
Al_2O_3	9.11	11.60	11.66	11.57	8.60	9.92	----------	----------	----------	10.41
S	.158	.201	.133	.116	.490	.200	----------	----------	----------	.216
Total	88.26	86.79	87.24	84.71	90.38	89.41				87.80

Trenches

	4[5]	14[5]				26[5]	19[5,7]	29[5]	31	Arithmetic average
Mn	6.92	6.27	----------	----------	----------	6.88	5.70	6.92	5.14	6.31
Fe	27.34	15.97	----------	----------	----------	23.23	22.24	20.66	19.89	21.56
P	.930	.636	----------	----------	----------	.984	.834	.876	.948	.868
MnO	8.94	8.10	----------	----------	----------	8.88	7.36	8.94	6.64	8.14
Fe_2O_3	39.09	22.83	----------	----------	----------	33.21	31.80	29.54	28.44	30.82
P_2O_5	2.131	1.457	----------	----------	----------	2.255	1.911	2.007	2.172	1.989
SiO_2	29.40	39.92	----------	----------	----------	33.97	37.18	35.69	35.99	35.36
CaO	1.76	1.29	----------	----------	----------	2.24	1.77	2.71	2.64	2.07
MgO	1.76	1.71	----------	----------	----------	2.16	1.58	1.36	1.76	1.72
Al_2O_3	7.86	12.14	----------	----------	----------	8.59	8.91	10.13	11.44	9.85
S	.024	.369	----------	----------	----------	.028	.037	.044	.032	.089
Total	90.97	87.82				91.33	90.55	90.42	89.11	90.04

[1] Composite calculated from two samples.
[2] Includes only the lower part of the unit.
[3] Does not represent the entire unit.
[4] Arithmetic average of two holes drilled from the same collar.
[5] Sample contacts not precisely included within nor coincident with stratigraphic contacts of unit.
[6] Weighted average of three samples.
[7] Contains magnetite-bearing zone.
[8] Includes only the upper part of the unit.

these rocks closely reflects the manganese content; in other words, the most manganiferous rocks are also the most ferruginous. Table 12*B* is a compilation of partial chemical analyses of the middle manganiferous unit. It illustrates the persistence of the chemical features of this formation. The only exception to this is in the northwesternmost second-order syncline, I, on Maple Mountain (see pl. 2), where metamorphism, probably in conjunction with original sedimentary facies differences, has produced rocks with somewhat different chemical features from the average for the unit.

The middle manganiferous unit has the highest manganese and iron tenor of the three units (table 12) of the Maple-Hovey deposit. The upper and lower stratigraphic boundaries of this unit generally coincide with an assay cutoff of approximately 10 percent manganese. The manganese tenor of the middle manganiferous unit is fairly restricted, ranging between 9.90 and 12.04 percent, but its iron content is more variable, and ranges from a minimum of 18.76 to a maximum of 27.27 percent. The manganese and iron content of some of the ironstone of this unit, however, are highly variable. In individual specimens of ironstone (table 8) iron ranges from 3.96 to 39.64 percent and manganese, from 4.89 to 26.08 percent. These values represent the total spread in the metal content of the analyzed ironstone; they are not coupled maximum and minimum values of manganese and iron for any one specimen.

The upper and middle manganiferous units generally contain the same manganese- and iron-bearing minerals, although the abundance of these minerals is markedly greater in the middle unit. The manganese in these units is mostly in braunite and ferroan rhodochrosite. The braunite occurs in extremely fine laminae and in thicker layers in both the laminated hematitic slate and in banded hematite ironstone. It also occurs as discrete, semicircular to elliptical pods or beadlike structures (see fig. 18*A*), especially in the more poorly hematitic red slate. The ferroan rhodochrosite occurs in layers as well as in pellets or pods (fig. 21). It is most abundant in the banded hematite ironstone. Spessartite garnet also occurs in both the upper and middle units.

The iron of the upper and middle manganiferous units is mostly in the form of hematite. A little iron is contained in ferruginous rhodochrosite.

The lithology of the lower manganiferous unit has been described earlier; the manganese and iron tenors of the different rocks constituting this unit is given in plate 4*A* and the partial chemical make-up of the unit is indicated by table 12*C*. The manganese tenor of the lower unit is roughly comparable to that of the lower portion of the upper unit, but its iron content is about twice that of the latter. (Compare tables 12*A* and 12*C*.)

The mineralogy and chemical features of the lower unit of the Maple-Hovey deposit differ somewhat from that of the upper and middle units. The manganese of the lower unit is contained mostly as carbonate which ranges in composition from ferroan rhodochrosite to manganoan siderite. The carbonate occurs in thin impure layers and laminae interbedded with red hematitic slate and green slate. Braunite is present in the banded hematite beds, but is less abundant than in the higher units. It has not been found in the hematitic shale. Spessartite garnet has not been seen in any of the rocks of the lower manganiferous unit. Some, however, may be present in the banded hematite ironstone interbeds, inasmuch as this type of rock contains spessartite in the middle manganiferous unit of the deposit. A dearth of spessartite in this unit is suggested by the high content of acid-soluble manganese in the unit as compared to that of the overlying units of the deposit (see table 25) and by microscopic examination.

Although the iron of the lower manganiferous unit is mostly in hematite, the unit contains considerably more ferruginous carbonate than the overlying units, and its ratio of iron to manganese is greater. See plate 3, and also compare table 12*A*, *B*, and *C*.

Table 12 also demonstrates a characteristic variation of the other chemical constituents within the three units of the Maple-Hovey deposit. The general exceptions to this are MgO and sulfur. Although the middle manganiferous unit apparently has the least amount of MgO of all three units, the MgO is not as strikingly different in abundance as most of the other constituents are between the three units. Sulfur also has different distribution characteristics than most of the other constituents in table 12 in that it is present in about equally minor amounts in the upper and middle manganiferous units, but is considerably more abundant in the lower manganiferous unit.

Partial chemical analyses are available for only the upper and lower manganiferous units of the Central Hovey deposit. (See table 13.) As the Central Hovey deposit is chiefly an outlying but more thoroughly metamorphosed fragment of the same manganiferous lens which forms the Maple-Hovey deposit, the general

TABLE 13.—*Partial chemical analyses of the upper and middle manganiferous units from composite samples of diamond-drill cores and a trench, Central Hovey deposit*

[Compiled from Eilertsen, 1952, table 2, p. 52, and table 6, p. 118. See plate 2 for location of drill holes and trenches]

	Upper manganiferous unit				Middle manganiferous unit			
	Diamond-drill holes		Trench 52[2]	Arithmetic average	Diamond-drill holes		Trench 52[2, 3]	Arithmetic average
	46[1]	48			46[3]	48		
Mn	5.67	5.52	6.76	5.98	8.60	10.61	8.26	9.16
Fe	11.96	11.39	10.67	11.34	20.63	23.22	18.99	20.95
P	.303	.370	.306	.326	.735	.930	.691	.785
MnO	7.32	7.13	8.73	7.73	11.10	13.70	10.65	11.82
Fe_2O_3	17.10	16.28	15.26	16.21	29.50	33.20	27.15	29.95
P_2O_5	.694	.848	.701	.748	1.684	2.131	1.583	1.799
SiO_2	42.53	42.53	42.85	42.64	29.60	22.70	32.31	28.20
CaO	2.73	1.68	1.15	1.85	3.79	4.07	2.87	3.58
MgO	2.08	2.69	2.24	2.34	1.58	2.23	1.68	1.83
Al_2O_3	14.85	14.77	15.02	14.88	10.02	8.96	10.54	9.84
S	.046	.091	.068	.068	.295	.160	.173	.209
Total	87.35	86.02	86.02	86.47	87.57	87.15	86.96	87.22

[1] Mostly from the lower part of the unit.
[2] Contacts do not exactly correspond with stratigraphic units.
[3] Represents calculated composite of two or more samples.

chemical features of these two deposits should be similar. Chemical analyses of individual rock types are not available for this deposit, but the partial chemical analyses in table 13 illustrate the general chemical features of the upper and middle manganiferous units of the Central Hovey deposit. A comparison of the analyses from the Central Hovey deposit with those for the same though less metamorphosed units of the Maple-Hovey deposit listed in table 12*A* and *B*, discloses that the biggest difference between them is the higher sulfur content in the Central Hovey deposit, which in the middle manganiferous unit is about eight times the sulfur in the middle manganiferous unit of the Maple-Hovey deposit. The average sulfur content of the upper manganiferous unit is also about twice as great as that of the corresponding unit in the Maple-Hovey deposit. These differences may be a result of metamorphism rather than of original chemical differences.

The manganese in the Central Hovey deposit occurs chiefly as a carbonate close to rhodochrosite in composition. Braunite and spessartite have not been found in this deposit although they are present in the Maple-Hovey deposit. The absence of spessartite in the Central Hovey deposit is indicated by a greater amount of acid-soluble manganese than in comparable units of the Maple-Hovey deposit. For example, over 95 percent of the manganese is acid soluble in the upper and middle manganiferous units of the Central Hovey deposit[13] as compared to an arithmetic average of only 74 percent for the comparable units in the Maple-Hovey deposit. (See table 25.)

The three manganiferous units of the Southern Hovey deposit also have distinct chemical features. Table 14 is a compilation of partial chemical analyses of this deposit. Unfortunately, the footwall manganiferous sequence (table 14*A*) is represented by only one analysis from diamond-drill hole 51. The manganese, iron, and phosphorus of this analysis suggest that the unit is most comparable, chemically, to the upper manganiferous unit of the Maple-Hovey deposit. The other four analyses in table 14*A* represents the hanging-wall manganiferous hematitic slate sequence, and their tenors of manganese, iron, and phosphorus most closely resemble those of the lower manganiferous unit of the Maple-Hovey deposit. Table 14*B* is a compilation of partial chemical analyses of the manganiferous banded hematite sequence of the Southern Hovey deposit; the analyzed samples do not, however, begin and end exactly at stratigraphic boundaries, but the bulk of each sample does come from within the unit. This unit has a striking chemical similarity to the middle manganiferous unit of the Maple-Hovey deposit, especially in its manganese, iron, and phosphorus.

The principal manganese mineral of the manganiferous banded hematite ironstone sequence in the Southern Hovey deposit is a manganiferous carbonate close to rhodochrosite in composition. The manganiferous carbonate occurs mostly in impure laminae of which it is the dominant constituent; it is also disseminated in hematite-rich laminae. Hematite occurs in distinct

TABLE 14.—*Partial chemical analyses of manganiferous interbedded hematitic and green slate, and banded hematite ironstone from composite samples of diamond-drill cores and trenches, Southern Hovey deposit*

[Trenches overlying drill holes are listed in same column. Compiled from Eilertsen, 1952, table 2, p. 52, and table 6, p. 118. See plate 2 for location of drill holes and trenches]

A. INTERVAL OF HEMATITIC AND GREEN SLATE

Diamond-drill holes

	51[1, 2]	55[3]	56[3]	Arithmetic average
Mn	6. 24	7. 14	7. 86	7. 08
Fe	13. 39	17. 03	19. 24	16. 55
P	. 438	. 728	. 732	. 633
MnO	8. 06	9. 22	10. 15	9. 14
Fe_2O_3	19. 14	24. 35	27. 51	23. 67
P_2O_5	1. 004	1. 668	1. 677	1. 450
SiO_2	39. 36	35. 00	31. 42	35. 26
CaO	2. 65	3. 42	2. 79	2. 95
MgO	2. 41	2. 02	2. 17	2. 20
Al_2O_3	14. 23	11. 57	10. 63	12. 14
S	. 120	. 068	. 290	. 159
Total	86. 97	87. 32	86. 64	86. 97

Trenches

	72[3]		82[3]	Arithmetic average
Mn	7. 92	--------	8. 37	8. 15
Fe	21. 27	--------	20. 93	21. 10
P	. 864	--------	. 918	. 891
MnO	10. 23	--------	10. 81	10. 52
Fe_2O_3	30. 41	--------	29. 92	30. 17
P_2O_5	1. 980	--------	2. 103	2. 042
SiO_2	31. 39	--------	31. 01	31. 20
CaO	2. 67	--------	2. 78	2. 73
MgO	1. 52	--------	1. 91	1. 72
Al_2O_3	10. 98	--------	11. 11	11. 05
S	. 048	--------	. 022	. 035
Total	89. 23		89. 67	89. 47

See footnotes at end of table.

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[13] Based on diamond-drill holes 46 and 48. Calculated from ratio of soluble manganese determined by hydrochloric acid method to total manganese as obtained by fusion method. Data abstracted from Eilertsen (1952, table 6, p. 118).

TABLE 14.—*Partial chemical analyses of magniferous interbedded hematitic and green slate, and banded hematite ironstone from composite samples of diamond-drill cores and trenches, Southern Hovey deposit*—Continued

B. INTERVAL OF BANDED HEMATITIC IRONSTONE

Diamond-drill holes

	51 [4]	55	56 [4] [5]	Arithmetic average
Mn	11. 20	10. 20	9. 16	10. 19
Fe	24. 84	19. 24	21. 46	21. 85
P	. 978	. 843	. 915	. 912
MnO	14. 46	13. 17	11. 83	13. 15
Fe_2O_3	35. 51	27. 51	30. 68	31. 23
P_2O_5	2. 241	1. 931	2. 096	2. 089
SiO_2	19. 13	26. 86	26. 69	24. 23
CaO	2. 54	4. 28	3. 94	3. 59
MgO	5. 27	1. 33	1. 44	2. 68
Al_2O_3	7. 36	8. 74	7. 95	8. 02
S	. 029	. 085	. 125	. 080
Total	86. 54	83. 91	84. 75	85. 07

Trenches

	72 [6]	77	82 [6]	Arthmetic average
Mn	10. 64	10. 63	9. 92	10. 40
Fe	28. 92	19. 73	23. 68	24. 11
P	1. 206	. 960	. 876	1. 014
MnO	13. 74	13. 73	12. 81	13. 43
Fe_2O_3	41. 35	28. 21	33. 86	34. 47
P_2O_5	2. 763	2. 200	2. 007	2. 323
SiO_2	18. 45	28. 93	25. 93	24. 47
CaO	3. 63	3. 29	2. 38	3. 10
MgO	1. 33	1. 37	1. 41	1. 37
Al_2O_3	7. 64	8. 38	9. 96	8. 66
S	. 014	. 016	. 012	. 014
Total	89. 92	86. 13	88. 37	87. 84

[1] Corresponds to same interval in columnar section (pl. 4).

[2] Represents the manganiferous footwall hematitic slate sequence.

[3] Represents the manganiferous hanging-wall hematitic slate sequence.

[4] Includes some manganiferous siliceous carbonate rocks underlying the footwall hematitic slate sequence.

[5] Composite of two samples.

[6] Includes the manganiferous footwall hematitic slate sequence.

laminae as well as being sparsely disseminated in the carbonate-rich laminae. In a few places, spessartite garnet is the chief constituent of several laminae. Braunite was not identified in any of the rocks of this deposit, although it occurs in the otherwise lithologically comparable Maple-Hovey deposit.

The tenor and variability of distribution of acid-soluble manganese in the different units of this deposit correspond well with the distribution of spessartite, a minor constituent of irregular occurrence, and the only known manganese mineral of these rocks not readily soluble in acid. Table 26 gives the acid-soluble manganese content of the enclosing hematitic slate and of the banded hematite- or ironstone-bearing unit. The average percentage of acid-soluble manganese in these rocks is appreciably greater than that in the upper and middle manganiferous units of the Maple-Hovey deposit (table 25*A* and *B*). It is also highly variable along the strike length of the deposit.

The only information on the chemistry of the two small lenticular hematitic deposits *E* and *F* on Hovey Mountain (see pl. 2) is their manganese and iron tenor as determined from channel samples across trenches and from the core of drill-hole 59 in the case of lens *E*. Composite assays across lenses *E* and *F* are given in table 15.

Most of the manganese in the rocks of these deposits probably is in the form of carbonate. The bulk of the iron probably is in hematite although some also occurs in magnetite in lens *E* and in the northeast end of lens *F*, as observed in trench 62. (See pl. 2.)

TABLE 15.—*Calculated composite assays, in percent, of the manganiferous hematitic lenses E and F on Hovey Mountain*

[Compiled from Eilertsen, 1952, p. 44, 46, 49, 50, 51, and 115. See plate 2 for location of drill holes and trenches]

Lens *E*

	Trenches		Diamond-drill hole 59
	89	90	
Manganese	8. 29	8. 61	8. 87
Iron	22. 34	23. 49	19. 74

Lens *F*

	Trenches				Arithmetic average
	62	104	69 (North)	121	
Manganese	5. 90	8. 20	11. 70	7. 27	8. 27
Iron	18. 39	17. 90	26. 70	20. 13	20. 78

CARBONATE FACIES

There are only two partial chemical analyses available of the siliceous carbonate deposits from the Maple and Hovey Mountains area (table 16), and these are both from the same magnetite-bearing lens *H*, which is intersected by diamond-drill hole 52 on the northwest slope of Hovey Mountain (pl. 2). Of these two analyses, one is from farther downdip than the other and includes some rock from outside the lens. For purposes of comparison, six analyses of both magnetite-free as well as magnetite-bearing siliceous carbonate beds from the Littleton Ridge deposit of the southern manganese district are also given in table 16.

TABLE 16.—*Partial chemical analyses of a siliceous carbonate lens on Hovey Mountain, and of the siliceous carbonate deposit on Littleton Ridge, southern manganese district, Aroostook County, Maine, from composite samples of diamond-drill cores*

[Compiled from Eilertsen, 1952, table 6, p. 118; and Eilertsen, 1954, table 5, p. 30· Analyses by Lerch Bros. for U.S. Bureau of Mines]

Diamond-drill hole	Hovey Mountain		Littleton Ridge deposit					
	52 [1,2]	52 [2,3]	62 [4]	63 [4]	64 [4]	65 [4]	66 [2]	68 [2]
Mn	8.24	6.64	8.16	7.12	5.71	6.62	8.26	6.82
Fe	19.93	14.15	19.47	16.67	17.56	13.37	22.31	16.27
P	.732	.496	.750	.612	.558	.411	.756	.519
MnO	10.64	8.57	10.54	9.19	7.37	8.55	10.67	8.81
FeO	25.64	18.20	25.05	21.45	22.59	17.20	28.70	20.93
P_2O_5	1.677	1.136	1.718	1.402	1.278	.942	1.732	1.189
SiO_2	28.48	39.00	27.81	30.57	33.85	35.91	21.41	35.60
CaO	3.28	3.64	1.82	1.72	1.60	1.63	2.20	1.31
MgO	2.21	2.62	.43	.93	1.57	.75	.43	1.60
Al_2O_3	11.11	12.03	7.90	9.38	11.36	13.02	6.50	12.38
S	.390	.160	.360	.260	.310	.960	.320	.150
L.O.I.[5]	n.d.	n.d.	14.94	14.73	10.94	10.28	17.52	8.19
Total	83.43	85.36	[6] 90.21	[6] 89.38	[6] 90.56	[6] 88.28	[6] 89.16	[6] 90.01

[1] Represents the stratigraphically lower lens.
[2] Magnetite bearing.
[3] Represents the stratigraphically lower lens, further downdip than the first sample.
[4] Magnetite free.
[5] Loss of ignition at 1,000°C determined by U.S. Bureau of Mines.
[6] Summation excludes sulfur as this is included with the loss on ignition fraction.

The amounts of manganese, iron, and the other constituents of the deposits on Hovey Mountain and Littleton Ridge are closely comparable. The figures for loss on ignition partly reflect the carbonate fraction of these deposits. As loss on ignition was run at 1,000° C, it also includes water and sulfur. Excluding sulfur, the residual constituents represented by the difference in the summation of the analyses from 100 percent for the Littleton Ridge deposit are probably mostly H_2O, Na_2O, K_2O (see tables 10 and 24) and oxygen (for the portion of the iron that occurs in the trivalent state, especially in the analyses of the magnetite-bearing samples). The difference of the summation from 100 for the Hovey Mountain siliceous carbonate lens also includes CO_2, which had not been reported in these analyses, as part of the unanalyzed residuum.

In addition to characteristic amounts of iron and manganese, siliceous carbonate deposits also differ from the hematitic type of deposit in their low MgO, relatively high sulfur, and high CO_2 contents. CO_2 is probably lower in the hematitic manganese deposits by inference from the CO_2 content of individual hematitic rocks; see tables 8*A* and 18. The low MgO content of these deposits is reflected in their mineralogy; the abundant chlorite in siliceous carbonate rocks in many cases is iron rich rather than magnesian.

The tenors of manganese and iron listed in plate 4*C* indicate the general grade of these metals in lenses *G* and *H* as well as in the enclosing slate. The higher manganese content of the lower lens, *H*, reflects the greater abundance of siliceous carbonate layers in this lens. Although the analyses of lens *H* given in table 16 do not represent comparable samples, they nonetheless point out some distinctive chemical features of this deposit. The most notable of these is the relatively high sulfur content. The lower manganiferous unit of the Maple-Hovey deposit and the middle manganiferous unit of the Central Hovey deposit are the only other formations in the area with a comparable sulfur content. In addition, 99 percent of the manganese, by calculation, is acid-soluble in lens *H*, and this value is comparable to that for the lower manganiferous unit of the Maple-Hovey deposit (table 25).

The manganese of these lenticular deposits is probably almost entirely contained in carbonate minerals, which are more abundant in the banded siliceous carbonate rocks than in the associated slate within the lenses.

Magnetite, pyrite, and pyrrhotite are the only recognizable opaque minerals in the siliceous carbonate rocks of this deposit. The magnetite is distributed in different amounts throughout the siliceous carbonate layers. It is mostly octahedral and occurs in layers. Pyrrhotite also occurs oriented along bedding in these rocks either as semitabular crystals or as elongate aggregates of many crystals. Distorted cubic metacrysts of pyrite are commonly alined within or along bedding. Magnetite occurs with both pyrite and pyrrhotite.

The intercalated chloritic slate is composed dominantly of a mat of chlorite with detrital quartz embedded in it. Carbonate, in small amounts, occurs interstitially in the chloritic groundmass as well as in distinct rhombs alined along banding or bedding.

Analyses only of the manganese and iron in almost all of the other lenses of siliceous carbonate rocks in the area are available. Only three of these lenses, however, have been sampled at more than one place, either along strike or downdip. (See table 17.) Two of these lenses lie on Hovey Mountain; one is the lens on the west slope of Hovey Mountain which was sampled in trenches 67 (west half) and 102 and which lies at the nose of an anticline plunging to the northeast; the other is on the south end of Hovey Mountain (immediately southeast of lens *E*) and was sampled in trenches 88, 95, 96, and 97. The third siliceous carbonate lens, whose metal tenor is known from more than one sample, lies on Maple Mountain. It was cored by diamond-drill holes 34 and 44, which were drilled along the northwest flank of the Maple-Hovey deposit. (See pl. 2.) The lens lies northwest of the fault bounding the Maple-Hovey deposit here and is not believed to crop out at the bedrock surface. (See pl. 2.)

TABLE 17.—*Calculated composite assays, in percent, of lenses of magnetite-bearing siliceous carbonate rock on Maple and Hovey Mountains*

[See plate 2 for location of trenches and drill holes. Compiled from Eilertsen, 1952, p. 46, 49, 50, 91, 92, 101, and 102]

A. **Trenches, Hovey Mountain**

	67 (west half)	102	Arithmetic average
Manganese	7.84	9.22	8.53
Iron	19.96	22.10	21.03

B. **Trenches, Hovey Mountain**

	88	95	97	Arithmetic average
Manganese	7.75	8.09	3.52	6.45
Iron	19.95	14.50	8.89	14.45

C. **Diamond-drill holes, Maple Mountain**

	34	44	Arithmetic average
Manganese	6.07	8.02	7.05
Iron	14.99	17.98	16.49

Three lenses of siliceous carbonate rock on Hovey Mountain have been sampled in only one trench each. One of these lenses is on the west side of Hovey Mountain and was exposed and sampled in the central part of trench 69. (See pl. 2.) The combined analyses of the samples from across this lens assay 7.25 percent manganese and 19.67 percent iron (Eilertsen, 1952, fig. 14). The other lenses of siliceous carbonate rock that have been sampled lie near the south end of Hovey Mountain. One of these was exposed and sampled in trench 86 and the calculated composite assay for this deposit is 8.07 percent manganese and 16.55 percent iron; the other was exposed and sampled in trench 98 and has a calculated composite tenor of 6.81 percent manganese and 12.23 percent iron (Eilertsen, 1952, p. 49, 50).

Although the siliceous carbonate rocks underlying the lowermost hematitic units of the Maple-Hovey (pl. 4*A*) and Southern Hovey deposits (pl. 4*B*) do not form distinct deposits in themselves, they are of particular interest because they are the only rocks of the carbonate facies that are generally free of primary magnetite in the area. Wherever they contain magnetite in the Maple-Hovey deposit, the magnetite is apparently authigenic and formed through structurally localized metamorphism (described later).

The siliceous carbonate zone below the lower manganiferous unit of the Maple-Hovey deposit consists of a sequence of green chloritic slate, unevenly interlayered with thin green beds of manganiferous, finely banded and laminated siliceous carbonate rock. Pyrite is intimately associated with these layers. (See fig. 29.) The manganese in this zone is chiefly contained as carbonate, which for the most part has optical properties close to manganoan siderite. Most of the iron in this zone is also contained as carbonate, although some of it may be contained in chlorite.

The rocks of this zone have not been as completely or systematically chemically analyzed as the other units of the deposits in the area. An assay cutoff of 1 percent manganese has been considered as coinciding with the lower limits of this zone. Based upon selected values obtained from the diamond-drill hole assay data tabulated by Eilertsen (1952, table 5, p. 55–116), the writer has calculated an arithmetic average thickness of 7.8 feet for this zone and a weighted average content of 3.84 percent manganese and 11.66 percent iron. The underlying typical green slate country rock contains less than 1 percent manganese and less than 7 percent iron.

The thickness and tenor of the siliceous carbonate rock differ considerably in relatively short distances along both the strike and dip of the bedding. The range in metal content is equally variable, the highest assay for manganese being 10.71 percent with a corresponding iron content of 13.43 percent, whereas the sample with the most iron contained 23.57 percent iron and 7.80 percent manganese.

VARIATION OF CHEMICAL CONSTITUENTS WITH PHOSPHORUS

One of the striking features of the chemical constituents of the three units in the Maple-Hovey deposit (table 12), exclusive of MgO and sulfur, is their marked linear variation with respect to phosphorus. Plate 6 shows scatter diagrams with Fe, Mn, CaO, SiO_2, and Al_2O_3 plotted along the ordinate and phosphorus along the abscissa. In addition to such variations of composite samples within the Maple-Hovey deposit the diagrams show similar variations for the Southern Hovey deposit (table 14) and the Central Hovey deposit (table 13), and for individual specimens of hematitic and of magnetite-bearing ironstone (table 8) and slate (table 18) from the middle and upper manganiferous units of the Maple-Hovey deposit.

TABLE 18.—*Chemical analyses of red and purple slate from the upper manganiferous unit of the Maple-Hovey deposit*

[Analyses by Wilbur J. Blake]

	Red slate		Purple slate	
Laboratory No. Field No.	51-1636-CD T-5-A	51-1637-CD T-12-C	51-1638-CD T-19-A	51-1639-CD T-19-B
SiO_2	60.00	55.71	56.31	60.65
Al_2O_3	16.73	17.28	17.98	18.34
Fe_2O_3	7.64	8.56	6.54	8.03
FeO	[1]1.00	[1]1.00	.94	.77
MgO	2.99	2.98	3.29	1.20
CaO	.17	.13	.27	.08
Na_2O	4.38	7.21	.27	.11
K_2O	3.65	2.97	5.77	6.33
H_2O-	.13	.16	.15	.13
H_2O+	2.25	.99	3.53	3.02
TiO_2	.75	.93	.75	.78
CO_2	.05	.16	.00	.00
P_2O_5	.10	.07	.07	.11
MnO	1.23	2.91	4.26	.52
Total	100.07	100.06	100.13	100.07

[1] Enough higher valent manganese was present to oxidize ferrous iron completely, if present.

The scatter diagrams obtained by plotting only the analyses from the Maple-Hovey deposit generally have the appearance of an elongate cloud or path, which suggests that the variables considered in each graph have a linear relation. A test of the significance of this apparent linearity was made, wherein phosphorus was considered as the independent variable and the respective metals, oxides, and sulfur of the tabulated analyses (table 12) were treated as the dependent variables. The equation of the regression line $y=a+bx$ (y=dependent variable, x=independent variable) for each scatter diagram was calculated. The statistical methods outlined by Brownlee (1953, p. 61–65) were used in deriving the equation for the regression line, the correlation coefficient, the residual variance about the regression line, and the confidence limits on either side of the regression line. These factors are explained below and summarized in table 19.

TABLE 19.—*Regression lines, correlation coefficients, residual variance, and confidence limits of the chemical constituents of the Maple-Hovey deposit*

[n.d.=not determined]

Independent variable (x)	Dependent variable (y)	Regression line	Correlation coefficient	Residual variance	95 percent confidence limits
P	Fe	$y=+19.13x+5.50$	+0.98	1.14	±2.36
P	Mn	$y=+6.18x+3.99$	+.75	1.60	±3.31
P	CaO	$y=+3.18x+.67$	+.75	.81	±1.68
P	MgO	$y=-.85x+2.40$	−.39	n.d.	n.d.
P	SiO_2	$y=-28.10x+53.10$	−.97	2.03	±4.20
P	Al_2O_3	$y=-11.04x+18.33$	−.96	.94	±1.95
P	S	$y=+.03x+.06$	+.08	n.d.	n.d.

Regression line $y=a+bx$, "is the line which gives the squares of the deviation of every point, measured parallel to the y axis in units of y, summed for all points, as a minimum. * * * [it is] the formula for deducing the most probable value of y corresponding to a given value of x * * *" (Brownlee, 1953, p. 64). Correlation coefficient (r) "has the characteristics such that if the relationship between the data can be represented exactly by a straight line then $r=\pm1$, positive if the straight line has a positive slope and negative if the line has a negative slope; if on the other hand there is no relation at all between the variables then $r=0$" (Brownlee, 1953, p. 62). Residual variance about the regression line or the standard error of estimate "is a measure of the variation or scatter about the line of regression" (Arkin and Colton, 1939, p. 76). Confidence limits are the limits within which there is reasonable chance of being correct in predicting values of y for given values of x (Brownell, 1953, p. 65). Confidence limits depend upon what probability level is considered significant; "for many purposes the 5 percent level is accepted * * *" (Brownlee 1953, p. 24). Thus, a 5 percent level of significance will correspond to 95 percent confidence limits; that is, "95 percent chance of being right is equivalent to a 5 percent chance of being wrong" (Brownlee, 1953, p. 33).

In general, the regression lines for the variation of Mn, Fe, CaO, SiO_2, and Al_2O_3 have a correlation coefficient well above that listed in the "Table of Correlation Coefficients" by Fisher and Yates (given by Brownlee, 1953, p. 187) for 22 degrees of freedom. Degree of freedom in this case is 22, or 2 less than the number of paired variables used to derive the regression line. The correlation coefficients of the regression lines of MgO and sulfur with relation to phorphorus are lower than this minimum correlation number and are not considered to be significant. Scatter diagrams have not been attempted for these two constituents. Scatter diagrams with regression lines and their respective confidence limits for the Maple-Hovey deposit analyses (table 12) have been drawn (pl. 6) only for Fe, Mn, CaO, SiO_2, and Al_2O_3, the constituents whose correlation coefficients indicate significance.

The comparable units for which diamond-drill hole analyses are available in the Central Hovey deposit (table 13) all plot within the confidence limits of the Maple-Hovey deposit regression line and fall within the cluster, or cloud of points, of their equivalent units; that is, the two analyses of the upper manganiferous unit of the Central Hovey deposit plot within the field of the analyses of the upper manganiferous unit of the Maple-Hovey deposit and the two analyses of the middle manganiferous unit also plot within the field of the middle manganiferous unit of the Maple-Hovey deposit. This correlation of chemical features substantiates the conclusion that the Central Hovey deposit is a more highly metamorphosed segment of the lens that forms the Maple-Hovey deposit, and is not a genetically different deposit.

The analyses from the interval of banded hematite ironstone of the Southern Hovey deposit (table 14*B*) also plot within the field of the middle manganiferous unit of the Maple-Hovey deposit. The manganiferous hanging-wall slate sequence of the Southern Hovey deposit (table 14*A*), however, plots within the field of the lower manganiferous unit of the Maple-Hovey deposit, and the manganiferous footwall hematitic slate sequence of the Southern Hovey plots within the field of the upper manganiferous unit of the Maple-Hovey deposit.

The only available comparable partial chemical analyses of a manganiferous hematitic deposit (oxide facies) outside of those on Maple and Hovey Mountains is the one analysis cited by Miller (1947, p. 25) for the Dudley deposit of the northern manganese district. This analysis[14] is as follows:

Mn	12.81
Fe	20.8
P	.676
MnO	16.54
Fe_2O_3	29.74
P_2O_5	1.549
SiO_2	26.3
Al_2O_3	8.3
CaO	1.27
MgO	1.33(?)
S	.52
Total	85.55

The metallic iron and manganese and the elemental phosphorus have been recast into the oxide form, as in the case of the partial chemical analyses of the Maple and Hovey Mountains area. The unanalyzed residuum is assumed to be similar to that postulated for the Maple and Hovey Mountains oxide deposit analyses: H_2O, CO_2, Na_2O, K_2O, and oxygen (in manganese oxide of higher valence than the MnO of the tabulation). Points representing this analysis from the Dudley deposit lie close to the regression line on the Fe and CaO diagrams (pl. 6*A* and *C*), but are more distant on the Mn, SiO_2 and Al_2O_3 diagrams (pl. 6*B*, *D*, and *E*). On the whole, the Dudley deposit, insofar as can be inferred from this one analysis, has some chemical features that are intermediate between those of the middle and lower manganiferous units of the Maple-Hovey deposit, although on the basis of its manganese tenor it is very similar to the middle manganiferous unit of the Maple-Hovey deposit (see table 12*B*).

The corresponding analyses for the relatively unreconstituted as well as more highly reconstituted banded hematite ironstone (table 8) and red and purple slate (table 18) from the Maple-Hovey deposit generally scatter widely around the regression lines (pl. 6) except for the CaO: P scatter diagram, in which case all the analyses fall within the confidence limits of the regression line.

Aside from their obvious quantitative chemical differences from the hematitic manganese deposits, the Fe, Mn, CaO, Al_2O_3 and SiO_2 content of the siliceous carbonate manganese deposits vary in much the same way with respect to phosphorus as the hematitic types do. Comparable paired analyses from these deposits obtained from table 16 have been plotted on the appropriate scatter diagrams (pl. 6) of the Maple-Hovey deposit. The diamond-drill hole samples representing entire segments of a deposit are shown by asterisks, and analyses of individual rock specimens are plotted simply as plus signs. With the exception of SiO_2 and Al_2O_3 (pl. 6*D* and *E*), all the analyses of composite samples plot within the confidence limits of the regression line calculated for the Maple-Hovey deposit. In some cases, such as the iron and manganese scatter diagrams, the analyses of the siliceous carbonate deposits fit the regression lines much more closely than do the analyses from the hematitic deposits. (See pl. 6*A* and *B*.) The poorer correspondence of the analyses of the siliceous carbonate deposits to the Al_2O_3: P regression line (pl. 6*E*), however, is marked; only 5 of the 8,

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[14] Analysis by the Manganese Ore Co.

or 62.5 percent, of the points fall within the 95 percent confidence limits of the regression lines. However, a visual examination of the plot of these points indicates that 7 of the 8 points are alinable along a path for which a straight line with a steeper slope than the plotted regression line can be drawn. This suggests that Al_2O_3 decreases with increasing phosphorus at a greater rate in the siliceous carbonate deposits than in the hematitic deposits. The points obtained by plotting the corresponding analyses of individual siliceous carbonate rocks (table 10) on the different diagrams have a scatter about the respective regression lines that is comparable to the scatter of the hematitic rock analyses, but in the case of manganese, the scatter of the siliceous carbonate rocks is strikingly smaller.

The variation of iron and manganese with phosphorus content in the Aroostook manganese deposits was initially noted by Miller (1947, p. 25). The analyses of samples of the Dudley deposit from drill hole 2 of the Manganese Ore Company indicated to Miller that the "phosphorus appears to be associated with the iron, for samples * * * that are high in iron but low in manganese are high in phosphorus, whereas samples high in manganese but with an average amount of iron have an average amount of phosphorus." Actually, the manganese variation with respect to phosphorus may also be linear or nearly so in the Dudley deposit, but the difference in the rates of variation of manganese and of iron with respect to phosphorus may be the reason why the variation of manganese with phosphorus was not as readily apparent.

Eilertsen (1952, p. 16, fig. 30) also commented on the linear relation of iron and phosphorus in the deposits of Maple and Hovey Mountains. He has plotted their ratio, using phosphorus as the ordinate and iron as the abscissa. His curve is based on 5 points, which are the weighted averages at specified manganese assay cutoffs. If Eilertsen's points are plotted on the iron scatter diagram (pl. 6*A*), they form a line with a steeper slope than in the regression line calculated by the writer. This difference in slopes stems from the difference in the data used; Eilertsen used both trench and diamond-drill hole assays of all the different types of deposits on Maple and Hovey Mountains whereas the regression line in plate 6*A* was calculated only from diamond-drill hole information from the Maple-Hovey deposit.

MINOR CHEMICAL CONSTITUENTS

Numerous geochemists have called attention to the relatively high concentrations of various metals and metalloids generally contained in sedimentary iron and manganese deposits. Notable amounts of lithium, potassium, calcium, barium, boron, titanium, cobalt, nickel, copper, zinc, thallium, lead, and tungsten are commonly present in manganese-rich sediments, and iron ores are enriched in such elements as scandium, vanadium, arsenic, bismuth, and lithium (Rankama and Sahama, 1950, p. 428, 516, 603, 650, 741). Goldschmidt (1937, p. 668) also found that molybdenum is concentrated by oxidate manganese compounds. The enrichment of these elements is generally attributed to the phenomenon of sorption at the time the iron and manganese deposits are being laid down as colloids in an aqueous environment. The hydrosols of manganese and iron, with their respective positive and negative charges, pick up suitable charged cations and anions that may be in solution and in some cases are thereby neutralized and flocculated. Freshly precipitated gels with an unbalanced charge also are capable of picking up suitably charged elements from solution. Goldschmidt (1937, p. 667–668) felt that the sorption effected by hydroxides of manganese and iron of such poisonous substances as selenium, arsenic, lead, antimony, and bismuth has been the mechanism which prevented the oceans from becoming toxic. Otherwise, the probable great amounts of such elements that have been supplied to the oceans throughout geologic time would have resulted in serious poisoning of the oceans.

An attempt has been made to evaluate whether the iron- and manganese-rich rocks of Aroostook County contain any significant concentrations of metals and metalloids. The available analyses from which to make such a comparison, although limited in number as well as being partial and qualitative, can nonetheless be used to some extent to evaluate possible sorption enrichment. The minor constituents for two samples of banded ironstone from the Maple-Hovey deposit are listed in table 20. Partial qualitative spectrographic analyses of the different units in the Maple-Hovey, Central Hovey, and Southern Hovey deposits and of a siliceous carbonate lens from the central manganese district are listed in tables 21, 22, 23, and 24. These spectrographic analyses correspond to some of the partial chemical analyses of diamond-drill hole samples listed in tables 12, 14, 13, and 18 and 16.

The partial qualitative spectroscopic analyses in tables 21, 22, 23, and 24 represent a reconnaissance examination of the samples listed. The analytical precision and techniques used in making the spectroscopic analyses are such that it is reasonable to consider that

Table 20.—*Quantitative spectrochemical analyses for minor elements in two samples of manganiferous banded ironstone from the Maple-Hovey deposit*

[Spectrochemical analyses by A. A. Chodos. Data expressed as decimal fractions of 1 percent. See table 8 for analyses of major constituents]

	Banded hematite	Banded magnetite-chlorite rock
Field No.	T12+142E	T11+270W
Laboratory No.	51-55SC	51-54SC
Ni	0. 005	0. 03
Co	. 005	. 02
Cr	. 005	. 01
Cu	. 001	. 003
V	. 01	. 02
Sc	. 0006	. 0009
Ba	. 01	. 01
Sr	. 08	. 08
Y	. 02	. 02
Yb	. 002	. 002
La	. 02	. 02
Zr	. 03	. 04
Ti	. 1	. 2

Looked for but not found: Ga, Pb, Be, Ag, Au, Pt, Mo, W, Ge, Sn, As, Sb, Bi, Zn, Cd, Tl, In, Nb, Ta, Th, U, B.

only about 80 percent of the samples fall within the ranges given, and about 20 percent of the analyses might actually overlap into the next higher or lower range; for example, an analysis given as 0.005–0.05 may possibly extend down to 0.003–0.03 or up to 0.008–0.08 (oral communication, M. J. Peterson, U.S. Bureau of Mines, 1955).

For the most part, neither the analyses of the two banded ironstones (table 20) nor those of the diamond-drill hole composites (tables 21 through 24) show any appreciable concentration of minor constituents over the amount of these constituents in sedimentary iron ores as compiled by Rankama and Sahama (1950, p. 428, 441, 447, 482, 483, 491, 517, 529, 564, 601, 623, 650, 685, 700, 713, 741). The only constituents in tables 21 through 24 which are present in fairly large amounts are K_2O, Na_2O, and Rb_2O. The potassium and sodium are believed to be contained chiefly in fine-grained feldspar and mica. The amount of the alkali that may have been introduced as detrital feldspar and mica and the amount which may have been fixed in the original sediments through sorption cannot be evaluated. The rubidium is probably substituting for potassium in the detrital feldspar and mica.

The analyses of minor constituents in individual ironstones are much less significant for comparative purposes, inasmuch as they represent only two samples from rocks known to have a fairly wide range in their major constituents. (See table 8.)

The apparent lack of enrichment in expectable minor elements in the Aroostook deposits, as suggested by these spectrographic analyses, is in part a matter of degree. It has previously been shown that there is a tenfold concentration of barium and a sixfold con-

Table 21.—*Partial qualitative spectrographic analyses of the upper, middle, and lower manganiferous units from composite samples of diamond-drill cores and trenches, Maple-Hovey deposit*

[Analyses by M. J. Peterson, U.S. Bureau of Mines; published by permission. See table 12 for analyses of major constituents. See pl. 2 for location of drill holes and trenches. n.d.=not determined]

	A. Upper manganiferous unit						*B.* Middle manganiferous unit		
	Diamond-drill holes				Trenches		Diamond-drill holes		
	37	40	41	45	31	47	24	40	41
Laboratory No.	E 840	E 833	E 836[1]	E 847	E 896	E 879	E 828	E 834	E 838
ZnO	<0. 01	<0. 01	<0. 01	<0. 01	<0. 01	<0. 01	<0. 01	<0. 01	<0. 01
NiO	. 002–. 02	. 003–. 03	. 002–. 02	. 002–. 02	. 001–. 01	. 001–. 01	. 002–. 02	. 001–. 01	. 001–. 01
CoO	. 001–. 01	. 002–. 02	. 002–. 02	. 001–. 01	. 001–. 01	. 001–. 01	. 003–. 03	. 002–. 02	. 002–. 02
B_2O_3	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01
As_2O_3	n.d.	. 01–. 1	. 01–. 1	. 01–. 1	n.d.	n.d.	. 01–. 1	. 01–. 1	. 01–. 1
Ga_2O_3	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01
TiO_2	. 01–. 1	. 02–. 2	. 01–. 1	. 03–. 3	. 01–. 1	. 03–. 3	. 02–. 2	. 005–. 05	. 005–. 05
V_2O_5	. 005–. 05	. 005–. 05	. 002–. 02	. 005–. 05	. 002–. 02	. 002–. 02	. 005–. 05	. 005–. 05	. 002–. 02
MoO_3	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01
CuO	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01
ZrO_2	. 002–. 02	. 002–. 02	. 002–. 02	. 001–. 01	. 001–. 01	. 001–. 01	. 002–. 02	. 002–. 02	. 002–. 02
Cr_2O_3	. 002–. 02	. 001–. 01	. 002–. 02	. 002–. 02	. 001–. 01	<. 01	. 001–. 01	. 001–. 01	. 002–. 02
SrO	. 005–. 05	<. 01	<. 01	<. 01	<. 01	<. 01	<. 01	. 02–. 2	. 005–. 05
BaO	<. 01	<. 01	. 005–. 05	. 01–. 1	. 01–. 1	. 02–. 2	<. 01	. 005–. 05	. 005–. 05
K_2O	. 5–5.	1. –10.	. 08–. 8	1. –10.	. 1–1.	. 08–. 8	. 05–. 5	. 08–. 8	. 5–5.
Na_2O	1. –10.	. 05–. 5	. 005–. 05	1. –10.	. 02–. 2	. 05–. 5	<. 01	>5.	1. –10.
Li_2O	. 005–. 05	. 01–. 1	. 01–. 1	. 005–. 05	. 001–. 01	<. 01	. 005–. 05	. 01–. 1	. 02–. 2
Rb_2O	. 02–. 2	. 03–. 3	. 01–. 1	. 02–. 2	. 01–. 1	. 01–. 1	. 01–. 1	. 01–. 1	. 02–. 2

See footnote at end of table.

TABLE 21.—*Partial qualitative spectrographic analyses of the upper, middle, and lower manganiferous units from composite samples of diamond-drill cores and trenches, Maple-Hovey deposit*—Continued

	B. Middle manganiferous unit					*C.* Lower manganiferous unit				
	Diamond-drill holes		Trenches			Diamond-drill holes			Trenches	
	37	45	31	29	47	31	35	41	31	29
Laboratory No.	E 841	E 848	E 870	E 874	E 877	E 824	E 832	E 839	E 871	E 875
ZnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NiO	.002–.02	.001–.01	.001–.01	.001–.01	.001–.01	.002–.02	.002–.02	.001–.01	.001–.01	.001–.01
CoO	.001–.01	.001–.01	.001–.01	.001–.01	.001–.01	.002–.02	.002–.02	.001–.01	.001–.01	.001–.01
B_2O_3	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
As_2O_3	.01–.1	.01–.1	n.d.	n.d.	n.d.	.01–.1	.01–.1	.01–.1	n.d.	n.d.
Ga_2O_3	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
TiO_2	.03–.3	.01–.1	.01–.1	.003–.03	.01–.1	.05–.5	.01–.1	.01–.1	.01–.1	.01–.1
V_2O_5	.005–.05	.005–.05	.002–.02	.001–.01	.001–.01	.005–.05	.005–.05	.005–.05	.002–.02	.003–.03
MoO_3	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
CuO	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
ZrO_2	.001–.01	.001–.01	.005–.05	.003–.03	.002–.02	.002–.02	.005–.05	.002–.02	.005–.05	.005–.05
Cr_2O_3	.002–.02	.002–.02	.001–.01	.001–.01	<.01	.001–.01	.002–.02	.002–.02	.001–.01	.001–.01
SrO	.01–.1	.008–.08	<.01	<.01	<.01	.005–.05	.01–.1	.005–.05	<.01	<.01
BaO	.01–.1	.03–.3	.01–.1	.01–.1	.02–.2	<.01	.01–.1	.02–.2	<.01	.008–.08
K_2O	.5–5.	.2–2.	.05–.5	.05–.5	.01–.1	.08–.8	1.–10.	.5–5.	.05–.5	.05–.5
Na_2O	>5.	>5.	.005–.05	.01–.1	.1–1.	1.–10.	>5.	.1–1.	<.01	.002–.02
Li_2O	.005–.05	.005–.05	<.001	.001–.01	<.01	.01–.1	.1–1.	.005–.05	.001	.001
Rb_2O	.02–.2	.02–2.2	.01–.1	.01–.1	.01–.1	.01–.1	.03–.3	.02–.2	.01–.1	.01–.1

[1] Includes only a small part of the unit.

TABLE 22.—*Partial qualitative spectrographic analyses of the upper and middle manganiferous units from composite samples of diamond-drill cores and a trench, Central Hovey deposit*

[Analyses by M. J. Peterson, U.S. Bureau of Mines; published by permission. See table 13 for analyses of major constituents. See pl. 2 for location of drill holes and trench. n.d.=not determined]

Laboratory No.	Upper manganiferous unit			Middle manganiferous unit		
	Diamond-drill holes		Trench	Diamond-drill holes		Trench
	46	48	52	46	48	52
	E 850	E 855	E 883	E 851 [1]	E 856	E 885
ZnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NiO	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01
CoO	.001-.01	.001-.01	.001-.01	.002-.02	.001-.01	.001-.01
B_2O_3	<.01	<.01	.001-.01	<.01	<.01	.001-.01
As_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ga_2O_3	<.01	<.01	<.01	<.01	<.01	<.01
TiO_2	.02-.2	.02-.2	.02-.2	.005-.05	.01-.1	.02-.2
V_2O_5	.005-.05	.002-.02	.002-.02	.002-.02	.002-.02	.002-.02
MoO_3	<.01	<.01	<.01	<.01	<.01	<.01
CuO	<.01	<.01	<.01	<.01	<.01	<.01
ZrO_2	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.002-.02
Cr_2O_3	.002-.02	.002-.02	<.01	.001-.01	.002-.02	<.01
SrO	.005-.02	.002-.02	<.01	.002-.02	<.01	<.01
BaO	<.01	.01-.1	.005-.05	<.01	.005-.05	.002-.02
K_2O	.5-5.	.5-5.	.05-.5	.1-1.	.08-.8	.03-.3
Na_2O	>5.	.5-5.	.02-.2	.01-.1	.01-.1	.008-.08
Li_2O	.005-.05	.002-.02	<.01	.005-.05	.001-.01	<.01
Rb_2O	.02-.2	.01-.1	.01-.1	.01-.1	.01-.1	.01-.1

[1] Includes only a small part of the unit.

centration of boron in a braunite-rich pellet from the Dudley deposit as compared with the red slate enclosing the pellet. However, this is a relative concentration between two selected analyses (table 7) and the actual concentrations effected, namely, 0.66 percent BaO and 0.12 percent B_2O_3 are not sufficiently large to carry through into samples representing formations many feet thick. Such a selective concentration of minor constituents would be masked by the diluting effect of the unenriched and more abundant enclosing wallrock, such as the red slate of the Dudley deposit. Therefore, although some geochemical concentration undoubtedly did take place during the formation of the Aroostook iron- and manganese-rich deposits, it probably was on a small scale and selective in distribution so that gross samples from deposits such as those on Maple and Hovey Mountains do not show it.

ACID-SOLUBLE MANGANESE

Differences in the amounts of manganese contained in a form soluble in mineral acids, such as concentrated hydrochloric acid, is a conspicuous chemical feature of both geologic and economic importance that characterizes the deposits on Maple and Hovey Mountains. The differences in acid-soluble manganese exist not only between different deposits but also between different units within a deposit. Table 25 summarizes the distribution of acid-soluble manganese in the three manganiferous units of the Maple-Hovey deposit. This table and similar tables for other deposits have been compiled from the figures published by Eilertsen (1952, tables 2 and 6), wherein the total manganese content of the samples, as determined by the fusion method, and the total manganese soluble in hydrochloric acid are given. The percent of acid-soluble manganese in the sample, therefore, is expressed by the ratio of the amount of

TABLE 23.—*Partial qualitative spectrographic analyses of the intervals consisting of manganiferous interbedded hematitic and green slate and banded hematite ironstone from composite samples of diamond-drill cores and trenches, Southern Hovey deposit*

[Analyses by M. J. Peterson, U.S. Bureau of Mines, published by permission. See table 14 for analyses of major constituents. n.d.=not determined]

	A. Interval of hematitic and green slate					*B*. Interval of banded hematite ironstone					
	Diamond-drill holes			Trenches		Diamond-drill holes			Trenches		
	51	55	56	72	82	51	55	56	72	77	82
Laboratory No	E 894	E 864	E 866	E 887	E 890	E 895	E 865	E 867[1]	E 888	E 889	E 891
ZnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NiO	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01
CoO	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.002-.02	.002.-02	.001-.01	.002-.02	.002-.02	.001-.01
B_2O_3	.001-.01	<.01	<.01	.001-.01	.001-.01	.001-.01	<.01	<.01	n.d.	.001-.01	.001-.01
As_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ga_2O_3	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
TiO_2	.01 -.1	.01 -.1	.01 -.1	.02 -.2	.01 -.1	.005-.05	.01 -.1	.002-.02	.01 -.1	.01 -.1	.01 -.1
V_2O_5	.002-.02	.003-.03	.003-.03	.002-.02	.002-.02	.001-.01	.001-.01	.001-.01	.002-.02	.002-.02	.001-.01
MoO_3	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
CuO	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
ZrO_2	.001-.01	.005-.05	.005-.05	.002-.02	.002-.02	.001-.01	.003-.03	.005-.05	.002-.02	.002-.02	.001-.01
Cr_2O_3	<.01	.001-.01	.001-.01	<.01	<.01	<.01	.002-.02	.001-.01	<.01	<.01	<.01
SrO	<.01	<.01	<.01	n.d.	<.01	<.01	.005-.05	<.01	<.01	<.01	<.01
BaO	.02 -.2	.01 -.1	.002-.02	.005-.05	<.01	.02 -.2	.03 -.3	.005-.05	<.01	.005-.05	<.01
K_2O	.05 -.5	.05 -.5	.05 -.5	.02 -.2	.02 -.2	.05 -.5	.05- .5	.03 -.3	.008-.08	.02 -.2	.01 -.1
Na_2O	.1 -1.	.08 -.8	.01 -.1	.003-.03	.005-.05	.1 -1.	.05 -.5	.01 -.1	.01 -.1	.005-.05	.005-.05
Li_2O	<.01	.001-.01	.001-.01	<.01	<.01	<.01	.001-.01	.001-.01	<.01	<.01	<.01
Rb_2O	.01 -.1	.01 -.1	.01 -.1	.01 -.1	.01 -.1	.01 -.1	.01 -.1	.01 -.1	.01 -.1	.01 -.1	.01 -.1

[1] Includes only a small part of the unit.

TABLE 24.—*Partial qualitative spectrographic analyses of a siliceous carbonate lens on Hovey Mountain and of the siliceous carbonate deposit on Littleton Ridge, southern manganese district, from composite samples of diamond-drill cores*

[Analyses by M. J. Peterson, U.S. Bureau of Mines, published by permission; Eilertsen, 1955, table 5A, p. 31. See table 16, for analyses of major constituents. n.d.-not detected]

	Lens on Hovey Mountain		Littleton Ridge deposit					
Diamond-drill hole	52	52	62	63	64	65	66	68
Laboratory No	E 862	E 863	E 961	E 962	E 963	E 964	E 965	E 966
ZnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NiO	.001−.01	.001−.01	.001−.01	.002−.02	.002−.02	.002−.02	.001−.01	.002−.02
CoO	.001−.01	.001−.01	.002−.02	.001−.01	.001−.01	.001−.01	.001−.01	.001−.01
B_2O_3	<.01	<.01	.001−.01	<.01	<.01	<.01	<.01	<.01
As_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ga_2O_3	<.01	<.01	<.01	<.10	<.01	<.01	<.01	<.01
TiO_2	.005−.05	.01 −.1	.005−.05	.005−.05	.01 −.1	.01 −.1	.005−.05	.02 −.2
V_2O_5	.001−.01	.001−.01	.002−.02	.002−.02	.005−.05	.005−.05	.001−.01	.005−.05
MoO_3	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
CuO	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
ZrO_2	.001−.01	.001−.01	.001−.01	<.01	<.01	<.01	<.01	<.01
Cr_2O_3	.001−.01	.001−.01	<.01	<.01	<.01	<.01	<.01	<.01
SrO	<.01	<.01	<.01	<.01	n.d.	n.d.	n.d.	n.d.
BaO	.002−.02	.001−.01	.005−.05	.005−.05	<.01	<.01	<.01	<.01
K_2O	.05 −.5	.03 −.3	.01 −.1	.03 −.3	.01 −.1	.03 −.3	.01 −.1	.03 −.3
Na_2O	.01 −.1	.005−.05	<.01	.002−.02	<.01	<.01	<.01	.005−.05
Li_2O	.001−.01	.001−.01	<.01	<.01	<.01	<.01	<.01	<.01
RbO_2	.01 −.1	.01 −.1	.01 −.1	.01 −.1	.01 −.1	.01 −.1	.01 −.1	.01 −.1

manganese determined by the acid method compared to the total manganese content of the sample obtained by the fusion method. This ratio has been calculated and expressed in percent in table 25. In similar manner, the percentage of acid-soluble manganese for the Southern Hovey deposit has been calculated and is listed in table 26. Acid-leach tests by the U.S. Bureau of Mines achieved a maximum percentage extraction of approximately 60 percent manganese (Conley, 1952, p. 17, 20) on material which presumably was taken mostly from the middle manganiferous unit; it reportedly assayed 11 to 14 percent manganese (see table 12*B*), and is consequently chiefly of manganiferous banded hematite ironstone.

The differences in acid-soluble manganese content between manganiferous units are directly related to the mineralogy of the deposits. Specifically, deposits or units within deposits that are spessartite-bearing contain less acid-soluble manganese than those without spessartite. In this respect, it is of interest that a speciman of manganiferous banded hematite such as T–43–A in table 9 has a calculated "normative" content of 21 percent spessartite. Microscopic examination of this specimen verifies the abundant content of spessartite. Approximately 30 percent of the total manganese of this rock (29.9 percent MnO) may, therefore, be bonded in spessartite garnet.

Table 25.—*Percentages of acid-soluble manganese in the manganiferous units of the Maple-Hovey deposit*

[Compiled from Eilertsen, 1952, table 2, p. 52 and table 6, p. 117–118]

A. UPPER MANGANIFEROUS UNIT

Diamond-drill holes

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
1[1, 2]	4.66	3.78	81
2[2]	6.48	4.44	69
12[2]	6.56	5.23	80
27[2]	6.80	5.00	74
37[3]	7.56	5.20	69
39[2]	6.51	4.86	75
40[2]	8.88	6.96	78
41[2, 4]	8.49	6.23	73
45[3]	5.83	4.16	71
Arithmetic average	6.86	----------	74

Trenches

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
7[1]	6.31	5.71	90
14[1]	6.48	5.27	81
31[1]	7.40	6.20	84
47[1]	4.92	3.80	77
Arithmetic average	6.28	----------	83

B. MIDDLE MANGANIFEROUS UNIT

Diamond-drill holes

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
1 and 2[4, 5]	12.04	9.68	80
12	11.46	8.43	74
24	12.04	8.91	74
27[4]	11.36	8.04	71
35[6, 7]	9.98	8.30	83
37	9.90	6.40	65
40	11.00	9.45	86
41	11.22	8.03	72
45	11.12	7.00	63
Arithmetic average	11.12	----------	74

Trenches

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
4[4]	14.92	11.95	80
7[4]	13.95	10.80	77
14[4]	12.38	9.87	80
19[4, 7]	11.68	10.75	92
29	13.67	9.20	67
31[4]	10.56	8.80	83
47[8]	10.96	8.72	80
Arithmetic average	12.59	----------	80

See footnotes at end of table.

Table 25—*Percentages of acid-soluble manganese in the manganiferous units of the Maple-Hovey deposit*—Continued

C. LOWER MANGANIFEROUS UNIT

Diamond-drill holes

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
1 and 2[4, 5]	6.80	6.22	91
12[4]	6.57	6.31	96
27[4]	6.46	6.38	99
31[4, 6]	6.69	6.62	99
35[4, 6]	5.39	5.31	99
41	7.21	6.88	95
Arithmetic average	6.52	----------	97

Trenches

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
4[4]	6.92	6.72	97
14[4]	6.27	5.68	91
19[4]	5.70	5.66	99
26[4]	6.88	6.63	96
29[4]	6.92	6.60	95
31	5.14	5.10	99
Arithmetic average	6.31	----------	96

[1] Includes only the lower part of the unit.
[2] Composite of two samples.
[3] Does not represent the entire unit.
[4] Sample contacts not precisely included within, nor coincident with stratigraphic contacts of unit.
[5] Arithmetic average of 2 holes drilled from the same collar.
[6] Weighted average of 3 samples.
[7] Contains more highly metamorphosed, magnetite-bearing zone.
[8] Includes only upper part of the unit.

Quite probably spessartite is an important manganese mineral in some of the deposits of Maple and Hovey Mountains, although it is not readily detectable in all types of ironstone. Perhaps it is more abundant in only certain types of ironstones and slates which, in gross, may constitute a large and important part of some of the formations or units.

The bonding of appreciable manganese in other acid-insoluble minerals such as rhodonite is less likely, because rhodonite occurs almost exclusively in very thin veinlets, which volumetrically are minor in comparison with the formations, such as the middle manganiferous unit of the Maple-Hovey deposit.

The high content of acid-soluble manganese in the lower manganiferous unit of the Maple-Hovey deposit suggests that spessartite is totally absent and that the bulk of the manganese is in the form of carbonate. This does not imply, however, that the acid-soluble manganese is contained exclusively as carbonate, because the

TABLE 26.—*Percentages of acid-soluble manganese in the Southern Hovey deposit*

[Compiled from Eilertsen, 1952, table 2, p. 52, and table 6, p. 118]

A. SEQUENCE OF ROCKS CONTAINING IRONSTONES

Diamond-drill holes

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
51	11. 20	9. 74	87
55	10. 20	10. 10	99
56 [1] [2]	9. 15	7. 34	80
Arithmetic average	10. 18	----------	89

Trenches

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
72 [3]	10. 64	8. 92	84
77	10. 63	10. 50	99
82 [3]	9. 92	9. 79	99
Arithmetic average	10. 40	----------	94

B. SEQUENCE OF ROCKS CONSISTING OF INTERBEDDED HEMATITIC AND GREEN SLATES

Diamond-drill holes

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
51 [4]	6. 24	5. 84	94
55 [5]	7. 14	7. 08	99
56 [5]	7. 86	7. 40	94
Arithmetic average	7. 08	----------	96

Trenches

	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percentage acid-soluble Mn
72 [5]	7. 92	6. 91	87
82 [5]	8. 37	8. 17	98
Arithmetic average	8. 15	----------	93

[1] Composite of two samples.
[2] Includes some footwall manganiferous siliceous carbonate rock.
[3] Includes the manganiferous footwall hematitic slate sequence.
[4] Represents the manganiferous footwall hematitic slate sequence.
[5] Represents the manganiferous hanging wall hematitic slate sequence.

acid-soluble mineral, braunite, is known to be present in the manganiferous banded hematite interbeds of the lower manganiferous unit. (See pls. 3 and 4.)

The chemical analyses of the Central Hovey deposit indicate that over 95 percent of the manganese is in an acid-soluble form in the upper and middle manganiferous units of this more highly metamorphosed deposit,[15] as compared to an arithmetic average of only 74 percent manganese [16] for comparable units in the Maple-Hovey deposit (table 25). Spessartite has not been observed in the manganiferous rocks of the Central Hovey deposit and the manganese of this deposit is apparently contained chiefly as carbonate. Although the mineralogy adequately explains the high content of acid-soluble manganese, the absence of spessartite is somewhat anomalous, as comparable units in the genetically similar Maple-Hovey deposit evidently contain appreciable amounts of this garnet. It is possible that unique conditions of metamorphism in the Central Hovey deposit not only destroyed braunite, but also resulted in the breakdown of spessartite.

The amounts and distribution of acid-soluble manganese in the Southern Hovey deposit are summarized in table 26. The average amount of acid-soluble manganese in the different units constituting this deposit is greater than the average for the Maple-Hovey deposit, but is more variable in amount along strike than in the Maple-Hovey deposit. The distribution of acid-soluble manganese in the Southern Hovey deposit is intimately related to the amount and distribution of spessartite as in the Maple-Hovey deposit. Spessartite, in addition to being present in lesser amounts than in the Maple-Hovey deposit, is also spotty in distribution within the Southern Hovey deposit.

Acid-soluble manganese in the siliceous carbonate deposits is high as a consequence of both the absence of spessartite and because the manganese of these deposits is almost entirely in carbonate. In the Maple and Hovey Mountains area, analyses usable for calculating acid-soluble manganese are available only from the segment of the northwesternmost lens, *H*, on Hovey Mountain cut by diamond-drill hole 52. (See pl. 2.) This deposit contains 99 percent acid-soluble manganese. The calculated acid-solubility of the siliceous carbonate deposit of Littleton Ridge is listed in table 27 for purposes of comparison.

TABLE 27.—*Percentages of acid-soluble manganese in the Littleton Ridge deposit, southern manganese district, Aroostook County, Maine*

[Compiled from Eilertsen, 1955, table 5, p. 30]

Diamond-drill hole	Total Mn (Fusion method)	Soluble Mn (Acid method)	Percent acid-soluble Mn
62	8. 16	8. 06	99
63	7. 12	7. 12	100
64	5. 71	5. 70	99
65	6. 62	6. 60	99
66	8. 26	8. 20	99
68	6. 82	6. 80	99
Arithmetic average	7. 12	----------	99

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[15] Based on analyses of U.S. Bureau of Mines diamond-drill holes 46 and 48 (Eilertsen, 1952, table 6, p. 118).

[16] This represents the arithmetic average of only the diamond-drill holes in table 25.

ORIGIN OF THE DEPOSITS

The Aroostook deposits are sedimentary iron- and manganese-rich rocks which are believed to have formed in a nearshore marine or brackish environment. There is no evidence that hydrothermal solutions emanating from the igneous rocks in the Aroostook manganese belt have directly formed any of the deposits by replacing favorable beds with iron and manganese. The differences in chemical composition between the upper, middle, and lower manganiferous units of the Maple-Hovey deposit are persistent over the whole deposit. Although the delicate banding of the ironstone (fig. 16) might have been largely preserved even with a considerable amount of replacement of an earlier banded rock, replacement could hardly be expected to operate over as large a vertical and horizontal distance as the Maple-Hovey deposit encompasses with the uniform addition and subtraction of constitutents in the three hematitic units of the deposit. If the Maple-Hovey deposit is unfolded and projected on to a horizontal plane as a lens, it has a minimum diameter of about 5,400 feet. As this diameter only represents the present outlines of the lens up to the edges beveled by erosion after folding, the Maple-Hovey lens apparently was originally more extensive than 5,400 feet. In a deposit this large, some unreplaced residuals of the original host rock should remain.

Possible ways in which the Aroostook deposits may have formed as sediments are (a) direct precipitation either with or without the active participation of organisms or organic matter, and (b) deposition of suspended colloidal particles. Actually, available information on the Aroostook deposits permits only speculation as to the extent of precipitation from true solution or as colloids, but it is tentatively assumed that at least iron, manganese, phosphorus, and calcium oxide were precipitated from true solution. The principles governing the formation of chemical sediments outlined by Krumbein and Garrels (1952) pertain mainly to deposits formed by chemical reactions involving true solutions. An evaluation of the evidence for chemical precipitation is, therefore, of importance before a given sediment can be interpreted in terms of the specific conditions of pH (hydrogen-ion concentration) and Eh (oxidation-reduction potential) they have outlined. As to the possibility of an organic process having formed the Aroostook deposits, a distinction between chemical and biochemical processes is difficult to make. Probably these processes are completely interdependent in most circumstances. For biochemical reactions to take place, such as the precipitation of iron and manganese by bacterial action, it is probably necessary to have a sufficient and constant supply of the metals in sea water in order to support the large population of bacteria necessary to effect an accumulation of significant amounts of the metals through their biological processes.

No one line of evidence at hand is independently significant in supporting the hypothesis that the Aroostook deposits formed from true solution rather than from colloidal suspension, although on the whole the evidence available seems more readily to support the hypothesis of true solution. For example, the absence of unusual concentrations of metals and metalloids in the Aroostook deposits, which reportedly are present in marine sedimentary iron and manganese deposits elsewhere (described earlier), suggests true solution. Had the Aroostook deposits, particularly the hematitic varieties, formed from the deposition of colloidal particles, the relatively high manganese and iron content of some of them, such as the middle manganiferous unit of the Maple-Hovey deposit (table 12*B*), should have resulted, through sorption, in relatively high concentrations of metalloids and other constituents. As previously stated these elements are not present in unusually large amounts in the Aroostock deposits.

Furthermore, if the Aroostook deposits formed as impure chemical sediments from colloidal suspensions rather than from true solution, chemical scavenging of certain ions from solution should be reflected in the deposits, in proportion to their iron and manganese tenor. For example, Goldberg (1954, figs. 1, 3–6 and p. 249, 253, 255–256) found that, "In the ferruginous sediments of the Pacific Ocean, iron oxides are accompanied by titanium, cobalt, and zirconium in amounts proportional to the iron content. Similarly, copper and nickel are linearly related to the manganese content." The middle manganiferous unit of the Maple-Hovey deposit has almost double the amount of manganese and twice to one and a half times as much iron as the upper and lower manganiferous units. (See table 12.) On the basis of Goldberg's data, it would be expectable to note a linear relation between titanium, cobalt, zirconium, and copper, and iron-manganese in the Maple-Hovey deposit, if that deposit were of colloidal origin. The distribution of the trace constituents in the three units of the Maple-Hovey deposit, however, is rather uniform. (See table 21.) Thus, the lack of any linear variation of the minor constituents with variations in manganese and iron appears indirectly to suggest an ionic rather than colloidal chemical origin for the Aroostook deposits.

If the waters in the basins of deposition were impoverished in such poisonous elements as molybdenum, selenium, arsenic, and lead at the time of deposition of iron and manganese then these minor elements could not have been concentrated by adsorption. In such case, the absence of significant concentrations of minor elements in the Aroostook deposits would not rule out the possibility of the deposits having been formed from colloidal particles of iron and manganese.

The small concentration of boron and barium in the braunite ovoid from the Dudley deposit may represent both ionic substitution as well as a small amount of sorption. This enrichment in boron and barium could have taken place at the depositional interface between water and sediment or between sediment and entrapped water. Considering the rock as a whole, the amount of enrichment represented by the trace element composition of this ovoid is quantitatively insignificant but it shows that the trace elements were present in the surrounding water and that their absence in the rock as a whole cannot be attributed to their absence from the depositional environment.

Other chemical features of the deposits also suggest that precipitation of the manganese and iron probably was not a result of colloidal or organic reactions. The striking covariance of iron, manganese, CaO, SiO_2, and Al_2O_3 with phosphorus of the deposits on Maple and Hovey Mountains has been demonstrated earlier. This feature is of particular interest because phosphorus in sea water is a strongly pH-dependent constituent (Krumbein and Garrels, 1952, p. 9). Assuming that the phosphorus in the Aroostook deposits is roughly an index of chemical sedimentation related to fluctuations in pH, the systematic variations of such constituents as iron and manganese with pH—phosphorus—(pl. 6*A* and *B*) are more likely to have resulted from ionic rather than colloidal reactions. Less systematic precipitation would be expected to result from flocculation of a dispersed system undergoing Eh-pH changes owing to the inherent variability of charges on colloids.

The inverse relation of the silica- and alumina-phosphorus curves (pl. 6*D* and *E*) as compared to the iron-, manganese-, and CaO-phosphorus curves (pl. 6*A*, *B*, and *C*) also conform with the hypothesis that the deposits formed as impure chemical sediments. These curves indicate a gradual change from a chemical environment to one in which clastic dilution was taking place. Such an interpretation corresponds both to the field relations as well as the nature of the data on which the scatter diagrams were constructed. The rocks that in large part are of detrital origin, such as those in the upper manganiferous unit of the Maple-Hovey deposit, have the least phosphorus and the most Al_2O_3 and SiO_2. The detrital nature of at least the quartz in such rocks is shown by its roundness under the microscope.

The scatter diagram of manganese with respect to total manganese and iron (pl. 7) also reflects the effects of detrital dilution. This diagram was constructed from the coupled assays of manganese and iron in diamond-drill core (Eilertsen, 1952, table 5) from the Maple-Hovey deposit exclusive of analyses of magnetite-bearing rocks. Separate regression lines have been calculated for the analyses from the three units. Each of these regression lines has a high correlation coefficient. (See explanation, pl. 7.)

If all the points in plate 7 are considered together it is apparent that the analyses converge from a region of great scatter near the higher values of total manganese and iron to a very limited scatter near the low values of total manganese and iron. The region of high scatter in plate 7 is almost entirely defined by the manganiferous banded hematite ironstone of the middle manganiferous unit, which originally probably formed as slightly impure chemical sediments, whereas the detrital rocks, such as the red, purple, and green slate of the upper manganiferous unit, define the part of the diagram with the least scatter. As the chemical sediments (manganiferous banded hematite ironstones) formed from solutions with many constituents, the precipitation of these constituents (chiefly as admixed oxides, carbonates, and phosphate) undoubtedly varied considerably in quantitative proportion between individual layers due to differences in such factors as concentration, Eh or pH, and rates of reaction at the time each layer was formed. The manganese: phosphorus diagram (pl. 6*B*) shows the greatest variability among the individual ironstone analyses of all the phosphorus scatter diagrams (pl. 6). This suggests that of the constituents graphed, manganese was most susceptible to wide fluctuations in its quantitative precipitation from layer to layer. As conditions of sedimentation at the time the Maple-Hovey lens was formed changed from chemical to detrital, the range in chemical composition of the sediments was less susceptible to the fluctuations inherent in chemical processes and was governed more rigorously by the more constant factors of a detrital environment. The rocks formed under a detrital regimen have a smaller scatter of chemical constituents, therefore, than strictly chemical sediments. Hence, the scatter diagram (plate 7) reflects probable detrital dilution in going from the chemical end members (high scatter–high total manganese plus iron) to the detrital rocks (low scatter–low total manganese plus iron).

The weight of evidence, therefore, although not conclusive, suggests that the iron and manganese were contributed to the Aroostook deposits from true solution. The following discussions will be based on the assumption that the Aroostook deposits formed from ionic reactions in true solution, with colloidal reactions probably being minor factors, particularly insofar as the accumulation of manganese, iron, phosphorus, and calcium oxide is concerned.

SOURCE OF METALS AND SITES OF DEPOSITION

Although it is generally agreed that the iron and manganese in the Aroostook deposits are syngenetic and the deposits are of sedimentary origin (White, 1943, p. 142; Miller, 1947, p. 33) there is some question as to the physical conditions under which the deposits formed as well as to the ultimate source of the iron and manganese. White (1943, p. 142–143) thought that the lithologic features and stratigraphic relations of the Aroostook deposits suggested a shallow marine geosynclinal environment of deposition greatly removed from the shore. Miller (1947, p. 35), evidently felt that the deposits could have been laid down in either seas or lagoons.

There is actually no direct evidence to support either a nearshore or offshore environment for the deposition of the Aroostook deposits. Nearshore basins with restricted circulation are believed to offer the most adequate environment, however, to achieve the balance between the factors needed—such as Eh, pH, and the transportation and concentration of the metals in true solution—to produce chemical sediments. Barred lagoons or estuaries distributed along a shoreline are therefore favored as the sites of deposition of the Aroostook deposits. Such basins may have included a sill on the seaward side which restricted ingress of marine waters into the basins, and one or more clastic traps on the landward side to limit the amount of detritus that entered them. Streams emptying into these basins could have supplied the iron and manganese in true solution, and at the same time kept the lagoonal or estuary waters sufficiently fresh, or possibly brackish (Castaño and Garrels, 1950, p. 767) and prevented the precipitation of the iron and manganese at or close to the mouth of the rivers, as would normally happen if the rivers emptied directly into the sea.

In addition, the basins were shallow enough to come within the zone of effective wave action. The oolitic habit of some of the braunite-rich pellets of the Dudley deposit in the northern manganese district probably resulted from the pellets being gently rolled about on the basin floor. Miller (1947, p. 34), has also found ripple marks in parts of this deposit. As the total thickness of any of the Aroostook deposits is less than 200 feet it is not probable that any of the basins they formed in were excessively deep at any time. This presupposes that the basin floors were free of marked vertical oscillations and that eustatic changes in sea level were negligible.

The iron and manganese of the Aroostook deposits probably were derived through terrestrial weathering of a volcanic terrane where, through the chemical breakdown of iron- and manganese-bearing minerals, the metals were taken into true solution by streams, possibly as bicarbonate, and transported to nearshore basins of sedimentation. Some of the greenstone of the Maple and Hovey Mountains area contain as much as 0.26 and 0.33 percent MnO and abundant iron oxide. (See table 5.) Weathered rock of this type readily could have supplied the iron and manganese to the streams tributary to the Aroostook depositional basins. Streams capable of transporting, in true solution, salts of iron (Huber and Garrels, 1953, p. 354–355) and manganese (Savage, 1936, p. 289–290) have a relatively low pH. Furthermore, for a well-aerated stream to carry the minimum reasonable concentration of iron in true solution in order to form a sedimentary iron deposit (5×10^{-5} mols per liter), it is necessary for the water to have distinctly acid characteristics (pH 5 or 6) (Huber and Garrels, 1953 p. 354). The amount of iron in true solution would be appreciably greater if the stream waters were reducing.

Volcanic activity has been proposed as the ultimate source of the iron and manganese for the closely related deposits near Woodstock, New Brunswick (Caley, 1936, p. 19), as well as for the Aroostook deposits (Trefethen, 1943, p. 28–29). Thick lava flows and ash beds have been reported from the Silurian and Ordovician in New Brunswick and eastern Quebec, respectively, and in southeastern Maine. Volcanic rocks are also present in the post-Lower Ordovician sequence of the Maple and Hovey Mountains area. It is evident, therefore, that volcanism was going on for at least part of the time when the Aroostook manganese- and iron-rich deposits were forming, even though some of the centers of volcanic activity were apparently quite far from the sites of iron and manganese accumulation. Direct contributions of metals through volcanism, however are considered to be a less likely source for the metals, because with the exception of thin volcanic ash beds in the Dudley deposit of the northern manganese district (Miller, 1947, p. 33) and in several of the deposits on Maple and Hovey Mountains volcanic rocks are nowhere known to be in direct association nor in similar stratigraphic position with the manganese deposits of either Aroostook County or those in New Brunswick. Although volcanism may not have directly contributed the metals to the Aroostook deposits, it may possibly have affected the pH of the sea water in the restricted basins of chemical sedimentation as well as the water of the streams emptying into such basins, by locally contributing large amounts of CO_2 gas to the atmosphere and thus upsetting the CO_2 equilibrium between atmosphere and surface water. In order for equilibrium to have been achieved again between the partial pressures of CO_2 in water and atmosphere, the water would have had to take up some of the volcanically generated CO_2, thus causing an increase in the hydrogen-ion concentration of the water. However, volcanism, being of a sporadic nature, probably was a minor factor in governing the pH characteristics of terrestrial and sea waters through CO_2 exhalations into the atmosphere during the epochs in which the Aroostook deposits formed.

Certain chemical features of the Aroostook deposits which will be described later, strongly suggest that the waters of the depositional basins probably were acid, or at most, very midly alkaline, throughout much of the time in which the deposits of Maple and Hovey Mountains were being laid down. The acidity of the basin waters must have resulted from the low pH of the tributaries debouching into them, irrespective of the conditions leading to the acidity of such stream waters. In order for the basin waters to have maintained the low pH induced by their feeder tributaries for any appreciable time, they must have had restricted circulation. These conditions seem to be best fulfilled where a generally unidirectional flow of water from the basins out to the sea occurs without considerable return inflow of marine waters. Such a restricted circulation could be set up and maintained in basins or estuaries bounded by a low sill or bar on the seaward side. The water of the basins, being fresher and consequently lighter than normal marine sea water, would float on the marine water as it spilled over the low bar into the open sea. If, however, the lighter waters spilling into the open sea reached buoyant equilibrium at a depth somewhat greater than the depth of the barrier sill, they would act as a seal, preventing the unrestricted inflow and mixing of marine waters with the basin waters (Fleming and Revelle, 1939, p. 97).

The absence of coarse clastic material in the Aroostook deposits may reflect an additional structural feature of the basins of deposition, or more probably, the physiographic condition of the landmass drained by the streams or rivers that emptied into the basins. For example, a clastic trap (Huber and Garrels, 1953, p. 356) may have existed between the mouths of the feeder streams and the part of the basin where chemical sedimentation took place. A small barrier bar or sill close to the mouth of the debouching streams could have decreased the velocity sufficiently so that the incoming waters were largely cleansed of their detritus. Actually, however, because waters carrying large amounts of dissolved salts probably drained low-lying landmasses, the clastic load of such streams probably always was small (Guild, 1953, p. 654–655). The absence of coarse clastic lenses close to and at the same stratigraphic level as the Aroostook deposits and the absence of appreciable coarse detritus within them suggests such a low-lying landmass at the time they were accumulating as sediments. Clastic traps, therefore, may have controlled only the amount of fine detritus that entered the basins of deposition and thereby the extent of detrital dilution of the chemical sediments.

PHYSICOCHEMICAL CONDITIONS OF DEPOSITION

The abundance of phosphorus as sedimentary cryptocrystalline apatite (includes collophanite of White, 1943, p. 134, and Miller, 1947, p. 23), and the absence of sedimentary calcite in most of the Aroostook deposits are the best clues for an acid or mildly alkaline depositional environment. (The calcic carbonate associated with the deposits of Maple and Hovey Mountains is found only in veinlets and not in sedimentary laminae. Most of the material examined from the northern and southern manganese districts also has this distribution of calcic carbonate. The sedimentary carbonate in the Aroostook deposits is generally close to ferroan rhodochrosite or manganoan siderite in composition.)

The absence or dearth of syngenetic sedimentary calcite and the relative abundance of calcium phosphate in the Aroostook deposits are significant as indicators of relative pH conditions in the waters of the basins of sedimentation. Krumbein and Garrels (1952, p. 9) point out that the controls governing phosphate deposition in a marine environment are strikingly similar to those for calcium carbonate; namely, both of these constituents are pH dependent, they are soluble in acid solutions, their solubility decreases with increasing alkalinity, and "both the carbonate ion and phosphate ion are in equilibrium with the same calcium ion in sea water." Furthermore, the solubility-pH curves of calcium phosphate and calcium carbonate are nearly parallel but the absolute solubility of calcium phosphate is much lower than that of calcite so that a

> pH increase of sea water saturated with both compounds will result in a sediment composed almost entirely of calcite and with only a trace of phosphorite.
>
> A sediment high in calcium phosphate and low in calcium carbonate can be formed only where conditions permit the continuous removal of calcium as the phosphate and in which the activity product of the carbonate is not exceeded. This might well occur in a restricted basin with a relatively low pH (7.0–7.5). In this environment calcium carbonate would not be expected to form. The carbonate ion remains low and constant because of its dependence on pH and the CO_2 partial pressure in the atmosphere. On the other hand, the phosphate ion might well be supplied as 'soluble phosphate' in association with sodium or other cation, and the phosphate-ion concentration could easily become sufficient to precipitate phosphorite, for it has no upper limit determined by formation of a gas phase, as does carbonate. (Krumbein and Garrels, 1952, p. 9).

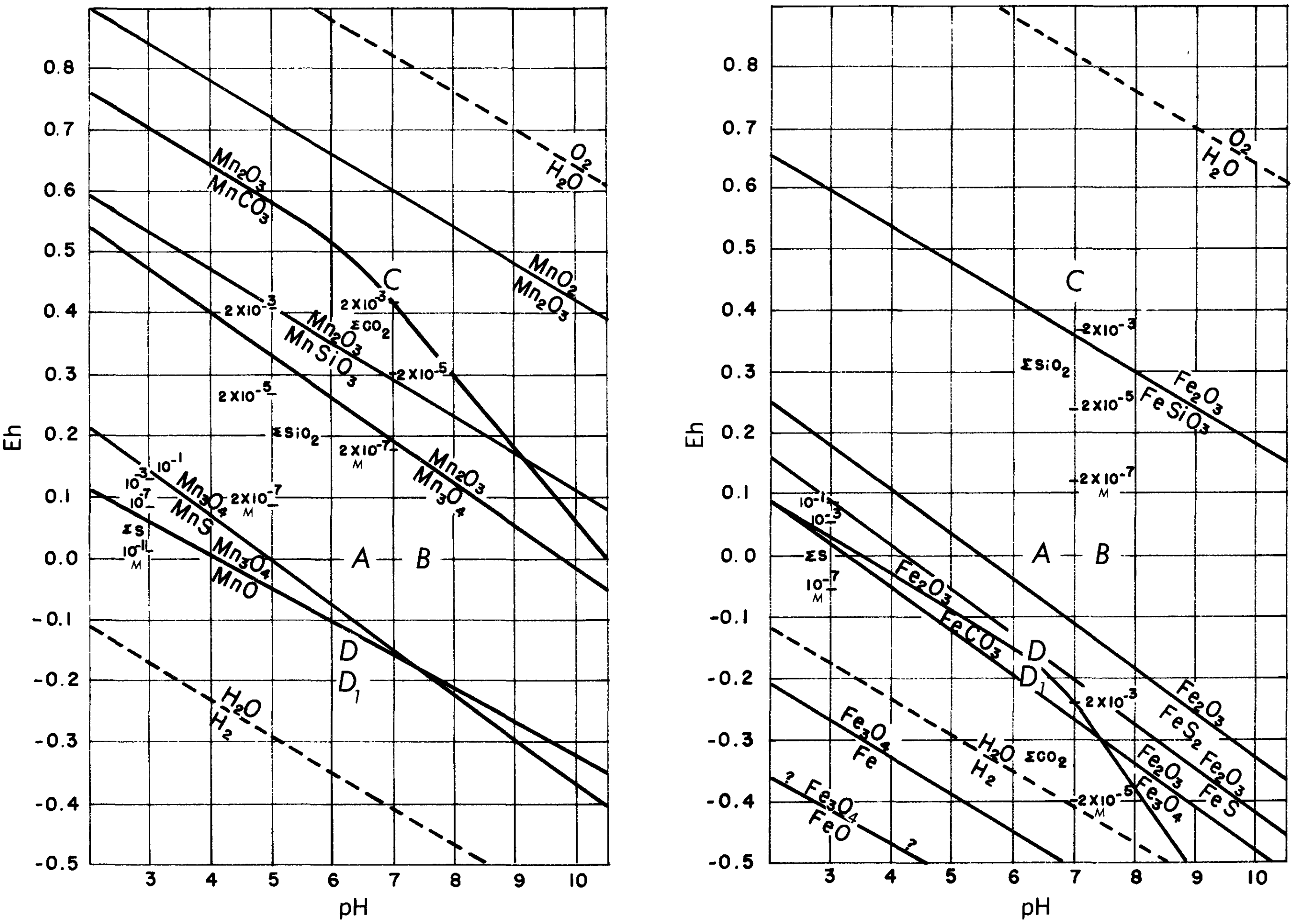
The physicochemical conditions for phosphate precipitation outlined above appear, in general, to offer an adequate explanation for the occurrence of apatite and absence of calcite as sedimentary constituents in the Aroostook deposits. The antipathetic relation of calcite and apatite seems clearly to place the pH environment under which most of the manganese- and iron-bearing rocks of the Aroostook deposits formed on the acid side of the limestone fence (Krumbein and Garrels, 1952, fig. 8, p. 26), namely, at a pH less than 7.8.

Stability field diagrams for oxides, carbonates, and sulfides of iron and manganese have been developed by many investigators in recent years (Krumbein and Garrels, 1952; Huber and Garrels, 1953; Moussard, [and others], 1954; Huber, 1956; Marchandise, 1956; and Krauskopf, 1957). Krauskopf's Eh–pH diagrams for anhydrous manganese and iron compounds with some modifications are shown in figure 37. These diagrams outline "only the maximum extent of the stability fields under natural conditions and [show] alternative precipitates that may form in response to various anion concentrations" (Krauskopf, 1957, p. 68). The published diagrams of the other investigators differ from those of Krauskopf in that "they show the particular compounds that would exist at equilibrium under specific conditions of Eh, pH, and concentrations of various anions."

The lines on the Eh–pH diagrams of figure 37 "are drawn for (a) total carbonate$=CO_2+HCO_3^-+CO_3^{--}=0.002M$ (equilibrium with atmospheric CO_2 at pH 8), (b) total sulfur$=H_2S+HS^-+S^{--}+SO_4^{--}=0.1M$, and (c) total silica=chiefly $H_4SiO_4=0.002M$ (amount soluble at 25°). Amounts by which these lines would be shifted by a decrease in concentration are indicated by the vertical lines with crossbars" (Krauskopf, 1957, p. 63). The calculations necessary to construct Eh–pH diagrams will not be discussed here. Krauskopf (1957, p. 80–82) briefly summarizes the primary calculations for the diagrams in figure 37, and the general principles of constructing Eh–pH diagrams are discussed and described by Krumbein and Garrels (1952). Of all the lines of the two diagrams in figure 37, the FeS_2 boundary of the iron diagram is the least certain (Krauskopf, 1957, p. 82).

Eh–pH diagrams have certain inherent shortcomings—for example, the rates of reaction cannot be evaluated from them—and cannot be used to strictly define the precise conditions under which observable mineral assemblages formed. Nonetheless, the diagrams in figure 37 provide a useful framework in attempting to visualize the general physiochemical conditions under which the Aroostook manganese- and iron-bearing sediments formed.

The following discussion is based on the assumption that the Aroostook deposits formed mostly on the acid side of the limestone fence, namely the pH of the basin waters was less than 7.8. Furthermore, it seems reasonable from the information available from present-day restricted basins of circulation that the waters of natural basins normally do not have a pH of less than 6. Arbitrarily accepting a pH of 6 as the limit of acidity in the Aroostook basins, the range of pH at the time the sediments were deposited is therefore assumed to have been between the narrow limits of 6 and 7.5. Because silica in natural waters is mostly in true solution and as the equilibrium solubility of such silica is not appreciably affected by pH up to values of 9, and even fairly concentrated solutions of silica are stable "in contact with the electrolytes of sea water" (Krauskopf, 1956, p. 15–21), the possible formation of silicate minerals as shown in figure 37 are also excluded from the discussion because of the limits of pH used. Within these limiting conditions the trends of the chemical reactions in the aqueous solutions (basin waters) in which the different lithologic facies in the



A. Manganese B. Iron

FIGURE 37.—Eh–pH diagrams for anhydrous manganese (*A*) and iron (*B*) compounds. Solid lines are boundaries of stability fields; each line separates the field of an oxidized form (above) from that of a reduced form (below). Crossbars on vertical lines show positions of field boundaries at lower concentrations of carbonate, sulfide and silica. Dashed lines are limits of possible oxidation-reduction potentials in water solution. Question marks along Fe_3O_4–FeO boundary indicate that under these conditions FeO is unstable with respect to Fe and Fe_3O_4. *A*—D_1 are explained in the text. Modified from Krauskopf (1957).

deposits of Maple and Hovey Mountains formed can be evaluated by a comparison of the mineralogy of such lithologic facies with figure 37.

OXIDE-CARBONATE FACIES

Manganiferous banded hematite ironstone is typically composed of irregularly interlayered laminae that contain as their chief constituents, (a) hematite or ferroan rhodochrosite, (b) mixtures of hematite and ferroan rhodochrosite, and (c) braunite or ferroan rhodochrosite. There are no free primary manganese oxides in these rocks. The manganese oxide, which forms a black film on rocks near the surface (described later) is formed through weathering and is not related to the problem of the origin of the rocks as impure chemical sediments. The Mn_2O_3 of the braunite in the banded hematite ironstone probably represents, however, an original oxide of manganese of a higher valence state than manganous oxide (MnO). Such a higher valent manganese oxide, which could have been either in the trivalent or quadrivalent state when originally formed, eventually could have become fixed as braunite ($3Mn_2O_3 \cdot MnSiO_3$) through chemical reaction with SiO_2 admixed in the muds. The chemical field in which an aqueous solution saturated with iron, manganese, and phosphorous could have precipated relatively pure as well as mixed manganese and iron oxide- and carbonate-bearing compounds must occupy a position in the area above the pyrite field in figure 37 (because sulfides are not present in the manganiferous banded hematite ironstone) and lie to the left of pH 7.8 (limestone fence) for reasons stated earlier. For example, if *A* in figure 37 represents a saturated solution in such a basin and precipitation takes place through addition of excess metal ions or through slight alkalinization of the basin waters (solution environment becomes, that at *B*) hematite (Fe_2O_3) and rhodochrosite ($MnCO_3$) would normally form as the stable solid phases in equilibrium with the basin waters. (Mild alkalinization of the relatively neutral or acid basin waters could occur periodically by mixing of small amounts of marine (alkaline) waters through inflow across the sill into the barred basin or estuary.) Precipitation under conditions at *A* or *B* could readily account for the mixed hematite and manganese carbonate layers of such rocks as the banded hematite ironstone of the middle manganiferous unit of the Maple-Hovey deposit. The layers composed dominantly of hematite in such rocks may have formed at times when the Mn^{++} concentration was relatively small and little or no $MnCO_3$ was being deposited. In similar manner, manganiferous carbonate layers relatively free of Fe_2O_3 could have been deposited when the basin waters became locally undersaturated with Fe^{++}.

The chemical precipitation of trivalent or tetravalent manganese oxides or both, as suggested by the braunite-bearing laminae described earlier, could not have occurred under the same physicochemical conditions as those described for the manganese carbonate-hematite layers. It is clear from a consideration of figure 37 that such oxides of manganese could form only if the basin waters were highly oxidizing.

The difference in oxidation potential necessary to form ferric oxide as compared to higher valent manganese oxides is considerable. Mason's (1949) observations on the alteration of certain phosphate minerals containing both iron and manganese is particularly instructive. He (Mason, 1949, p. 68) noted that these

> minerals show a stepwise alteration, characterized by the complete oxidation of the iron to the trivalent state before the divalent manganese is affected. This alteration gives rise to a number of mineral species * * * containing divalent manganese and trivalent iron. The oxidation potential required to convert ferrous to ferric iron is so much lower than that required to convert divalent manganese to the trivalent or tetravalent state that the oxidation of the ferrous iron proceeds to completion before the manganese is affected.

Table 28 lists the partial chemical analyses of two samples of braunite-rich layers and one sample of a hematitic layer from banded hematitic ironstone of the Maple-Hovey deposit. The manganese in the braunite-rich layers is reported as MnO because of the analytical procedure used. However, much of the manganese in these layers must necessarily be present as Mn_2O_3, owing to the chemical composition of braunite ($3\ Mn_2O_3 \cdot MnSiO_3$). X-ray examination of the samples listed in table 28 indicates that the braunite-rich laminae (DDH 41–10 and DDH 41–24) also contain feldspar, rhodochrosite, and a small amount of unidentified material. Apparently braunite makes up approximately 50 percent of the minerals in these laminae. (See fig. 20.) On the other hand, the hematitic lamina contains chiefly hematite and only small amounts of unidentified minerals (X-ray examination). In order to achieve the marked concentration and effective separation of manganic oxides from iron oxide in the braunite-rich laminae of table 28 under a limiting range of pH (6–7.8), it was evidently necessary therefore for a solution at *A* in figure 37 to undergo changes in oxidation potential so as to attain an oxidizing environment as at *C* or even higher. Thus, with an increase in Eh from *A* towards *C* a solution saturated with iron, manganese, and phosphorous would precipitate manganese-carbonate, hematite, and apatite; most of the iron in solution probably would have been precipitated as Fe_2O_3 before the $MnCO_3$–Mn_2O_3 boundary was crossed. Above this boundary, therefore, the basin waters would be nearly free of Fe^{++} and Mn_2O_3 would precipitate in lieu of $MnCO_3$. Possibly even MnO_2 might have formed above this boundary, especially if manganese-precipitating bacteria were present. Any MnO_2 present would have acted as a very effective catalyst to accelerate the rate of precipitation of additional manganese oxides (Zappfe, 1931). Possibly a lamina such as DDH 41–21 in table 28 formed when the prevailing Eh was in the hematite field of figure 37, but below the manganese oxide fields. The laminae represented by analyses DDH 41–10 and DDH41–24 undoubtedly formed under oxidizing conditions above the $MnCO_3$–Mn_2O_3 interface of figure

TABLE 28.—*Partial chemical analyses of braunite-rich and hematite-rich laminae from the Maple-Hovey deposit*

[Rapid-method analysis by Leonard Shapiro]

	Braunite-rich laminae		Hematite-rich laminae
	DDH 41-10	DDH 41-24	DDH 41-21
SiO_2	27.1	21.7	14.1
MnO	44.5	45.6	4.0
Fe_2O_3	3.6	3.4	72.7

37. The final oxidation state of the manganese oxides in the trivalent state (braunite) probably is the result of the diagenetic and metamorphic processes to which the manganese oxide-bearing layers were subjected after having been deposited as muds. It is not certain, therefore, from the present mineralogy of the rocks just what higher oxides of manganese were originally precipitated. Nonetheless, the precipitation of manganese oxides higher than the bivalent state must have taken place only under relatively high Eh conditions. Such a condition could have prevailed when the basin was very shallow and became highly aerated, or when highly oxygenated stream waters poured into it and raised the overall Eh of the basin, or as a result of a combination of both. Oxygen contributed photosynthetically from marine plants could also have been important.

CARBONATE-IRON SULFIDE FACIES

The magnetite-free siliceous carbonate rocks of the deposits on Maple and Hovey Mountains as described in an earlier part of this report are composed of irregularly interbedded thin layers and laminae which may be either rich in carbonate (approximately ferroan rhodochrosite or manganoan siderite) or chlorite (fig. 27), or else contain mixtures of these minerals (fig. 28). Pyrite is present either as an accessory or occurs in distinct laminae (fig. 29). Apatite is also an important constituent. The sedimentary carbonate of the siliceous carbonate rocks of the northern district, however, is described as a manganese- and iron-bearing calcic variety by White (1943, p. 136). This identification rests on bead tests for iron and manganese and the effervescence of the carbonate when treated by warm hydrochloric acid. Such reactions could as easily result from carbonate close to ferroan rhodochrosite or manganoan siderite. Nevertheless, if calcic rather than rhodochrositic or manganoan sideritic carbonate is actually dominant in the siliceous carbonate rocks of the northern manganese district, it probably indicates a more alkaline environment of deposition than the one that presumably prevailed in the basins of sedimentation in which the manganiferous lenses on Maple and Hovey Mountains formed.

The general Eh–pH conditions under which the various lithologic facies of siliceous carbonate rocks formed is also deducible from figure 37. If a solution at A were brought into an Eh–pH evnironment as at D the iron mineral that would form is pyrite, especially if anaerobic bacteria were present. Sideritic carbonate would form if the total sulfur of the system fell below the siderite interface as at D. Thus, within a very limited range of Eh fluctuation, either sideritic layers or pyritic layers would form (see fig. 29), as the total sulfur content of the system varied with respect to the total CO_3 content. Apatite would also form in both the carbonate and pyrite facies (fig. 30) and calcite would not be precipitated for reasons outlined above.

Manganese carbonate would also precipitate out at D along with pyrite. On the basis of the general similarity between the manganese and iron stability diagrams, one would assume that the manganese sulfide, alabandite (MnS), would have formed with pyrite or sideritic carbonate in some of the manganiferous siliceous carbonate rocks of Aroostook County. However, alabandite has not been identified in any of the sulfide-rich laminae of the Aroostook manganiferous rocks; apparently the manganese of such rocks is almost entirely contained in carbonate. The absence of alabandite even when the sedimentary environment was at D_1 undoubtedly is attributable to the relative concentrations of total CO_3 and sulfur in the system.

A cycle of fluctuation such as $D \rightleftharpoons D_1$ therefore could account for the pyrite and manganese- and iron-carbonate interlayers as in figure 29. Undoubtedly, the stability field boundaries in figure 37 are probably gradational rather than sharp, so that reactions also take place in the transition zone between the fields. Chemical reactions along the transition zone between the FeS_2 and $FeCO_3$ boundary probably formed the layers of mixed pyrite and carbonate commonly present in the pyritic siliceous carbonate rocks of the Maple-Hovey deposit.

MAGNETITE-BEARING ROCKS

Recent studies of iron deposits such as those in the Lake Superior region (James, 1954, p. 261–263; White, 1954, p. 38–40) and at Singhbhum, India (Spencer and Percival, 1952, p. 378), have refocused attention on the probable primary nature of magnetite in some of the sedimentary iron-formations of the world. In the ferruginous manganese deposits of Aroostook County, however, magnetite is believed to have been formed by metamorphism.

The localization and distribution of magnetite in some of the deposits on Maple and Hovey Mountains clearly demonstrates that magnetite is of metamorphic origin here. Magnetite-bearing rocks in the Maple-Hovey and Southern Hovey deposits, for example, commonly are found at or near the axial planes of folds or are in very tight folds. (See pl. 2.) At such places the magnetite occurs in layers that correspond to original bedding. The layered magnetite-bearing rocks do not, however, have stratigraphic continuity even over relatively short distances; in fact, the magnetite-bearing zones apparently cut across lithologic boundaries. The geologic sections through drill-holes 31, 26 and 32, and 35 and 42 (see pl. 2[17]) illustrate the typical manner in which magnetite occurs in the Maple-Hovey deposit. In the drill core of these holes, magnetite-bearing rocks clearly occur at different stratigraphic positions in different parts of the Maple-Hovey deposit. The section through drill-holes 35 and 42 also illustrates that magnetite-bearing rocks are not stratigraphically localized even over such very short distances as a few hundred feet. For example, in hole 35 magnetite-bearing rocks are present at two places; one zone is in the middle manganiferous unit and the other, thicker zone, includes part of the rocks near the base of the middle manganiferous unit and all the lower manganiferous unit. These magnetite-bearing rock zones are either absent or do not correspond stratigraphically with magnetite-bearing rock zones in the drill core of hole 42, which only are about 150 feet up the dip from those in hole 35. (See pl. 2.) A similar lack of stratigraphic continuity between magnetite-bearing rocks in close proximity is indicated by the section through drill-holes 26 and 32. Magnetite-bearing rocks are present in a thick zone within the middle manganiferous unit in hole 32, but magnetite-bearing rocks are absent in hole 26. (See pl. 2.)

In surface exposures, the characteristic abrupt change along strike from magnetite-bearing to magnetite-free ironstone is apparent in fold ④ on Maple Mountain. (See pl. 2.) Magnetite is abundant along the axial plane of this anticline, particularly in the middle and lower manganiferous units of the deposit as exposed in trench 19, but is absent in all of the manganiferous units on the northwest limb of the anticline as exposed in trench 1A, about 250 feet along strike from trench 19.

The above examples only deal with the probable metamorphic origin of magnetite in hematitic-facies rocks. Similar evidence indicates that the magnetite in the carbonate-facies rocks also formed by metamorphism rather than as a primary sedimentary or diagenetic mineral.

Among the conditions probably necessary to form sedimentary magnetite in iron-formation are "* * * low O_2 and CO_2 atmospheric pressures at the time of deposition * * *" (James, 1954, p. 258). Although the Aroostook deposits were formed under the fluctuating oxidation-reductions conditions necessary to the formation of magnetite, namely, "* * * mildly oxidizing to mildly reducing * * *" (James, 1954, p. 273), the necessary pH conditions of alkalinity (low atmospheric CO_2 pressure) were never attained because, judging from their apatite-calcite ratios, the Aroostook deposits formed in more or less neutral environments. In terms of figure 37*B* therefore, the basins of sedimentation in Aroostook County never attained the Eh-pH environment of the magnetite field, which appears on the lower right corner of the diagram.

DEPOSITIONAL HISTORY OF THE DEPOSITS

The deductions pertaining to the history of the basins in which the Aroostook deposits formed must be almost entirely guided by the lithology, mineralogy and petrography, and chemical composition of the rocks formed in them. The regional geology of the Aroostook manganese belt is at present only imperfectly known and any discussion of tectonic factors that may have controlled the physicochemical environment is for the most part speculation.

OXIDE-FACIES (HEMATITIC) DEPOSITS

The Maple-Hovey and Southern Hovey deposits probably furnish a good example of the sequence of events that occurred during the development of such hematitic manganese deposits. The following discussion will be confined mostly to the Maple-Hovey deposit which is considered typical of the oxide facies (hematitic) in the Aroostook manganese province. The salient stratigraphic and lithologic features upon which the interpretation of the depositional history of the Maple-Hovey deposit is based are summarized in plate 4*A*. Plate 4*B* shows a closely similar columnar section of the Southern Hovey deposit.

The Maple-Hovey deposit is underlain by green slate of detrital origin containing small amounts of pyrite. This pyrite, even though minor, suggests reducing conditions preceding the chemical deposition of significant quantities of iron and manganese. The green slate grades upward into a sequence of pyritic siliceous carbonate rock indicating that with exclusion or restriction in the amounts of argillaceous debris conditions became favorable for chemical sedimentation. This is believed to have resulted from the development of a restricted lagoon. Occasional shiftings of the river channels tributary to the basin of deposition could

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[17] The collar of drill-hole 31 is near 34,850 N., 17,000 E.; the collar of drill-holes 26 and 32 is near 33,350 N., 16,700 E.; and the collars of drill-holes 35 and 42 are centered respectively near 33,540 N., 16,210 E., and 33,330 N., 16,160 E.

have isolated the basin from receiving fresh, oxygenated waters and allowed stagnation to set in periodically. The abundant pyrite in these siliceous carbonate rocks clearly suggests that the depositional environment was strongly reducing and, as judged by the apatite-calcite ratio, was probably less than 7.8.

Immediately above the siliceous carbonate rocks of the Maple-Hovey deposit is the lower manganiferous unit of the deposit; it consists mostly of thin hematitic layers intercalated with layers of green slate, laminae of siliceous carbonate, and with some beds of banded hematite. (Compare with the Southern Hovey deposit, pl. 4*B*.) Probable fluctuation of Eh such as $A \rightleftharpoons D$ in figure 37 resulted in deposition of interlayered siliceous carbonate and hematitic shale in this unit. The interlayers of banded hematite (see pls. 3 and 4*A*) probably represent more highly oxidizing conditions of limited duration in the time interval represented by the lower manganiferous unit. The interbeds of green slate may be the result of periodic changes in sedimentation during this epoch, from essentially chemical precipitation to the deposition of fine clastic material. Such detrital incursions may have resulted from storms that so increased the volume, velocity, and loads of streams pouring into a clastic trap as to destroy the efficacy of the trap. Large amounts of mud and silt could have entered the basin of deposition at such times and by detrital dilution temporarily prevented the deposition of iron- and manganese-rich rocks. It was during a clastic phase of deposition that the graptolite found within this unit (p. 23) was buried in a layer of green slate; the graptolite has been preserved by pyritization.

The middle manganiferous unit of the Maple-Hovey deposit is believed to represent fairly stable conditions of chemical sedimentation with minor detrital dilution—low SiO_2 and Al_2O_3 in banded ironstone (see table 8*A*)—and only minor incursions of clastic material as represented by the few slate beds intercalated within this unit (see pls. 3 and 4A). The waters of the basin probably attained their highest oxidation state at this time, especially while manganese oxides (braunite-bearing layers) were being deposited. The level of oxidation dropped for the periodic deposition of manganese carbonates and hematite, as described above. The rather high oxidizing condition prevailing during the time of the formation of the middle manganiferous unit is reflected in its low sulfur content (compare table 12*B* with table 12*C*), as well as that of some of its constituent rocks (see table 8*A*). Pyrite has not been found in these rocks. If the absence of pyritic layers is a reliable indicator of a constant supply of fresh terrestrial water, then the tributary drainage probably had also been stabilized by the time the middle unit was being deposited.

The generally high oxidizing conditions, which characterized the epoch during which the middle manganiferous unit formed, prevailed into the time represented by the lower part of the upper manganiferous unit of the Maple-Hovey deposit. The contact between the middle and upper manganiferous units is gradational. The upward changes in the upper unit from banded hematite ironstone to mainly red and purple slate intercalated with green slate and some hematitic layers in its upper portion (see pls. 3 and 4*A*) indicate a change from relatively acid and oxidizing conditions of (impure) chemical sedimentation to conditions of clastic sedimentation. The red slate, and to some extent the purple slate, probably represent mixtures of small amounts of chemically precipitated iron and manganese and large amounts of clastic material. The lower phosphorus content of the red and purple slate (see tables 12*A* and 18), compared to the banded ironstone (tables 8*A* and 12*B*), further suggests a change from chemical to clastic sedimentation.

Eventually, the argillaceous sediments, now represented by the green slate overlying the manganiferous rocks, filled the basins and they ceased to exist as sites of chemical deposition. Thus, the chemical sedimentation regimen of both hematitic (oxide facies) and siliceous carbonate rock (carbonate facies) deposits probably came to a close with the encroachment and final ascendency of detrital sedimentation. This probably happened when the protective clastic traps of the basins became filled and could no longer exclude the fine detritus from entering the basins in large volumes.

The slopes of the regression lines of SiO_2 and Al_2O_3 (pl. 6*D* and *E*) with respect to phosphorus (described earlier) also imply such a change. However, it is not possible to conclusively evaluate how much of the SiO_2 and Al_2O_3 in these bulk analyses was introduced with detrital constituents and what portion may have precipitated chemically. The slope of the regression line of SiO_2 and Al_2O_3 is in the direction opposite to those of iron, manganese, and CaO (compare with pl. 6*A*–*C*). The alumina curve is enigmatic as alumina precipitates at the neutral point but is soluble in very acid or highly alkaline solutions (Rankama and Sahama, 1950, p. 502). Because the solubility of silica is not changed until a pH of about 9 is reached (Krauskopf, 1956, p. 23), and as the deposits on Maple and Hovey Mountains probably formed in relatively neutral or acid environments, the silica curve (pl. 6*D*) may actually represent only detrital SiO_2 (fine-grained quartz and silicate minerals) rather than any chemically precipitated SiO_2.

The fairly regular distribution of MgO in all three manganiferous units of the Maple-Hovey deposit (compare tables 12*A*, *B*, and *C*) suggests that it was being supplied at a constant rate irrespective of physico-chemical conditions, if it was a syngenetic constituent. Changes from a predominantly chemical to a more detrital environment also had little effect on the relative abundance of MgO. Certainly it has no statistically significant variation with respect to phosphorus as have many of the other constituents.

The gray and green sparsely pyritic slate conformably overlying the upper manganiferous unit of the Maple-Hovey deposit is believed to represent the final changes from partly chemical to almost entirely clastic deposition, in a mildly reducing environment, after the restricted basin of iron- and manganese-rich sedimentation was destroyed.

The Southern Hovey deposit and the Dudley deposit (northern manganese district) have the same stratigraphic lithologic features as the Maple-Hovey deposit (see pl. 4*B*) as well as comparable mineralogy and chemical features (compare tables 12 and 14). The stratigraphic section of the Dudley deposit has not been subdivided by Miller (1947, between p. 56 and 57), but it can be subdivided into 3 units with metal tenor and lithology that is fairly comparable with those of the Maple-Hovey and Southern Hovey deposits. The writer has observed this lithology in drill cores from the Dudley deposit, and White (1943, p. 134), has described "a very heavy dark green beds, mostly at the west side of the deposit [stratigraphically lower side], consisting mainly of chlorite and slightly manganiferous carbonate." Thus, the chemical sedimentary history of the three largest hematitic manganese deposits in Aroostook County appears to have followed the same sequence of events as outlined for the Maple-Hovey deposit.

CARBONATE-FACIES DEPOSITS

The depositional history of siliceous carbonate rocks (carbonate facies) has already been largely reviewed in discussing the interval consisting of siliceous carbonate rocks that underlies the Maple-Hovey deposit. The ubiquitous and abundant iron-rich chlorite of the siliceous carbonate deposits may indicate that some of the iron was deposited as silicate. The chlorite now present in the deposits is probably a product of diagenesis and low-grade metamorphism subsequent to deposition. However, its intimate association within laminae of carbonate, and particularly its occurrence in conformable layers composed entirely of chlorite, clearly demonstrates either its primary sedimentary origin or its metamorphic origin from some primary mineral deposited with the carbonates.

METAMORPHISM OF THE DEPOSITS

DIAGENETIC CHANGES

The problem of diagenesis of the Aroostook deposits deserves brief mention before discussion of the metamorphism. Diagenesis is here used, in its broadest sense, to include all the physical and chemical processes leading to lithification. Most geologists exclude these processes from metamorphism. However, a clear-cut distinction between diagenetic and metamorphic products, especially in weakly metamorphosed rocks such as the Aroostook deposits, is generally not possible. Chlorite, for example, forms under low-grade regional metamorphism (Turner, 1948, p. 96), as well as through diagenetic processes (Pettijohn, 1949, p. 245). Feldspar and stilpnomelane are other minerals of similar uncertain origin in the Aroostook deposits. Feldspar can form as an authigenic mineral in argillaceous rocks through processes unrelated to and preceding metamorphism (Gruner and Thiel, 1937). Tyler (1949, p. 1104–1106) favors a metamorphic origin for the stilnomelane in the Lake Superior ores; James suggests (1954, p. 266–267) that it may be metamorphic only in part, and Gruner (1946, p. 12) considers stilpnomelane to be a primary mineral.

Postdepositional changes in the principal iron and manganese compounds of the Aroostook deposits are likewise difficult to appraise. Presumably, the iron and manganese of the hematitic manganese deposits (oxide facies) were precipitated, in part, as oxides. The diagenetic changes during lithification probably included dehydration and molecular rearrangements. In the case of iron, hematite was one of the ultimate products of these processes. Some of the hematite was recrystallized into its present finely crystalline, acicular habit by regional metamorphism. The possible transformations involved in the development of braunite from primary oxides of manganese are even more obscure. As suggested earlier, chemical reactions between manganese oxides and SiO_2 may have formed braunite ($3Mn_2O_3 \cdot MnSiO_3$). Whether the braunite was formed during diagenesis or metamorphism is not clear from its textural relation and associations with other minerals. The poikilitic habit of some of the braunite (see fig. 20) is not critical evidence as this structure could conceivably form during either process.

Except for magnetite, whose metamorphic origin seems certain (see p. 96–97), few of the iron and manganese minerals occurring in primary layers in the Aroostook deposits can be specifically attributed to a metamorphic as opposed to a diagenetic or purely sedimentary origin. The carbonates are undoubtedly syngenetic constituents, but even these may have undergone some chemical change since their precipitation, by reaction with sea water before burial, by reaction with interstitial water after burial, or during metamorphism. Most of the carbonate has undergone textural modification, having recrystallized to some extent during regional metamorphism. This is generally shown in thin section by the well-crystallized rhombic crystals of carbonate embedded in a chloritic mat in the siliceous carbonate rocks.

REGIONAL METAMORPHISM

The rocks of the Aroostook manganese province belong largely to the muscovite-chlorite subfacies of the greenschist metamorphic facies. This mild grade of metamorphism, however, has not equally affected the entire Aroostook manganese belt. In some parts of the northern manganese district, the rocks are virtually unmetomorphosed shale and argillite. The presence of biotite in the Dudley deposit (White, 1943, p. 134) is, therefore, anomalous with respect to the low-rank regional metomorphic grade of the northern manganese district. White (1943, p. 143) has attributed the presence of magnetite and specularite in the deposits of the southern manganese district and their absence in the northern manganese district to regional metamorphism. Such regional metamorphism would normally be expected to affect some of the deposits in the Woodstock, New Brunswick, area, which lies immediately east of the Aroostook southern manganese district. However, the magnetite contained in the New Brunswick iron- and manganese-bearing rocks is evidently restricted to certain parts of the deposits rather than occurring throughout them (Anderson, 1954, p. 7). The localized distribution of magnetite in the Woodstock area resembles in its distribution the magnetite attributed to structurally localized metamorphism in the Maple and Hovey Mountains area. This metamorphism will be described shortly.

Magnetite is present in all the deposits of the Maple and Hovey Mountains area of Aroostook County, Maine, although it is restricted to only small parts of some of the larger deposits.

Spessartite garnet is present in the hematitic manganese deposits of the Maple and Hovey Mountains area but has not yet been observed in the siliceous carbonate deposits. It is an expectable constituent of manganiferous rocks of the muscovite-chlorite zone of metamorphisms, inasmuch as it forms rather readily in the presence of only small amounts of manganese (Harker, 1939, p. 55, 217–218). However, it has not been reported from either the northern or the southern manganese districts of the Aroostook manganese belt. In the northern district, regional metamorphism was probably too mild to form spessartite. It may be present in the southern manganese district, where the metamorphic rank is approximately equal to that of the Maple and Hovey Mountains area, but no detailed petrographic study has been made of the rocks of this district.

STRUCTURALLY LOCALIZED METAMORPHISM

In a number of tight subsidiary folds, the rocks are somewhat more highly metamorphosed (magnetite bearing) than elsewhere within the area of the deposits on Maple and Hovey Mountains. The more metamorphosed magnetite-bearing rocks, wherever megascopically recognized, are indicated on the geologic map (pl. 2) by a superposed pattern of randomly oriented hachures. Because of its close spatial association with particularly tight folds, this metamorphism is here called structurally localized metamorphism.

The Maple-Hovey deposit in particular has undergone structurally localized metamorphism at many places: in syncline I at the northwest end of Maple Mountain, in the axial region of anticline ④ along trench 19 on Maple Mountain, and in flexure ⑧ along the southeast limb of the major fold between Maple and Hovey Mountains. (See pl. 2.) Syncline VI at the southwest end of the Southern Hovey deposit is another example of structurally localized metamorphism. These subsidiary folds evidently were the foci for pronounced local recrystallization.

The intensity and distribution of this metamorphism, if judged by the amount of magnetite in the rocks, therefore, is suggested in part by the magnitude and distribution of magnetic anomalies (pl. 2). In general, the large positive magnetic anomalies in plate 2 are relatively narrow in width where the magnetic rocks are near or at the surface. Under a thick overburden they decrease in amplitude and increase in width. This is illustrated by the anomaly along the northwest side of the Maple-Hovey deposit which is probably related to the small anticline plunging southwestward. Near the surface, where only a relatively thin mantle of glacial overburden overlies the bedrock (pl. 2, sections of diamond-drill holes 34 and 44), the anomaly is relatively narrow in width and of large amplitude. The anomaly decreases in amplitude and broadens considerably down-plunge along the anticlinal fold, where the iron- and manganese-bearing rocks are overlain by a considerable thickness of magnetite-free, gray and green slate (pl. 2, section *B–B'*).

Some of the magnetic anomalies, such as most of those on Hovey Mountain which overlie third-order folds ⑫, ⑬, and ⑭ on the southwest end of the Maple-Hovey deposit (pl. 2), do not correspond with areas in which magnetite-bearing rocks are exposed at the surface. In these folds, the rocks exposed in natural outcrop or in trenches do not contain megascopically recognizable magnetite, nor other features of higher rank metamorphism. The magnitude of the magnetic anomalies centered over these folds, however, suggests that magnetite-bearing rocks lie at a relatively shallow depth.

In some of the subsidiary folds of the Maple-Hovey deposit, magnetite is absent in the hematitic rocks, but is present in the siliceous carbonate rocks below them. Fold ⑦, near the crest of Maple Mountain (see pl. 2), is one such example. Diamond-drill hole 15 has shown that some of the siliceous carbonate rocks which here underlie the magnetite-free hematitic units of the deposit have abundant magnetite, visible in polished surfaces of drill core. Magnetite shows a similar distribution in fold ①, penetrated by diamond-drill hole 11 on Maple Mountain (see pl. 2) where the hematitic rocks are free of magnetite and the underlying siliceous carbonate rocks contain magnetite. The magnetic anomalies associated with the folds ① and ⑦, therefore, appear to be caused by the magnetite in the siliceous carbonate rocks at these places. At first glance, the magnetic anomaly associated with fold ① appears to be centered over the lower manganiferous unit (hematitic) in which, however, magnetite has not been recognized. Actually, this magnetic anomaly is vertically centered above the magnetite-bearing siliceous carbonate rocks, as is demonstrated by the position in which they were intercepted at depth in diamond-drill hole 11. The hole is inclined 45° N and the strata dip about 45° S.

The small magnetic anomaly along the northwest limb of fold ① and near the northwest end of trench 14 on Maple Mountain is apparently also caused by magnetite exclusively in the siliceous carbonate rocks underlying the lower manganiferous unit of the Maple-Hovey deposit. Some of the siliceous carbonate layers in diamond-drill hole 12 (which is oriented along trench 14), as well as those in diamond-drill hole 28, contain magnetite, whereas the rocks in the stratigraphically overlying hematitic units are apparently magnetite free. Polished-surface examination of siliceous carbonate rocks from diamond-drill holes 13, 16, and 17 in the southeastern second-order fold V on Maple Mountain (pl. 2) did not reveal any magnetite. The small magnetic anomalies that lies within this fold close to its axial plane and along its southeast limb (between the northwest ends of trenches 5 and 6), however, might be caused by small amounts of magnetite locally developed in the siliceous carbonate rocks below the hematitic units of the deposit at these places. The very large magnetic anomaly in flexure ⑧, between diamond-drill holes 26 and 32, and 35 and 42, as mentioned earlier, is chiefly caused by magnetite contained in parts of the hematitic rocks of the middle and lower manganiferous units, and probably by magnetite in the underlying siliceous carbonate rocks as well. Magnetite was not megascopically detected in the latter, but a horseshoe magnet showed drill core of these rocks to be magnetic.

The siliceous carbonate layers underlying both the Maple-Hovey and the Southern Hovy deposits are free of magnetite along the relatively less deformed limbs of these deposits. Magnetite was not found in the siliceous carbonate rocks in diamond-drill hole 17 (near 33,700 N. and 17,400 E.) in the Maple-Hovey deposit. Furthermore, the absence of magnetic anomalies comparable in magnitude with those related to the magnetite-bearing siliceous carbonate rocks in diamond-drill holes 11 (fold ①) and 15 (fold ⑦) suggest that magnetite is absent in the zone of siliceous carbonate rocks extending between trench 6 (near 34,000 N. and 18,000 E.) nearly to the plane of diamond-drill holes 26 and 32 (near 33,300 N. and 16,700 E.) on Maple Mountain.

CHANGES ACCOMPANYING STRUCTURALLY LOCALIZED METAMORPHISM

The hematitic rocks that have been subjected to structurally localized metamorphism, particularly the banded hematite ironstone of the Maple-Hovey deposit, differ from their less metamorphosed equivalents in the following respects: (a) virtual absence of braunite, (b) presence of magnetite and paucity or absence of hematite, (c) abundance of chlorite, notably in certain layers and in the pressure shadows of magnetite (fig. 25), (d) presence of biotite, and (e) coarser and more abundant muscovite. Carbonate, close to rhodochrosite in composition, is abundant in the recrystallized ironstone, and stilpnomelane, although not precisely indentified as such, may also be present.

The development of magnetite is the most conspicuous and apparently the most important mineral change in siliceous carbonate rocks that have been affected by structurally localized metamorphism. Magnetite in carbonate-facies rocks typically is localized in the carbonate layers (see fig. 38). The carbonate in these layers generally is close to manganous siderite and ferroan rhodochrosite in composition.

Coarsening of pyrite grain size is another feature of the more highly metamorphosed parts of deposits. James (1954, p. 250) also noted a similar relationship of coarsening of grain size of pyrite with higher metamorphism in the sulfide facies of iron-formation in the Lake Superior region.

The more highly recrystallized ironstone faithfully preserve the primary sedimentary laminations of the original rocks and the chlorite growths in pressure shadows of magnetite are alined within these planes of stratification.

Pyrrhotite occurs as a very sparse and minor constituent in some of the magnetite-bearing siliceous carbonate rocks (described earlier). There is no direct evidence of hydrothermal origin for the pyrrhotite but it may be a product of metamorphism.

Color differences of uncertain origin are generally associated within or near rocks affected by structurally localized metamorphism. The Central Hovey deposit, which, judging by its high magnetite content, has been greatly affected by structurally localized metamorphism, apparently has also undergone marked color modifications. For example, the color of the green slate immediately enclosing the deposit, and that interlayered with the ironstone, is a considerably darker green than the typical green slate of the area. The red and purple slate of the Central Hovey deposit, also, is

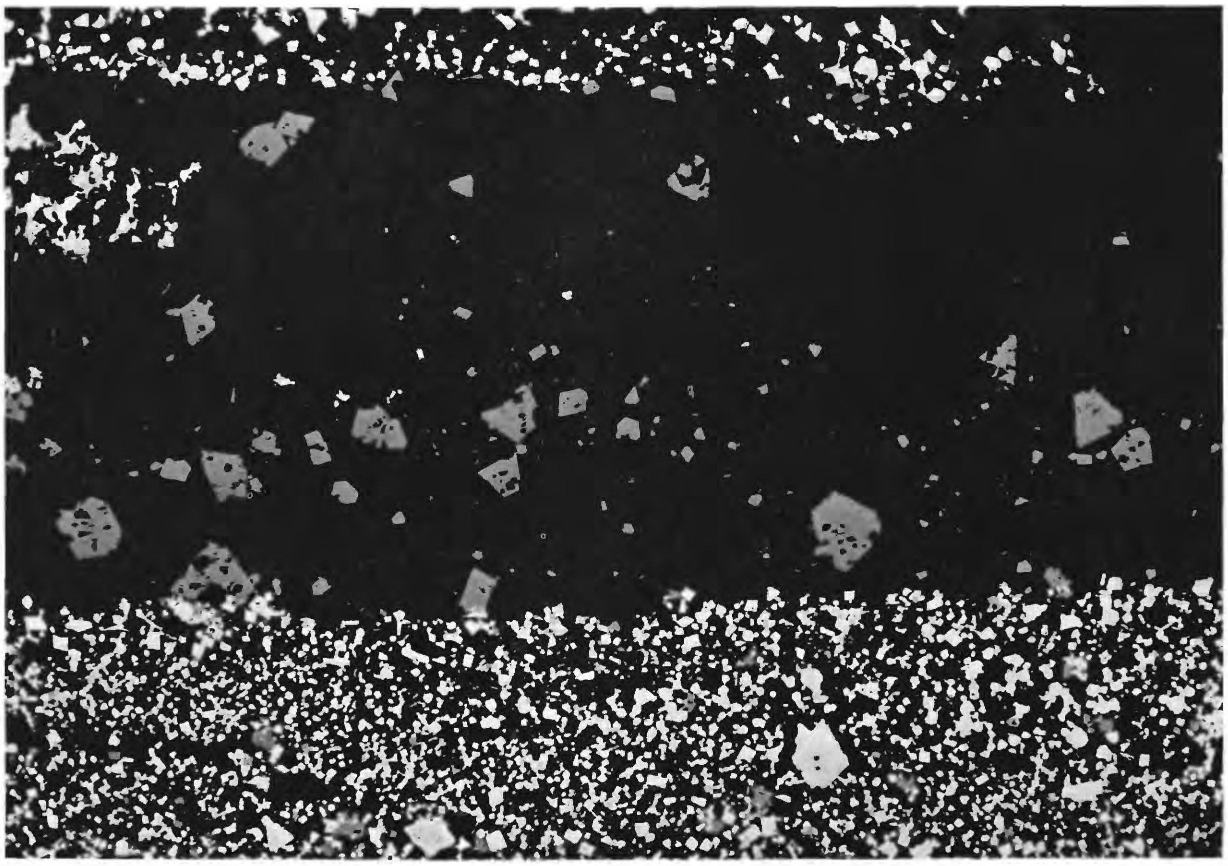

FIGURE 38.—Photomicrograph of a magnetite-bearing, pyritic carbonate-facies rock from the zone stratigraphically underlying the Maple-Hovey deposit. Magnetite (light gray) is more abundant and coarser grained in the carbonate layer (dark gray) and finer grained as well as sparse in the laminae of pyrite (white). The intersitial dark-gray matrix of the pyrite layers is chiefly carbonate and chlorite. Plane light; × 132.

dull in hue as compared to similar rocks in the magnetite-free parts of the Maple-Hovey deposit.

Chemical changes accompanying structurally localized metamorphism can only be evaluated for the hematitic facies of rocks as there are no comparable chemical analyses available for the carbonate-facies rocks. The chemical changes accompanying the structurally localized metamorphism of hematitic rocks are indicated in an approximate manner by comparing the chemical analyses of magnetite-free and magnetite-bearing ironstone from the middle manganiferous unit of the Maple-Hovey deposit (table 8). The results of this comparison are summarized in table 29. The first and second columns of table 29 list the average arithmetic chemical analyses obtained from tables 8*A*, *B*, for banded hematite and the more highly metamorphosed banded magnetite-chlorite ironstone. The third column indicates the difference in weight percent between these analyses. The problem of properly evaluating the chemical differences in table 29 is complicated by the fact that the specimens of ironstone that have undergone only regional metamorphism and the ironstone that in addition, has been more highly reconstituted by structurally localized metamorphism are not from exactly the same stratigraphic horizons. Thinning and thickening of strata, by flowage during folding, and discontinuous exposures (commonly available only as a result of trenching) precluded collecting of precisely stratigraphically equivalent specimens between relatively less metamorphosed and more highly metamorphosed layers. (The specimens whose chemical analyses are listed in table 8 were actually collected as representatives of the various types of the more abundant ironstone within the middle manganiferous unit of the Maple-Hovey deposit.) Hence, although chemical constituents appear to decrease or increase in the more highly recrystallized ironstone as compared to the less metamorphosed ironstone if judged entirely on the basis of the numerical values listed in table 29, these apparent changes may actually reflect the sampling technique rather than the effects of metamorphism.

TABLE 29.—*Chemical changes represented by algebraic increment of oxides between less metamorphosed (magnetite-free) and more highly metamorphosed (magnetite-bearing) manganiferous ironstone of the Maple-Hovey deposit*

	Average analysis of weakly metamorphosed manganiferous banded hematite ironstone [1]	Average analysis of more highly metamorphosed manganiferous magnetite-chlorite ironstone [2]	Weight percent oxide increment
SiO_2	20. 84	17. 35	−3. 49
Al_2O_3	4. 13	3. 53	−. 60
Fe_2O_3	40. 06	37. 96	−2. 10
FeO	. 00	12. 71	[3] +12. 71
MgO	1. 49	1. 51	+. 02
CaO	4. 97	5. 49	+. 52
Na_2O	. 78	. 05	[3] −. 73
K_2O	. 88	. 63	−. 25
H_2O-	. 14	. 49	+. 35
H_2O+	. 84	2. 07	[3] +1. 23
TiO_2	. 18	. 12	−. 06
CO_2	4. 20	4. 33	+. 13
P_2O_5	3. 07	4. 03	+. 96
MnO	18. 27	9. 41	−8. 86
Total	99. 85	99. 68	----------
Fe	28. 02	36. 43	+8. 41
Mn	14. 15	7. 29	−6. 86

[1] Arithmetic average from table 8*A*.
[2] Arithmetic average from table 8*B*.
[3] Represents an increment reflected in all samples in table 8*A* and *B*.

Among the chemical changes believed to have resulted entirely from structurally localized metamorphism are the development of FeO (there is no FeO in the banded hematite ironstone), the increase in H_2O, and decrease in Na_2O. These are the only three persistent chemical differences that are reflected in all of the samples on which the average analyses are based (table 8*A*, *B*). The apparent addition or depletion of the other oxides listed in table 29 do not carry through all the specimens which constitute the arithmetic averages under comparison, although some of them may be significant. Some of them, however, may represent local original chemical differences.

Field and petrographic relation of the more highly meamorphosed ironstone indicate moreover that, except possibly for H_2O, the metamorphism responsible for these changes was a reorganization of the constituents within the deposits, rather than metasomatic reconstitution whereby appreciable constituents were added or subtracted. For example, the iron and manganese tenor of channel samples across some of the manganiferous units of magnetite-chlorite ironstone and of less metamorphosed banded hematite rocks within the Maple-Hovey deposit are closely comparable (see table 30), and indicate there has not been any metasomatic addition or subtraction of iron or manganese during structurally localized metamorphism. The increase in iron and decrease in manganese shown in table 29, therefore, most likely reflects random variation or arithmetic weighting of original chemical differences in ironstone types rather than metamorphically induced chemical changes.

The structurally localized and selective metamorphism which some of the manganiferous banded hematitic ironstone and banded siliceous carbonate

TABLE 30.—*Comparison of manganese and iron tenor between channel samples represented by diamond-drill cores of more highly metamorphosed (magnetite-bearing) and less metamorphosed (magnetite-free) ironstones from the middle and lower manganiferous units of the Maple-Hovey deposit*

	Mn	Fe
***A.* Middle manganiferous unit**		
More highly metamorphosed (magnetite-bearing) rocks: [1]		
Drill-hole 31 [2]	8. 78	23. 17
32 [3]	12. 82	27. 92
35 [4]	11. 52	26. 62
35 [5]	10. 85	29. 80
42 [6]	10. 82	25. 91
Arithmetic average	10. 96	26. 68
Less metamorphosed (magnetite-free) rocks:		
Arithmetic average [7]	11. 12	24. 09
***B.* Lower manganiferous unit**		
More highly metamorphosed (magnetite-bearing rocks: [1]		
Drill-hole 31 [8]	8. 01	17. 17
35 [9]	5. 16	27. 01
Arithmetic average	6. 59	22. 09
Less metamorphosed (magnetite-free) rocks:		
Arithmetic average [10]	6. 52	20. 24

[1] Compiled from Eilertsen, 1952, p. 88-98.

[2] Sample interval 75.0-95.0 feet. Contains only part of the unit.

[3] Sample interval 355.7-382.0 feet. Contains only part of the unit.

[4] Sample interval 412.2-422.8 feet. Contains only part of the unit.

[5] Sample interval 455.0-468.5 feet. Contains only part of the unit.

[6] Sample interval 198.9-210.0 feet. Contains only part of the unit.

[7] Obtained from table 12*B*. Represents arithmetic average of 10 diamond-drill holes.

[8] Sample interval 185.0-207.0 feet. Contains only part of the unit.

[9] Sample interval 468.5-507.5 feet. Contains the entire unit.

[10] Obtained from table 12*C*. Represents arithmetic average of 7 diamond-drill holes.

rocks have undergone has resulted in their compositional convergence towards rocks with a similar mineral make-up, namely, carbonate-magnetite-chlorite rocks. Magnetite, rhodochrositic carbonate, and iron-chlorite appear to be a stable metamorphic assemblage of the Maple and Hovey Mountains area manganese- and iron-bearing deposits just above the level of the chlorite-muscovite facies. It is, therefore, generally difficult to surmise the primary lithology of the more highly metamorphosed rocks in the district. It is not clear, for example, if some of the carbonate-magnetite-chlorite layers of the Central Hovey deposit represent metamorphically reduced original hematitic ironstone or reconstituted siliceous carbonate rocks which were originally intercalated with the hematitic layers.

METAMORPHIC PROCESSES

Magnetite in the hematitic-facies rocks is believed to have formed through the reconstitution of hematite. From the preceding discussion, this transformation apparently required only the chemical reduction of part of the ferric iron in hematite to ferrous iron, and proceeded as an isochemical reaction apparently, as little iron was added or subtracted during this metamorphism. (See table 30.) The degree of reconstitution of hematite to magnetite must have been quite variable at the different places in the Maple-Hovey deposit where structurally localized metamorphism took place, because there are magnetite-bearing ironstones in which hematite presumably is entirely absent and many which contain different proportions of magnetite and hematite. The absence of braunite in the magnetite-bearing ironstone developed through structurally localized metamorphism probably also reflects the reducing environment prevailing at the time of such metamorphism. Probably the Mn_2O_3 radicle of braunite was reduced to MnO; the $MnSiO_3$ radicle either was mobilized, in part, and precipitated as rhodonite in the veinlets that cut these rocks (p. 65), or was broken down to MnO and SiO_2. The MnO from braunite may have formed rhodochrosite by reaction with the fluids (described below) which metamorphosed these rocks. Any SiO_2 that may have formed through the destruction of braunite probably formed quartz.

In addition to reductive transformations, the hematitic ironstone that underwent structurally localized metamorphism was also hydrated, as shown by the significant increase in water in the magnetite-bearing ironstone formed by this metamorphism. This water is presumably fixed in the abundant chlorite present in the magnetite-bearing ironstone.

The Na_2O that was removed from the hematitic ironstone by structurally localized metamorphism may have become fixed in the plagioclase of the veinlets that cut the deposits and the slate that encloses them.

The magnetite in the siliceous carbonate rocks, as judged by its localization in primary carbonate layers (see fig. 58), is believed to have formed from the $FeCO_3$ of manganoan siderite or ferroan rhodochrosite. In essence this requires an oxidation reaction along the general lines:

$$6FeCO_3 + O_2 \longrightarrow 2Fe_3O_4 + 6CO_2$$

Actually, this reaction probably was of a more complicated nature.

The abundant chlorite commonly present in the magnetite-bearing siliceous carbonate rocks suggests that they underwent hydration during structurally localized metamorphism in similar manner to the magnetite-bearing ironstone metamorphically formed from hematitic rocks.

Any hypothesis that attempts to explain the structurally localized metamorphism, such as in the Maple-Hovey deposit, therefore, must reconcile (a) the apparent reductive processes that affected the hematitic rocks and the oxidation reactions that simultaneously affected the carbonate rocks, and (b) the simultaneous hydration of both primary facies rocks. Thompson's suggestions (1957, p. 855) as to the possible role the activity of oxygen (controlled externally) may have on determining the iron oxides developed in pelites by metamorphism may be applicable in explaining the metamorphic mineral changes which apparently took place in the deposits on Maple and Hovey Mountains. The conditions necessary to form magnetite in these deposits could have been achieved if the activity or chemical potential of the oxygen in the fluids permeating and moving through the rocks was such that magnetite was the stable mineral phase at a certain critical temperature. Therefore, in order for the system fluid-hematite and fluid-$FeCO_3$ to adjust towards equilibrium at the prevailing oxidation-reduction potential of the environment (the oxygen pressure of the fluid), hematite was reduced to magnetite and sideritic carbonate was oxidized to magnetite.

$FeCO_3$ in the carbonate-facies rocks, however, may have broken down if the activity of CO_2 and CO in the fluids permeating the rocks at structurally favorable places was such that $FeCO_3$ was unstable at the prevailing temperature. Possibly $FeCO_3$ could have altered along lines suggested by the equation

$$3FeCO_3 \longrightarrow Fe_3O_4 + 2CO_2 + CO.$$

Apparently the resulting iron mineral assemblage is one of disequilibrium in the ironstone that underwent structurally localized metamorphism as both hematite and magnetite and siderite and magnetite are present respectively in the reconstituted hematitic rocks and carbonate facies rocks. Disequilibrium mineral assemblages also are present in the volcanic rocks of the area (p. 33). On the other hand, as braunite was apparently completely destroyed in the hematitic-facies rocks by this metamorphism, chemical equilibrium was apparently attained for the system braunite-fluid. The MnO formed from the destruction of braunite may have reacted with the CO_2 in the fluids to form rhodochrosite. Some of the CO_2 in the fluids could have been derived from the structurally underlying carbonate-facies rocks where metamorphism was simultaneously destroying $FeCO_3$ and forming magnetite and CO_2. This CO_2 may have been transported (either as a dissolved gas or as bicarbonate) upward by the fluids to the hematitic-facies rocks where braunite was being reduced to MnO.

If magnetite in the siliceous carbonate rocks underlying the hematitic units of the Maple-Hovey deposit formed through the oxidation of $FeCO_3$ of manganoan siderite or ferroan rhodochrosite, it is possible that the carbonate contained in these rocks was residually enriched in manganese. This necessarily follows, providing that the $MnCO_3$ radical in isomorphous mixture with $FeCO_3$ did not concurrently oxidize to a manganese oxide such as hausmannite (Mn_3O_4). Oxides of manganese have not been conclusively identified in the magnetite-bearing rocks of the carbonate facies. In some places, however, the carbonate within which magnetite has formed is dusted with a red, extremely fine grained mineral. Under reflected light in thin section, the mineral has a red color and also shows a blood-red internal reflection in polished section, and is weakly anisotropic. It is possible this material may be an oxide of manganese such as hausmannite. Carbonate laminae dusted with this mineral have a distinct red cast in hand specimen. The red color of zincite from Franklin, New Jersey, has been explained as the result of small quantities of exsolved Mn_3O_4 (Palache, 1935, p. 38.)

Presumably the chemical nature of the fluids at the time of metamorphism probably was fairly constant on a regional scale. Therefore, the critical temperature necessary to develop magnetite as a stable phase and to destroy braunite was apparently reached only in certain close folds or along the axes of such folds. Higher temperature here may have been attained during deformation partly because of greater mechanical heat developed in close folding. It is also probable that the mashing and fracturing resulting from close folding was mostly along the axial region of such folds. Thus, in addition to acting as thermal nodes, close folds also probably acted as channelways for the regional fluids, particularly along their axial regions.

Invariably, where magnetite is present in hematitic-facies rocks it is also present in the siderite (manganoan)-bearing carbonate-facies rocks that underlie them. There are no places where only hematitic-facies rocks contain magnetite and the underlying carbonate-facies rocks are magnetite free. There are, however, places where magnetite is present in the carbonate-facies rocks but is absent in the overlying hematitic facies. This distribution pattern of magnetite in structurally metamorphosed hematitic facies and carbonate facies suggests that the sideritic, carbonate-facies rocks were more readily oxidized by the regional fluids than hematitic rocks were reduced by them.

The hydration that accompanied the oxidation-reduction reactions described above probably also took place because the activity of the H_2O in the fluids was higher than that in the rocks (Thompson, 1957, p. 844). Thus, both the hematitic- and carbonate-facies rocks gained water during structurally localized metamorphism, because the system evidently was open to H_2O, and chlorite was the stable mineral in both facies of ironstone at the prevailing temperature and pressure.

In general, therefore, structurally localized metamorphism is a special case of regional metaphorism. The mineral assemblages of the manganese- and iron-bearing rocks formed by such metamorphism represent an adjustment towards equilibrium because of somewhat higher temperatures in tight folds as compared to the regional temperature. Such adjustment may have been facilitated by the greater amount of mashing and fracturing in tight folds, permitting acceleration of chemical reaction and faster diffusion of regional fluids through these folds. Assuming a constant composition, excluding volatiles, the processes effecting structurally localized metamorphism can be considered as a function of the variables pressure, temperature, and the chemical activity of O_2, H_2O, or CO_2 and CO, or all of these constitutents. Locally, the chemical activity of sulfur was important (see p. 76).

OXIDATION AND ENRICHMENT

Secondary enrichment in the manganese- and iron-bearing deposits of the northern and southern manganese districts of Aroostook County, Maine, is confined to the zone of oxidation, which extends about to the top of the present water table (White, 1943, p. 144; and Miller, 1947, p. 30). At the Dudley deposit of the northern manganese district, for example, where the terrain is fairly level, the water table and the depth of oxidation are about 20 feet below the surface. As the position of the water table generally varies with topography, the zone of oxidation is probably deeper for deposits on the tops of hills. Secondary enrichment is caused by manganese and iron oxides which coat bedding planes and joint and cleavage surfaces, and replace the rock within about 2 inches from closely spaced cracks. In some places, the leaching of carbonate has produced a less dense earthy rock that may contain limonite.

Rocks with marked fissility and abundant joint and cleavage cracks are more easily penetrated and replaced by oxidizing solutions than more dense and compact rocks. Miller (1947, p. 27) believes that the hematitic variety of manganese deposits develops manganese and iron stains more readily than those composed of siliceous carbonate rocks.

Miller (1947, p. 31, 32) has made an extensive analysis of the oxidized zone at the Dudley deposit, for which many chemical analyses were available. He has found that although visual evidence is present for some enrichment down to a depth of about 20 feet, the greatest enrichment of manganese is confined to within a few feet of the surface. The enriched rocks average 2 or 3 percent more in manganese than unoxidized rocks at depth. In addition, oxidation has enriched the deposit more in iron than in manganese.

Some deposits have a negligible oxidized zone possibly as a result of glacial erosion. If this is the case, the enrichment by oxidation must be preglacial (White, 1943, p. 146). On the other hand, Miller (1947, p. 35) believes that the present thin mantle of enriched rock is of postglacial age; the glaciation having removed most if not all of any preglacial supergene zones that may have existed.

MAPLE AND HOVEY MOUNTAINS AREA

In general, the hematitic manganese deposits of Maple and Hovey Mountains have been oxidized and enriched in manganese and iron in similar fashion to the Dudley deposit. Table 31 lists the iron and manganese assays of trench samples, overlying or sufficiently close to diamond-drill holes, to permit comparisons of the grade of the manganese- and iron-bearing strata at the surface and at depth within the Maple-Hovey deposit. The corresponding analyses from trenches and diamond-drill holes are listed on the same line. The trench analyses are listed columnarly in the order of topographic height; those at the top of the column have the lowest topographic position and those towards the bottom are the topographically highest trenches. The arithmetic differences in manganese and iron content of trench and diamond-drill hole samples are given; a positive sign indicates the amount by which the trench assay exceeds the diamond-drill hole assay, and a negative sign indicates the amount by which the diamond-drill hole assay exceeds the trench assay. Plate 8 is a bar graph of the arithmetic differences between the assays of iron and manganese in trench and diamond-drill hole samples (table 31) plotted in order of increasing elevation of the trench samples. The solid bars indicate the amount of metal by which the trench assays exceed the comparable diamond-drill hole assays and conversely the open bars indicate the amounts by which the

TABLE 31.—*Calculated manganese and iron in the upper, middle, and lower manganiferous units, Maple-Hovey deposit*

[Trenches overlying diamond-drill holes are cited on the same line. Compiled from Eilertsen, 1952 table 1, p. 24–51; and table 5, p. 55–116. Assays in Eilertsen's tables have been recalculated to conform to unit boundaries. A positive (+) sign indicates the amount by which the trench assay exceeds the diamond-drill hole assay; a negative (−) sign indicates the amount by which the diamond-drill hole assay exceeds the trench assay]

Elevation of collar of trench (feet)	Trenches			Drill holes			Difference in Mn content of trench and drill-hole samples	Difference in Fe content of trench and drill-hole samples
	No.	Mn (percent)	Fe (percent)	No.	Mn (percent)	Fe (percent)		
A. UPPER MANGANIFEROUS UNIT								
1075	22	2.74	7.63	38	2.12	6.38	+0.62	+1.25
1140	31	8.14	13.62	40	7.17	10.28	+.97	+3.34
1180–1185	[1]15	3.55	8.06	[1]17	1.31	6.58	+2.24	+1.48
1185	[2]18	2.63	10.47	[2]22	5.00	11.86	−2.37	−1.39
1200–1205	[2]17	4.40	15.57	[2]19	4.34	11.24	+.06	+4.33
1200–1210	[1 3]8	5.71	10.42	[1]8	7.17	12.70	−1.46	−2.28
1230	14	4.97	11.12	[4]12	3.59	11.56	+1.38	−.44
1245–1250	[4]6	3.48	9.24	5	7.28	13.67	−3.80	−4.43
1260	[3]45	7.54	14.09	54	5.72	11.41	+1.82	+2.68
1265–1292	29	5.55	12.12	37	6.65	12.77	−1.10	−.65
1275–1285	26	9.72	15.33	41	5.20	11.62	+4.52	+3.71
1335	[3]47	4.24	9.19	45	4.91	9.27	−.67	−.08
1330–1340	[1]4	6.50	8.85	[1]1 & 2	[5]5.47	[5]10.23	+1.03	−1.38
Average		5.32	11.21		5.07	10.74		
B. MIDDLE MANGANIFEROUS UNIT								
1070	22	9.18	19.22	38	9.46	20.25	−0.28	−1.03
1135	31	10.50	24.76	40	10.89	25.13	−.39	−.37
1170–1180	15	15.05	22.09	17	10.54	23.98	+4.51	−1.89
1185	[2]18	11.57	24.36	[2]22	9.91	24.78	+1.66	−.42
1205	[2]17	8.48	23.92	[2]19	9.38	24.70	−.90	−.78
1210–1220	[3]8	12.44	24.60	8	11.15	24.34	+1.29	+.26
1225	14	12.12	26.77	12	10.90	26.39	+1.22	+.38
1245	6	10.15	19.47	6	11.61	28.12	−1.46	−8.65
1245–1265	[6 7]H	11.08	29.60	7	11.76	26.23	−.68	+3.37
1250–1260	45	11.07	23.52	54	10.65	24.58	+.42	−1.06
1255–1265	29	13.87	23.04	37	11.67	25.70	+2.20	−2.66
1260–1270	19	11.67	21.57	[2]31	9.15	23.11	+2.52	−1.54
1265–1280	[3]2	13.70	25.06	11	10.39	27.18	+3.31	−2.12
1270	11	14.69	28.14	9	11.46	24.42	+3.23	+3.72
1270–1275	26	11.02	28.30	41	11.41	24.85	−.39	+3.45
1320–1325	9	11.29	25.98	15	11.52	27.27	−.23	−1.29
1320–1335	4	13.55	24.31	1 & 2	[5]11.43	[5]27.09	+2.12	−2.78
1335	47	10.69	18.87	45	10.90	19.38	−.21	−.51
1340	[6]A	11.75	28.30	13 & 14	[5]11.31	[5]26.91	+.44	+1.39
Average		11.78	24.30		10.82	24.97		
C. LOWER MANGANIFEROUS UNIT								
1135	31	5.20	19.74	40	4.71	19.31	+.49	+.43
1165–1170	15	9.17	29.00	17	4.76	24.98	+4.41	+4.02
1185–1192	[2]18	7.48	17.19	[2]22	5.60	15.55	+1.88	+1.64
1207–1210	[2]17	4.53	14.55	[2]19	4.17	15.67	+.36	−1.12
1215–1225	[3]8	9.07	19.46	8	7.51	19.30	+1.56	+.16
1220–1225	14	4.76	15.97	12	5.89	17.46	−1.13	−1.49
1235–1245	6	7.39	22.79	6 & 16	[5]5.41	[5]23.11	+1.98	−.32
1240–1250	45	6.35	21.87	54	7.56	20.14	−1.21	+1.73
1250–1255	29	6.12	18.67	37	6.14	17.71	−.02	+.96
1255–1265	[7]2	5.84	17.50	11	5.85	16.52	−.01	+.98
1265–1272	26	6.58	23.61	41	7.02	19.60	−.44	+4.01
1268	22	7.37	27.57	38	3.71	20.16	+3.66	+7.41
1270	11	9.81	26.41	9	7.38	15.78	+2.43	+10.63
1270–1285	[2]19	6.07	23.83	[2]31	7.55	18.57	−1.48	+5.26
1310	[7]1	8.85	15.79	10	7.03	19.52	+1.82	−3.73
1310–1320	[3]9	7.72	19.47	15	6.47	20.85	+1.25	−1.38
1310–1320	4	7.60	27.63	1 & 2	[5]6.55	[5]22.25	+1.05	+5.38
Average		7.05	21.24		6.08	19.20		

[1] Represents mostly the lower part of the unit.
[2] Includes magnetite-bearing zone.
[3] Trench considered to be approximately comparable to associated drill hole because of physical proximity.
[4] Represents most but not all of the unit.
[5] Arithmetic average of two holes.
[6] Manganese Ore Co. trench and sample; Miller, 1947, pl. 18.
[7] Sample does not represent the entire unit.

diamond-drill hole samples exceed the trench samples in iron and manganese. The trench analyses generally are higher than those of comparable diamond-drill holes in both manganese and iron. The differences in assay values may in part reflect the sampling and grouping of data; also, some of the smaller assay differences may be within the limit of error of the analyses. By and large, however, they represent the surficial enrichment undergone by the metalliferous units of the Maple-Hovey deposit through oxidation as well as solution and redeposition of iron and manganese.

The minor surficial enrichment of manganese and iron in the Maple-Hovey deposit, as well as other deposits of the Maple and Hovey Mountains area, resulted primarily from leaching of carbonate containing these metals, and is best developed in the lower manganiferous unit. In some of the manganiferous banded ironstone, leaching of carbonite-rich laminae has produced shallow, finely ribbed outcrop surfaces. Small pods or pellets rich in manganese silicates, particularly spessartite garnet, commonly stand out in marked relief. Such pods are generally coated by a black manganese oxide, a result, in part, of surficial oxidation. Manganese and iron, taken into solution during leaching, have eventually been deposited as oxide surface coatings. Miller (1947, p. 30) has noted that secondary oxides of manganese and iron in some of the deposits of the northern and southern manganese districts have effectively enriched the enclosing shale in zones as much as 10 feet wide on both sides of the primary metalliferous rock. No such width of enrichment has been noted in the deposits on Maple and Hovey Mountains; the oxides of iron and manganese appreciably stain the enclosing, virtually barren, slate at distances no more removed than a few feet from the contacts of the deposits.

Secondary manganese oxide of variable composition and amorphous to X-rays characteristically occurs as a black film with a silvery sheen, which has a striking resemblance to ink spilled and freshly dried on a smooth surface. Secondary iron oxides are less conspicuous than those of manganese. In a few places, iron oxides form a dense, layered and corrugated hematitic coating. This peculiar coating has only been noted on outcrops of slate in the upper manganiferous unit of the Maple-Hovey deposit.

The chemical analyses available for constituents other than manganese and iron are too few in number to warrant graphic comparison. The partial chemical analyses of samples from trenches and corresponding drill holes of the Maple-Hovey deposit (table 12) and of the Southern Hovey deposit (table 14) indicate that only sulfur and MgO show a consistent trend; they are less abundant in analyses of trench samples. A depletion of sulfur and MgO, therefore, probably accompanied iron and manganese enrichment. The other constituents, namely, CaO, P_2O_5, SiO_2, and Al_2O_3, do not show any recognizable trend either towards enrichment or depletion in trench samples as compared to diamond-drill hole samples.

Although Miller (1947, p. 27) states that the siliceous carbonate manganese deposits are less susceptible to secondary enrichment than the hematitic deposits, this relation has not been observed by the writer in the deposits on Maple and Hovey Mountains. Secondary iron and manganese stains are equally abundant in both varieties. The more dense and compact rocks of either rock type, however, are less stained than their more fissile varieties.

IMPORTANCE OF SECONDARY ENRICHMENT

Secondary enrichment of the Aroostook manganese- and iron-bearing deposits is more of academic interest than of economic significance. Its effects have been negligible both qualitatively and quantitatively; it has not effected a sufficient enrichment at any place within the Aroostook manganese belt to make "ore" out of any part of the deposits; nor has the minor enrichment of manganese and iron occurred more than a few feet below the bedrock surface. The enrichment that has occurred must, nonetheless, be taken into consideration in metallurgical sampling. In some deposits, the surficial manganese enrichment may represent a considerable percentage of the total manganese in the rock. Inasmuch as the manganese of the secondary oxides is in a different chemical state than the manganese in unweathered rock, their solubilities in acids of different strengths would vary. Samples designed for hydrometallurgical tests must, therefore, be chosen from both oxidized or unoxidized material or exclusively from fresh rock, which is quantitatively more abundant in the Aroostook deposits.

ECONOMIC POSSIBILITIES

RESERVES OF MANGANESE AND IRON

NORTHERN AND SOUTHERN DISTRICTS

None of the Aroostook deposits contain ore in the strict sense of the word. Ore is used loosely in this report to include the iron- and manganese-bearing rocks within the Aroostook deposits regardless of their tenor and marketability.

Miller (1947, p. 6, 36–39) has summarized the manganese reserves of Aroostook County based on the prospecting records generously made available to him by the Manganese Ore Co. He has subdivided the ore reserves into three categories that are defined by the degree of accuracy with which they can be calculated. "Measured reserves" were calculated from detailed prospecting and sampling information and their limit of error is probably not greater than 20 percent. "Indicated reserves" were computed from sparser prospecting information, supplemented by projections based on geologic evidence. This category probably has a fairly wide margin of error. "Inferred reserves" can only be roughly estimated and are deduced from geologic evidence where few or no measurements as to size and grade are available. Miller (1947, p. 36) also used the following limiting conditions in his estimates of reserves.

> In calculating the reserves of manganese a deposit is not considered minable by surface methods to a depth in excess of twice its width; the tonnage of manganese at a deposit 20 feet wide, for example, is calculated to a depth of only 40 feet. Where prospecting or geologic evidence indicate continuity downward, deposits more than 50 feet but less than 100 feet wide are calculated to a depth of 100 feet, and deposits more than 100 feet wide to a depth of 200 feet. Although the Dudley deposit is known to extend deeper than 200 feet and others probably do also, no calculations of ore below this level have been made, on the supposition that the expense of mining this deep ore by surface methods would be prohibitive, and that the grade of the ore would not warrant the expense of underground mining.
>
> A 5 percent cut-off is used in the calculations for all deposits, except the Dudley * * *. No rock below 5 percent grade has been included except where thin zones of low-grade material are interbedded with ore sufficiently high in manganese to bring the average above the cut-off grade. The weighted average of the higher- and lower-grade material is then applied to the combined width in calculating tonnage. This method was adopted in the belief that separation of low-grade zones a few feet thick from higher-grade ore by selective mining would not be feasible in working deposits of this type.

Table 32 is a compilation of the total manganese reserves of the northern and southern manganese districts of Aroostook County. It is a compilation based on Miller's table 1 (1947, p. 38), from which the reserves of the deposits on Maple and Hovey Mountains have been deleted, as the recent investigations by the U.S. Bureau of Mines has greatly enlarged these figures.

Although reserves for the associated iron in the deposits of the northern and southern manganese districts have not been calculated by previous investigators, the order of magnitude of such reserves can nonetheless be evaluated. Thus, the total equivalent ore of the measured, indicated, and inferred categories to a depth of 200 feet is approximately 20 million long tons and averages 8.7 percent manganese (obtained from table 32) and about 17.4 percent iron, inasmuch as the tenor of iron of the deposits in these districts is estimated to be nearly twice that of manganese (Miller, 1947, p. 1.)

TABLE 32.—*Manganese reserves of the northern and southern manganese districts, Aroostook County, Maine*

[Calculated from data in Miller, 1947, table 1, p. 38]

	Depth of 100 feet		Depth of 200 feet	
	Long tons of contained Mn	Average grade (percent)	Long tons of contained Mn	Average grade (percent)
Measured ore	543, 000	10. 3	970, 000	10. 2
Measured and indicated ore	791, 000	9. 3	1, 340, 000	8. 4
Measured, indicated, and inferred ore	1, 100, 000	8. 8	1, 735, 000	8. 7

MAPLE AND HOVEY MOUNTAINS AREA

Eilertsen (1952, p. 16) calculated the reserves of the Maple and Hovey Mountains area on the basis of detailed trenching and diamond drilling by the U.S. Bureau of Mines. His results are given in table 33. These are total reserves for the district which include measured, indicated, and inferred ore. The reserves are "indicated by diamond drilling and inferred by geology" (Eilertsen, 1952, p. 2).

TABLE 33.—*Summary of the reserves calculated by Eilertsen (1952, p. 16) for the Maple and Hovey Mountains area, Aroostook County, Maine*

Classification	Long tons	Mn	Fe	P	SiO_2	S	Al_2O_3	Ca	MgO
Minimum 10 percent Mn	121, 000, 000	11. 2	23. 9	0. 90	25. 4	0. 05	7. 61	3. 28	1. 39
5 to 10 percent Mn	135, 000, 000	6. 8	17. 9	. 70	36. 0	. 12	11. 43	2. 55	2. 01
Total	256, 000, 000	8. 9	20. 7	0. 80	31. 0	0. 08	9. 62	2. 89	1. 72

A reevaluation of the reserves of the Maple and Hovey Mountains area has been made for this report. Eilertsen had primarily grouped his assays from trenches and diamond-drill cores so that his calculations would conform to specific manganese cutoff values. In the present report, the assay data (Eilertsen, 1952, tables 1 and 5) have been recombined to coincide as nearly as possible with stratigraphic units. Also, the writer has made slight revisions in the geologic and structure contour maps since submitting preliminary versions to Eilertsen for use in his report; the revised maps have been used for the present reserve calculations (pls. 2 and 5). The chief revisions in these maps are of the fault relation between the Central

Hovey and the Maple-Hovey deposits, and of the fault relation within the Central Hovey deposit.

Reserve calculations were carried out by the end-section method (Forrester, 1946, p. 564). The spacing of end sections was determined primarily by the location of diamond-drill holes as well as by the complexity of geologic structures; wherever there is complex folding and faulting closer spaced cross sections were used. Table 34 lists the tonnage factors used for calculating reserves in the different deposits. The specific gravities of the formations listed in table 34 are weighted averages of the rocks composing each unit, based upon stratigraphic sections such as those on plate 4. Although the density of prospecting information in some parts of the deposits is fairly high, the inherent complexity of the geologic structure makes it inadvisable to classify any of the reserves as "measured." Therefore, only indicated and inferred ore reserves have been calculated. The indicated and inferred reserves of the unoxidized hematitic and siliceous carbonate ores down to vertical depths of 100 and 200 feet from the bedrock surface are listed in table 35. The inferred oxidized reserves of the district are listed in table 36. Visual evidence and assay information, based on comparisons of trenches and diamond-drill core, suggest that secondary enrichment of manganese and iron oxides in the Maple and Hovey Mountains area is practically a surficial phenomenon, being most marked in the upper few inches or feet of the deposits. Also, it is not equally developed in all parts of the deposits. (See pl. 8.) An average depth of 1 foot was used throughout the district in calculating the reserves of oxidized ore in the deposits. Because of the uncertainties as to the distribution, amount, and effective depth of oxidation, the oxidized ores have been calculated entirely as inferred reserves.

TABLE 34.—*Calculated specific gravity and tonnage factors used in reserve calculations of the deposits on Maple and Hovey Mountains*

Deposits	Specific gravity	Tonnage factor (cubic feet per long ton)
Maple-Hovey:		
Upper manganiferous unit	3.1	11.6
Middle manganiferous unit	3.7	9.7
Lower manganiferous unit	3.3	10.9
Central Hovey:		
Upper manganiferous unit	3.2	11.2
Middle manganiferous unit	3.5	10.2
Lower manganiferous unit	3.0	12.0
Southern Hovey and small hematitic lenses	3.5	10.2
Siliceous carbonate lenses	3.2	11.2

TABLE 35.—*Indicated and inferred unoxidized ore reserves to depths of 100 and 200 feet in the Maple and Hovey Mountains area, Aroostook County, Maine*

Lithologic types	Depth of 100 feet			Depth of 200 feet		
	Long tons	Mn	Fe	Long tons	Mn	Fe
	Indicated ore reserves and weighted averages					
Hematitic	29,000,000	7.4	17.9	55,000,000	7.6	18.2
Siliceous carbonate	-----	-----	-----	-----	-----	-----
Total	29,000,000	7.4	17.9	55,000,000	7.6	18.2
	Inferred ore reserves and weighted averages					
Hematitic	4,000,000	7.2	15.4	8,000,000	7.1	15.1
Siliceous carbonate	800,000	6.4	16.0	1,000,000	6.5	16.2
Total	4,800,000	7.1	15.5	9,000,000	7.0	15.2
	Indicated and inferred ore reserves and weighted averages					
Hematitic	33,000,000	7.4	17.6	63,000,000	7.5	17.8
Siliceous carbonate	800,000	6.4	16.0	1,000,000	6.5	16.2
Total	33,800,000	7.4	17.6	64,000,000	7.5	17.8

TABLE 36.—*Inferred oxidized ore reserves to a depth of 1 foot in the Maple and Hovey Mountains area, Aroostook County, Maine*

Lithologic type	Long tons	Mn	Fe
Hematitic	390,000	7.8	18.2
Siliceous carbonate	12,000	6.5	16.3
Total and weighted averages	402,000	7.8	18.1

The total indicated and inferred, oxidized and unoxidized reserves for the district are listed in table 37. These reserves compared extremely well, in terms of total metal, with the estimate made earlier by Eilertsen (see table 33), the difference being, respectively, about 3 and 5 percent more manganese and iron than in Eilersten's calculations. The similarity of these figures stems from the fact that both Eilertsen and the writer were fundamentally measuring the same thing. The lower assay cutoff of 5 percent manganese used by

TABLE 37.—*Total indicated and inferred hematitic and siliceous carbonate ore in the Maple and Hovey Mountains area, Aroostook County, Maine*

Lithologic type	Long tons	Mn	Fe
Hematitic	322,000,000	7.2	17.2
Siliceous carbonate	3,000,000	6.5	16.5
Total and weighted averages	325,000,000	7.2	17.2

Eilertsen corresponds for practical purposes with the stratigraphic boundaries used by the writer. (See pls. 3 and 4.)

TOTAL RESOURCES OF THE AROOSTOOK BELT

The established manganese and iron reserves in the Aroostook manganese belt are summarized in table 38. Actually the reserves of manganese and iron in the Maple and Hovey Mountains area represent the ultimate resources of that area (within the stratigraphic cutoff limits, and insofar as the deposits have been defined through exploration), whereas the known or inferred reserves for the northern and southern manganese districts are calculated at a 5 percent manganese cutoff down to a depth of only 200 feet. This necessarily excludes reserves contained in a number of deposits, such as the Dudley, in the northern manganese district, and the Littleton Ridge deposit of the southern district, which are known to extend to depths greater than 200 feet.

An evaluation of the order of magnitude of the ultimate resources is possible, however, in the northern and southern manganese districts. All the manganese deposits of the Aroostook manganese belt are sedimentary lenses of different sizes, and a comparison of the ratios of the different types of reserves can be made within reasonable limits of geologic speculation in the three districts. For example, the ratio of ore reserves to a depth of 200 feet, as compared to the ultimate ore reserves in the Maple and Hovey Mountains area is about 1 to 5. (Compare tables 35 and 37.) Applying this ratio to the approximately 20 million long tons of ore within 200 feet of the surface in the northern and southern manganese districts (calculated from table 32), it seems reasonable to assume that approximately 90 to 100 million long tons of manganese ore containing about 8 percent manganese is present in these districts as ultimate resources.

TABLE 38.—*Manganese and iron resources within the Aroostook manganese belt*

	Long tons	Mn	Fe
Maple and Hovey Mountains area reserves[1]	325, 000, 000	7. 2	17. 1
Northern and southern manganese district reserves[2]	20, 000, 000	8. 7	17. 4
Total and weighted averages in Aroostook manganese belt	345, 000, 000	7. 3	17. 1

[1] Represents the "ultimate" resources of the district, in so far as its deposits have been presently defined, within the stratigraphic limits used for the ore calculations.
[2] Includes total known reserves down to a depth of only 200 feet.

For purposes of the following discussion, however, only the reserves in table 38 will be used.

EVALUATION

The manganese deposits of Aroostook County, Maine, have one of the three largest reserves of low-grade manganese ore in the United States. As in the case of the deposits near Chamberlain, South Dakota, and the subgrade or unoxidized manganiferous iron ore deposits of the Cuyuna range in Minnesota, the chief obstacle to the development of the Aroostook ores has been one of technology.

The hematitic variety of ore, in which most of the manganese is held as carbonate and braunite, has thus far been the principal subject of experiments in beneficiation and metallurgy. Ore of this type is highly refractory to processes such as gravity concentration, roasting and magnetic separation, and flotation (Lamb, Warnke, and Woodward, 1953), because of the extremely fine grain size of the manganese minerals, and their intimate admixture with hematite and gangue. The siliceous carbonate ores of Aroostook County may present a different problem in beneficiation from the hematitic variety, as their manganese is mostly in carbonate.

In addition to standard ore-dressing techniques, the hematitic-type deposits of the Maple and Hovey Mountains area have been tested by the U.S. Bureau of Mines for manganese extraction by the metallurgical processes of matte smelting, leaching with acids and other reagents, volatilization as chloride using both solid and gaseous reagents, and by the Sylvester process for the recovery of manganese concentrates (see Conley, 1952, p. 17–23, for details and results). By and large, most of the methods tested thus far have proven impractical for treating the hematitic manganese ores of Maple and Hovey Mountains. For example, recovery of manganese by leaching with various acids resulted in a maximum percentage extraction of about 60 percent. Part of this poor recovery can be attributed to the fact that most of the tests used ore from the middle manganiferous unit of the Maple-Hovey deposit, which has low acid-solubility characteristics (see table 25*B*), possibly because spessartite is locally abundant in it. The drawbacks of the other techniques are either poor recovery of manganese, inability to recycle reagents, excessive costs as a result of high fuel consumption, and expensive treatments in preparing the ores for the extractive processes.

With the exception of the Maple and Hovey Mountains area, the manganese deposits in Aroostook County are close to highways and generally not more than a few miles from the tracks of the Bangor and Aroostook Railroad. The Maple and Hovey Mountains area is at present accessible by a graveled tote road and an access road constructed by the U.S. Bureau of Mines in the course of their field investigations. The nearest ocean shipping point is Searsport, Maine, located about 190 miles from Bridgewater, Maine, which is approximately at the geographic center of the Aroostook manganese belt.

Most of the large deposits in Aroostook County, such as the Dudley deposit of the northern manganese district and the Maple-Hovey and Southern Hovey deposits of Maple and Hovey Mountains, could initially be worked by open pit. The greater part of the total reserves of the Maple and Hovey Mountains area (see table 37), however, would eventually have to be obtained by underground mining. Cleavage in the slate enclosing the deposits and in parts of some of the manganiferous units may cause slumping of quarry walls and necessitate more than usual support of walls and backs in underground mining methods. Selective mining of the deposits on the basis of assay cutoffs is possible up to certain minimum widths, which would differ for surface or underground mining methods. However, as the Aroostook ores are all low grade, they presumably could only be economically exploited if worked on a large scale, so that selective mining of narrow beds only a few feet thick would probably not be economically feasible.

In 1953 the United States produced 111,610,000 short tons of steel, which required about 17.05 pounds of manganese for each short ton of steel produced (DeHuff, 1956, table 4, p. 502). This manganese consumption is equivalent to about 1,770,000 long tons of standard metallurgical grade ore containing 48 percent of manganese. Therefore, although serious technologic and economic problems exist in the extraction of the manganese of the Aroostook deposits, they represent an important resource, potentially capable of meeting the metallurgical requirements of the United States for many years should a suitable metallurgical process be developed to treat them.

The manganese contained within 200 feet of the surface in the Aroostook manganese belt (See tables 35 and 38) potentially represents the equivalent of about 13 million long tons of 48 percent standard metallurgical grade ore (see table 39); this is comparable to the metallurgical requirements of the United States, at the 1953 consumption rate, for about 7 years. The established total manganese resources of the Aroostook manganese belt (see table 38) on the other hand are comparable to the requirements of metallurgical grade manganese ore for about 30 years. The foregoing reserve figures are based on a 100 percent recovery of manganese. Even with 70 percent recovery, they would still be able to fulfill national requirements for about 5 years with readily accessible ore, or for about 20 years in terms of total known reserves.

TABLE 39.—*Potential manganese resources of Aroostook County, Maine, in terms of equivalent standard grade metallurgical ore*

	Reserves in terms of equivalent standard metallurgical grade ore (48 percent Mn)		Potential supply based[1] on 1953 consumption rate of standard metallurgical grade ore	
	(Long tons)		(Years)	
	100 percent recovery of Mn	70 percent recovery of Mn	100 percent recovery of Mn	70 percent recovery of Mn
Equivalent 48 percent Mn ore within 200 feet of surface	13,000,000	9,000,000	7	5
Equivalent total 48 percent Mn ore within presently known deposits	52,000,000	36,000,000	30	20

[1] 1,770,000 long tons of standard grade (48 percent Mn) manganese ore. Calculated on basis of 1953 U.S. steel production of 111,610,000 short tons requiring 17.05 pounds per each short ton of steel produced (DeHuff, 1956, table 4, p. 10).

In addition to the large manganese potential of the Aroostook deposits, the associated iron could be recovered as a coproduct; although, with respect to national requirements the iron resources of Aroostook County (table 38) are small, being the equivalent of only about 115 million long tons of standard base ore containing 51.5 percent iron (Wade and Alm, 1955, p. 258), assuming 100 percent of the iron were recoverable. A byproduct of iron concentrates may well be an important economic factor, however, in exploiting the Aroostook deposits. An additional byproduct of the Aroostook ores may be phosphorus, which possibly could be extracted and marketed as a fertilizer product for local consumption.

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