REPORT

OF THE

STATE GEOLOGIST

ON THE

MINERAL INDUSTRIES AND GEOLOGY

OF

VERMONT

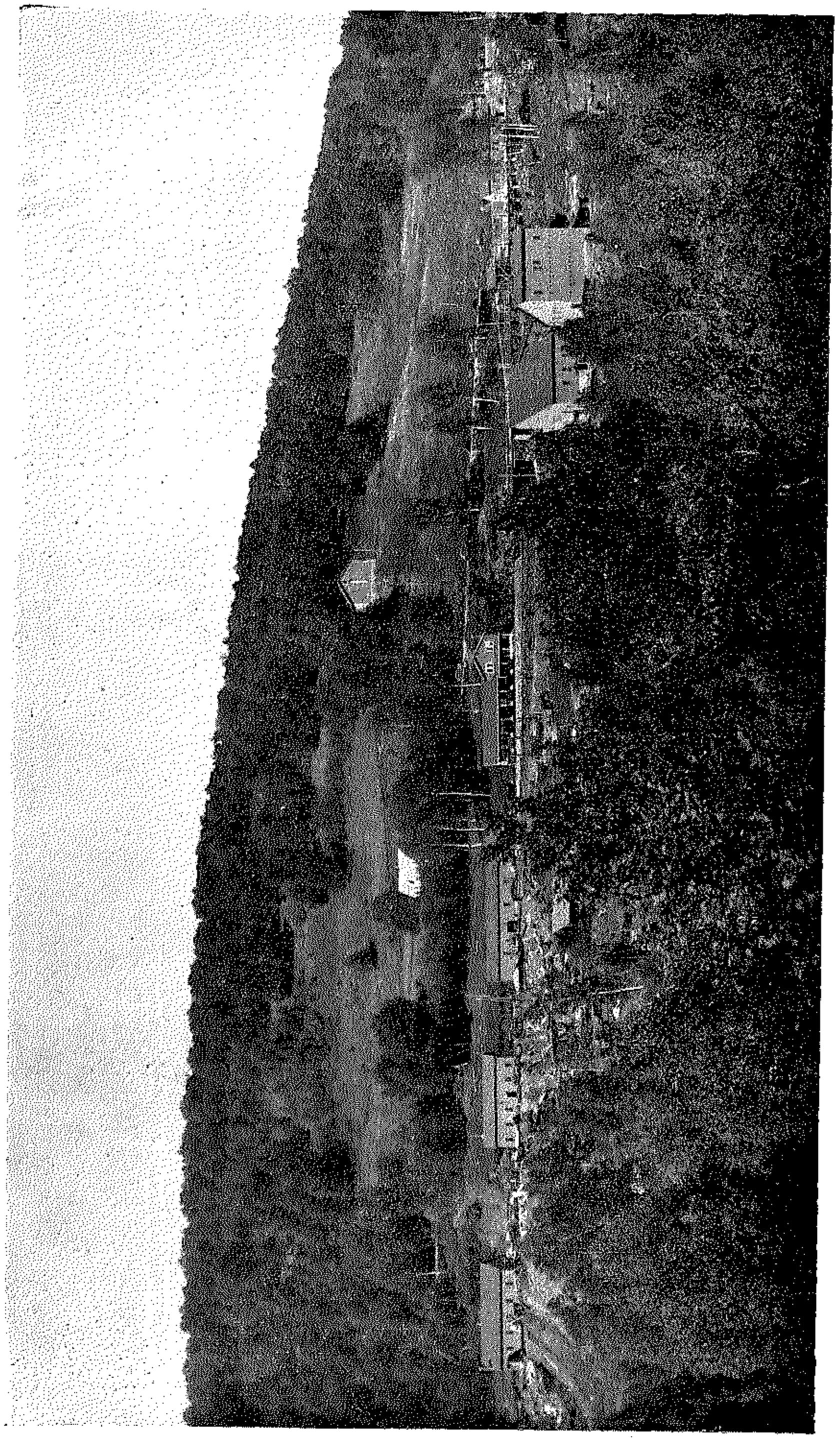
1943 - 1944

TWENTY-FOURTH OF THIS SERIES

ELBRIDGE C. JACOBS

F.G.S.A.

State Geologist



PLANT OF THE VERMONT COPPER COMPANY

Copperas Hill in the background. Mine entrance at the left between the first and second buildings.

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FREE PRESS PRINTING CO., BURLINGTON VT.

STATE OF VERMONT
OFFICE OF THE STATE GEOLOGIST
BURLINGTON

To the Conservation Board,
Department of Natural Resources,
Montpelier, Vermont.

Gentlemen: I herewith present my biennial report, as State Geologist, for 1943-1944.

This report is very largely devoted to the Vermont Copper Company's mine and operations at South Strafford—a continuation of the Reopening of the Vermont Copper Mines in the last report—and with the geology of the Strafford Quadrangle in which two of the mines and several copper prospects are located.

It is a matter of much satisfaction to be able to present Professor Charles G. Doll's Preliminary Report and Geological Map of the Strafford Quadrangle which were made possible by private funds. Such detailed studies are urgently needed and it is hoped that increased appropriations by the Legislature will enable the geologist to extend them to the other thirty-five quadrangles wholly within the State, a task which will require many years' work to complete.

Many of the States have published geological maps and there are many requests for such a map of Vermont. The last one dates from 1861, is long out of print, and is of very little value since geology has made great advances since then. When a sufficient number of quadrangles have been studied and mapped a preliminary geological map of the State can be published.

Supplementing Professor Doll's work the geologist presents an article on the petrology of some of the formations in Strafford township, a subject of much scientific importance.

The present status of the Vermont mineral industries is briefly given.

Respectfully submitted,

ELBRIDGE C. JACOBS,
State Geologist.

Fleming Museum,
University of Vermont,
December, 1944.

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ILLUSTRATIONS

I

The Vermont Copper Company, Inc.[1]

ELBRIDGE C. JACOBS

Officers: Chairman of the Board, George Adams Ellis; President and General Manager, Frederick W. Snow; Vice-Presidents, Stanley C. Wilson, E. A. De Villermont; Treasurer, Frederick H. Stokes; Directors: the above, E. A. Ellis and J. H. Moore.
Operating staff: Mine superintendent and chief engineer, J. C. Wangaard; Mill superintendent, H. A. Johnson; Mine captain, C. F. Banker; Accountant, C. B. Benson.
Consulting Geologist: H. M. Kingsbury.
Mine and mill: At South Strafford, Orange County, Vermont.

The Vermont Copper Company has been in production since October, 1943; its ore reserves are ample for many years to come; its mining equipment is up to date; its milling plant has proved its worth; there seems nothing to prevent copper production from becoming one of the important peacetime industries of the State.

Never before in the long history of copper mining in Vermont have the problems of the geology of the deposits and the mining and concentration of the ore been so thoroughly studied and mastered. The various departments of the enterprise are in the hands of men of wide experience: Mr. Snow, a graduate of the University of Utah, was for many years the superintendent of the Magma Copper Company of Arizona; manager of the Consolidated Copper and Sulphur Company of Eustis, Quebec; in charge of the Canadian operations of the U. S. Smelting and Refining Company; etc. Mr. Kingsbury, an alumnus of Harvard University, is a noted mining geologist whose mining missions have taken him to many parts of the world: Russia, Africa, South America, India, New Guinea, and other countries. He was for many years with the Mining Trust Company and with John Taylor and Sons, both of London, England. He has also carried on investigations for the Phelps Dodge Corporation and other mining interests in this country. Mr. Wangaard received his E.M. degree from the University of Minnesota School of Mines. He has worked in the Coeur d'Alene, Idaho, lead-zinc-silver district and on the Messabi Iron Range of Minnesota. He was employed for eight and one-half years in the engineering department of Lamaque Gold Mines, Ltd., of Bourlamaque, Quebec, before accepting a position with the Vermont Copper Co. Mr. Johnson, of the Montana School of Mines, obtained his metallurgical experience in Montana and Utah and was associated with the Gallagher Engineering Company of Salt Lake City, who designed the Vermont Copper Company's mill.

[1] See Reopening of the Vermont Copper Mines; E. C. Jacobs, 23d. Report Vermont State Geologist (1941-42). Two papers have recently been completed by members of the U. S. Geological Survey: Preliminary Report on the Geology of the Orange County Copper District, Vermont, by W. S. White and J. H. Eric; and Geology of the Elizabeth Copper Mine, Vermont, by W. E. White. These papers have been deposited by the U. S. Geological Survey in the office of the State Geologist, Fleming Museum, University of Vermont, where they may be studied by those interested.

Mr. Banker is a native of Vermont and has exceptional ability as a practical underground operator and leader of men.

It is apparent that the future of our copper enterprise is in the hands of thoroughly competent gentlemen and that every effort will be made to produce all the copper possible, first for the war effort and then for the great work of reconstruction which lies ahead. The chief handicap to production here, as everywhere, is the acute labor shortage. This is being gradually overcome and it is hoped soon to bring production up to 15,000 tons of ore per month.

THE PROPERTIES

The properties of the Vermont Copper Company are located on a mineralized zone some 20 miles long by 5 miles maximum width, extending roughly north and south in the eastern part of Orange County, in the townships of Strafford, Vershire and Corinth. To the north, and probably on the same zone, lies the property of the Consolidated Copper and Sulphur Company at Eustis, Quebec.

The deposit at South Strafford was first used for the manufacture of copperas (hydrous sulphate of iron) as early as 1793, was first mined for copper in 1830 and has been operated intermittently ever since. The present Elizabeth Mine was named for Mrs. James W. Tyson, Sr., in 1881; its further history is sketched in the Report of the Vermont State Geologist for 1941-42 and in the U. S. Geological Survey reports to which reference has been made above.

Copper was first discovered in Vershire in 1821. After changing ownership several times the property came under the control of Smith Ely in 1865 and later, as the Ely Mine, became one of the largest copper producers in the United States—this before the development of the western copper mines. Maximum production was reached in 1880 when 3,186,175 pounds of copper were recovered. The enterprise failed in 1883, whether because of poor management or the exhaustion of the known ore body is uncertain. Since that time various attempts were made to rehabilitate the mine but they were unsuccessful.

At Pike Hill, in Corinth, the Union Mine was first operated in 1866 and from that time to 1881, quoting Weed,[1] 31,504 tons of ore, presumably hand sorted, averaging 8.5 to 10 percent copper, were mined. For unknown reasons the mine was idle from 1881 to 1906, when it was acquired by the Pike Hill Mines Company.[1]

The Eureka Mine lies somewhat south of the Union and dates from about 1860. Production began in 1863 with 369 tons of ore; in 1906 304,377 pounds of copper were recovered. In 1906 the Pike Hill Company bought the property[2] and worked it in conjunction with the Union. Maximum production was reached in 1918 with 509,654 pounds of copper and 2,056 ounces of silver.

[1] W. H. Weed: Notes on the Copper Mines of Vermont; Bull. 225 U. S. G. S. (1904), and the Copper Deposits of the Appalachian States; Bull. 455 U. S. G. S. (1911).
[2] The Mines Handbook; vol. 18, part 1 (1931).

The mines were closed in 1919 probably on account of the drop in the price of copper following the first World War.

In 1942 the Elizabeth, Ely, Eureka and Union mines were acquired by the Vermont Copper Company, Inc.

Besides these well-known properties several other so-called mines and prospects of uncertain history exist in the mineral zone: In Corinth township the Smith Mine lies a short distance south of the Eureka and the Cookville Mine some three miles south and east of the Smith. In Vershire the Dimond property is about a mile south of the Ely. The Gove and Orange mines are in the central part of Strafford, while the South Mine lies about a mile south of the Elizabeth. Some of these enterprises date back to the Civil War; the Smith Mine was active as late as 1916.

A geophysical party of the U. S. Bureau of Mines, under the direction of Dr. G. R. MacCarthy is engaged in exploring those parts of the mineral zone whose geological structure suggests the probability of copper. The "self-potential" method is found to give the best results.

THE ELIZABETH MINE

The Elizabeth Mine is located at the east base of Copperas Hill, one and one-half miles southeast of the village of South Strafford and about four miles west of the Connecticut River. Its location is shown on the Strafford Quadrangle of the U. S. Topographical Survey and on the frontispiece.

The Vermont Copper Company began work here in April, 1942. Extensive drilling operations were conducted to delimit the known ore bodies and discover new ones. The old buildings were torn down and new ones built (frontispiece); the old haulage adit was straightened and enlarged; standard 36-inch gauge tracks were laid from the mine to the mill, crushing and concentrating machinery were installed and a new, up-to-date mill was constructed.

PHYSIOGRAPHY

The mineralized zone referred to above lies on the Vermont Piedmont (a dissected peneplain) east of the Green Mountains, and is a rolling country of hills and low mountain ridges with intervening valleys. The maximum relief is about 2,300 feet. White and Eric[1] give the average relief as 500 feet. Strafford township is drained by the West Branch of the Ompompanoosuc River and its tributaries.

GEOLOGY

The geology of the region is extremely complicated and has required long and detailed study since on its correct interpretation lies the key to the occurrence of the ore.

Following the acquisition of the property by the Vermont Copper Company a preliminary examination, including geological investigations, was made by Mr. Kingsbury who subsequently interested the U. S. Geological Survey and

[1] *Op. cit.*

the Bureau of Mines in the district. After a visit of Mr. Ralph Cannon, head of the copper branch of the Survey, a party of four geologists under the direction of Mr. W. S. White was appointed to carry on field studies, including surface and underground mapping, which continued from September, 1942, to October, 1943. An extensive diamond drilling program was also started at this time by the Bureau of Mines that gave valuable geological information.

The University of Vermont Department of Geology also became interested and assigned Prof. Charles G. Doll to do independent mapping of the surface geology in the Strafford quadrangle which includes the Elizabeth and Ely mines. His work was carried on through the past three summer seasons. (Professor Doll's paper and map follow this article.)

The following quotation is taken from W. S. White's paper, Geology of the Elizabeth Copper Mine, referred to on page 1:

"The rocks in the vicinity of the Elizabeth Mine are metamorphosed sediments, probably of Ordovician and Devonian age. The most abundant rock is quartz-mica schist, consisting essentially of quartz, muscovite and biotite. All gradations from mica schist containing relatively little quartz to almost pure quartzite are found. Small garnets are common to these rocks and crystals of kyanite occur locally.

"Interbedded with the quartz-mica schist are layers, up to 50 feet in thickness, of schist that contains abundant crystals of hornblende in addition to the quartz and biotite. The layers locally grade into schist without hornblende, and there is a good deal of hornblende-free schist in the area extending for 2,000 feet north of the South Mine. . . . This rock was probably formed by metamorphism of sediments rich in carbonate of iron and magnesium. Associated with the hornblende schist is a garnet-muscovite schist in which some of the garnets are over an inch in diameter. Long crystals of hornblende, largely altered to biotite, are common in this rock. A gneissic rock, well banded in layers of coarse and fine crystals and containing abundant crystals of oligoclase feldspar, occurs in the open cut (Plate 1) and in the southern workings of the Elizabeth Mine. This gneiss is probably a metamorphosed volcanic rock. The layers have clearly undergone all the deformation recognizable in the associated schists.

"All the rocks have been highly deformed. Their bedding is much folded on a small scale, and they are characterized by a well-developed schistosity, which strikes about 7°E. and has an average dip of 63°E. The bedding, as determined both from field observations and from comparing the position of a zone of hornblende schist at the surface with its position at depth, strikes more easterly and dips more steeply than the schistosity. This discordance is probably due to folding on a large as well as a small scale. Both the major and minor folds plunge for the most part gently northward, though horizontal crests and even southerly plunges were observed. The rocks are so uniform and the schistosity so well developed that the bedding has had no mechanical effect in localizing the vein zone and the ore shoots.

"Apart from minor faults, the latest stage of deformation is represented

by a fault along which the Elizabeth vein extends. The footwall of the vein, being parallel to the schistosity of the underlying rocks, has a general strike of N. 7°E. and an average dip of 63°E. The majority of the individual measurements of dip give values close to the average, but they range from 35° to vertical. The fault is presumably a reverse fault, but neither the direction nor the amount of movement on it is known. The schistosity of the hanging wall has been warped, probably by drag along the fault. A broad synclinal roll in the schistosity, locally broken off by a small reverse fault on the east limb, lies close to the top of the main ore body, and similar rolls of smaller size may be observed locally within the ore body. These rolls generally plunge from 5°-15°N., but in places their crests are horizontal. They and the fault zone followed by the vein are the only structural features that influence the localization of the ore."

THE ORE

The ore at the Elizabeth Mine consists of chalcopyrite (sulphide of copper and iron) disseminated in pyrrhotite (sulphide of iron) but also occurring in considerable masses of pure chalcopyrite. Associated with these minerals are small amounts of silver, pyrite, and traces of gold and sphalerite. The gangue minerals are quartz, feldspar, and mica. C. S. Anderson[1] gives the approximate composition of the ore mined in 1929-30 as follows: Quartz, 15 percent; feldspar, 15 percent; mica, 10 percent; pyrrhotite, 53 percent; and chalcopyrite, 7 percent. It is to be noted that the pyrrhotite present exceeds the chalcopyrite over seven times.

ORIGIN OF THE ORE

White and Eric,[2] writing of the deposits as a whole, believe that "the sulphide minerals were deposited at high temperatures, probably from hydrothermal solutions that originated at depth directly or indirectly from the intrusion of igneous rocks such as those exposed north of the district. No direct means are available of determining the depth at which sulfide deposition took place, but any attempt to restore the folded structure of the region above the present surface shows that the surface of the land at the time of deformation must have lain many thousands of feet above this present surface. Evidence that the ore deposits were formed during the last stages of the regional deformation, and thus at considerable depth, is consistent with the high-temperature mineral assemblages and the lack of mineral zoning in the deposits, as well as with the lack of low-temperature wall-rock alteration adjacent to the deposits."

"Deposition of the sulfides appears to have been controlled almost entirely by physical environment rather than by the chemical composition of the wall-rocks. Places favorable for ore deposition existed along faults or shear zones, as at the Elizabeth, and in flexures in the cleavage, as at Ely. At these two mines most of the copper was deposited in elongate areas, probably of greater

[1] C. S. Anderson: Mining and Milling in the Vermont copper district; Eng. & Mining Jour., vol. 231, pp. 208-210 (1931).

[2] *Op. cit.*

permeability or lower pressure than the surrounding rocks, that are oriented parallel to the regional plunge of fold axes and were probably determined directly or indirectly by the same forces that produced the folds. Where such linear control was lacking, sulfides were deposited irregularly through the rocks, largely along cleavage planes, forming concordant tabular deposits with irregular outlines, as at the Eureka-Union mine."

Mr. Kingsbury's studies have shown that the pyrrhotite and chalcopyrite were introduced into the country rock after it had been metamorphosed. The chalcopyrite is found disseminated in the pyrrhotite and therefore is younger than the pyrrhotite. Hence the order of geologic events was (1) the folding, faulting, and metamorphism of the original sediments into the schist and gneiss which now make up the country rock, and (2) the introduction of the sulphide minerals by pressure from below into the fault planes and shear zones and into permeable portions of the country rock.

THE ORE BODIES (*Plate I*)

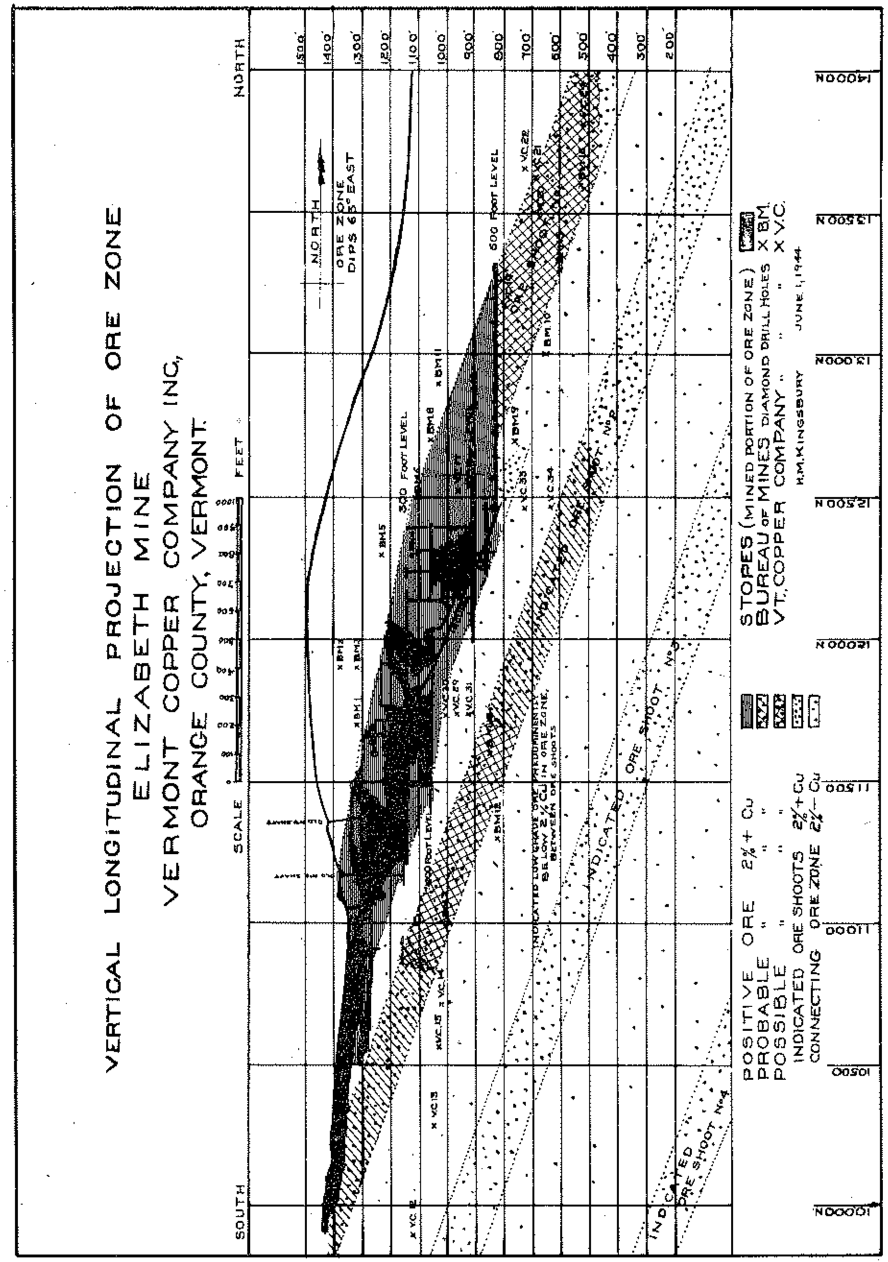
The ore zone in which mining operations are proceeding can be traced at the surface over a length of about one mile. The open-cut,[1] where mining operations began in 1793, is in the northern part of this zone. Underground operations were later extended to the north under country where no recognizable zone is exposed at the surface. In this zone the better grade ore occurs in several shoots,[2] or richer portions, which represent the more intensely mineralized sections. They pitch, like the major or minor folds in the schist, at the comparatively low angle of 15 to 20 degrees to the north within the zone, which is inclined steeply 63 degrees to the east.

The main ore shoot has been developed by underground workings for a distance of 2,000 feet along the pitch, from the surface outcrop, and 1,000 feet further by diamond drilling. The horizontal length as developed averages around 1,200 feet. In a few places the ore has been mined to a width of 65 feet but the average width is from 15 to 20 feet. The pyrrhotite and copper bearing sulphides in some places extend across the full width of the zone but often occur in several wide bands separated by nearly barren schist or by schist with disseminated and interfingering irregular stringers of sulphides.

Thus far mining operations on the main ore shoot have reached to the 600-foot level, but diamond drilling has shown that this shoot is persistent at least to a vertical depth of 1,000 feet, or 400 feet vertically below the present 600-foot, or bottom level. Some 17,000 feet of diamond drilling, including about 3,500 feet from underground, was done prior to 1916 by a former company, and some 10,000 feet, in 1942 and 1943, by the U. S. Bureau of Mines. This drilling and the subsequent geological investigations have indicated the probability of there being three other important ore shoots not previously suspected. One of these has been partly proved by the drilling done by the

[1] The light, horizontal lines are not levels but elevation lines: 200 ft., 300 ft., etc., above sea level. The open cut is the black area at the left: elevation about 1400 ft., and between vertical coordinates 10,000 and 10,600. The legend for stopes should be perfectly black.

[2] Ore shoots are irregular masses, of tabular habit, lying in the foliations of the country schists and, furthermore, as stringers, interfingering with the country rock, and also disseminated through it.



Bureau of Mines; and recently by drilling carried out by the company from the 600-foot level.[1] The ore in these shoots, as in the main ore shoot in which mining is now being done, should average about two percent copper.

It can be inferred from data now available that the parts of the zone between the ore shoots probably average well below two percent copper. Plans now being contemplated concerning improved facilities for crushing and handling an increased tonnage would result in an appreciable reduction in mining and milling costs, thus making it possible to extend mining substantially into these lower grade parts of the ore zone where very appreciable tonnages, containing between 1.5 and 2 percent copper, may reasonably be expected. Such an operation would of course also result in an increased tonnage of pyrrhotite which would form a valuable by-product when and if a market for its sulphur and iron content can be assured, a matter which is now being investigated.

On the plate the stopes, or mined portions of the ore, are seen in relation to the main ore body. The 300-foot, 400-foot, 500-foot and 600-foot levels are shown together with the inclined shaft connecting them. Figures at the right give feet above sea level. Vertical lines are 500 feet apart, measured from an arbitrary point.

Practically no timbering in the mine is needed. The mine "makes" but little water: about twenty gallons a minute. The average temperature in the workings is 60°F.; of the rock, 75°F. Ventilation is aided by a fan on the 300-foot level.

Electric power for the plant is supplied by the Central Vermont Public Service Corporation over a transmission line seven and one-quarter miles long from the Union Village generators.

Water is pumped from the Ompompanoosuc River to storage tanks, one of which is seen on the frontispiece.

FORMER OPERATIONS

When the Vermont Copper Company began operations, in 1942, the main ore shoot (Plate I) had been opened up by levels approximately 100 feet, 200 feet, 300 feet, 400 feet, 500 feet, and 600 feet vertically below the surface. A haulage adit had been driven westward from a point at the level of the present mill buildings (frontispiece) 1,360 feet long, with an easterly grade of 2.25° to cut the 300-foot, or haulage, level. Through this adit ore was hauled by an electric locomotive on 28-gauge tracks to the mill.

From the 300-foot level an inclined shaft had been driven northward, and downward at about a 25° slope, for 820 feet to a point 320 feet vertically below the 300-foot level, and from this shaft the lower levels were driven north and south for varying distances. Raises connected some of the levels vertically.

Ore had been mined between these levels but chiefly above the 300-foot level. The stopes, or mined sections, are seen on the plate. Mr. Kingsbury estimates that, from the time mining operations began (in the open cut) in

[1] Since this was written diamond drilling has been carried 250 ft. vertically below the 600-foot level and good ore proved.

1793, till 1930 about 320,000 tons of ore were mined, averaging between two and three percent copper.

It is doubtful if, during this time, any considerable amount of money was made. The reasons for the failure to produce copper profitably seem to have been the following:

1. Insufficient exploratory work not only from outside drilling but also from within the mine itself.
2. High mining costs due to production on too small a scale.
3. Improper metallurgical treatment: Roasting and smelting of the ore at the mine was tried and proved unsuccessful.[1] This was followed by various methods of concentration, including flotation, but unsuitable equipment and inexperience resulted in uneconomical operation.
4. Failure to save and market the by-products of sulphur and iron in the pyrrhotite.
5. The low prevailing prices for copper at critical times in the mine's history: in 1885, in 1919 after the first World War, and in 1930.

PRESENT STATUS

A better understanding of the geology of the ore bodies and improved drilling operations both within the mine and from the surface have shown the presence of much greater amounts of ore than were formerly thought to exist. Since the present company began operations more ore has been developed or well indicated, beyond the limit at which all former operations ceased, than was removed during the entire previous history of the mine. Furthermore, within the stoped areas, additional tonnages of high grade ore have been discovered which had been overlooked during previous operations. Ore "in sight" (that measurable in three dimensions) at present amounts to 270,000 tons and averages 2.25 percent copper; "probable ore" is estimated at 410,000 tons; and "possible ore" at 750,000 tons. The ore has been found to carry about 12 cents per ton in silver and a trace of gold.

The plant is thoroughly modern and has been designed to treat a large tonnage of ore in order to reduce mining and concentration costs to a minimum.

MINING OPERATIONS

Mining methods in use at present include the bench system and the shrinkage stope system; these will reduce mining costs materially.

Mining operations are highly mechanized: Scrapers or slushing machines are used exclusively and power mucking machines load the broken ore into mine cars which are hauled through the haulage adit to the mill by an electric locomotive.

MILLING

The ore as it comes from the Elizabeth Mine consists of the valuable minerals, chalcopyrite and pyrrhotite, and the worthless minerals associated with

[1] Report of the State Geologist for 1941-42, p. 12.

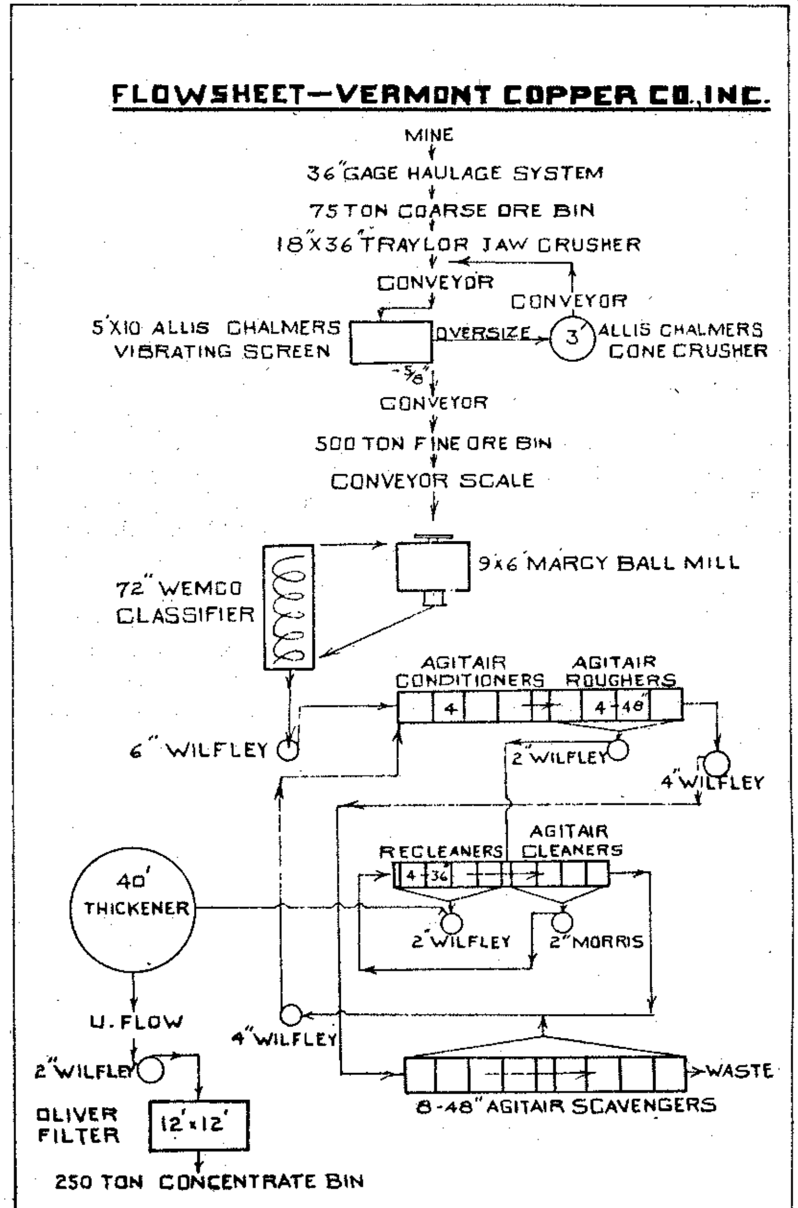


Plate II

them which are called the gangue. The object of milling, as at present practiced, is to separate and concentrate the chalcopyrite into a product rich enough to be shipped and smelted. Later the pyrrhotite may also be recovered. The flowsheet (Plate II) shows the sequence of operations.

The process consists of four major operations: crushing, fine grinding, flotation, dewatering.

Crushing includes two steps: coarse crushing (and screening), and fine crushing. Coarse crushing is accomplished in an 18″ x 36″ Traylor jaw crusher which reduces the ore from mine size of 18 inches and less to a maximum size of 3.5 inches. An endless conveyor belt carries the crushed ore to a vibrating screen which removes all particles under ⅝ inch. The oversized material is further reduced in size by an Allis Chalmers cone crusher to ⅝ of an inch and finer. This is returned to the vibrating screen. The ore, which is now all less than ⅝ inch in size, is conveyed to the fine ore storage bin.

This ore is next conveyed to the Marcy ball mill for fine grinding, passing on the way over the conveyor scale which automatically records the tonnage of ore treated. The ball mill consists of a rotating steel cylinder nine feet in diameter and six feet long, lined with alloy steel and partially filled with steel balls. These balls are of course worn down in the grinding process and more are added from time to time. Sufficient water is added with the ore to keep the ball mill discharge at 75 percent solids. The pulp emerges from opposite the feed end and more water is added. A launder carries the pulp to the Wemco classified which is a revolving archimedes screw operating in an inclined trough. The overflow from this classifier, with 25 percent solids, is now ground sufficiently fine; the coarser particles settle to the bottom of the classifier and are moved up the inclined trough and again passed through the ball mill. The classifier overflow, containing the ore ground to the fineness necessary to liberate the chalcopyrite from the waste, is now ready for flotation.

FLOTATION

Flotation is a process of mineral separation which has been developed during the present century to a point where it is now one of the leading processes, if not actually the leading process, used in the concentration of ores. It involves surface phenomena, the separation depending on the nature of the mineral surfaces. Some minerals are water avid and easily wetted while others are not. Water-avid surfaces are designated as *polar* in nature, while water-repellent surfaces are designated as *nonpolar*.

Froth flotation has today superseded all other types of flotation processes. In this a pulp, or mixture of about three parts of water, by weight, to one part of finely ground ore is delivered to the flotation apparatus. Here the pulp is agitated in contact with air and a frothing agent with the result that air bubbles attach themselves to the nonpolar minerals in the pulp and rise as a mineral-bearing froth to the surface. The purpose of the frothing agent is to give stability to the air bubbles which would otherwise break immediately on reaching the surface. At South Strafford the frothing agent is a 50-50 mixture of pine oil and pentasol alcohol, 0.05 pound per ton of dry ore.

Besides the frothing agent other flotation reagents are added in the flotation cells to act selectively on the surfaces of the mineral particles, either with the object of increasing nonpolarity and expediting flotation, or with the reverse object of increasing polarity and preventing flotation.

In general the surfaces of sulphide minerals, such as chalcopyrite, are easily made nonpolar and so will float while the pyrrhotite and gangue-mineral surfaces can be made polar and so will sink, thus effecting the desired separation. At South Strafford this is done by keeping the "pH" (hydrogen ion concentration) of the pulp at 9.5 (which means a slightly alkaline suspension) by adding about 2.5 pounds of lime per ton of dry ore. Twelve-hundredths pound of amyl xanthate per ton of dry ore is added to promote the formation of nonpolar surfaces on the chalcopyrite, and 0.14 pound of sodium cyanide per ton of dry ore to render the surfaces of the pyrrhotite polar. The surfaces of the gangue minerals are naturally polar. Therefore in the flotation cells the chalcopyrite is recovered and the remaining minerals discarded. Since flotation in one set of cells will not recover all the chalcopyrite the process must be continued as indicated on Plate II.

Pyrrhotite is a valuable by-product and can be recovered by a second flotation step with suitable pH and reagents; it is not done at present.[1]

The flotation series used at South Strafford (Plate II) consists of conditioner cells followed by rougher, recleaner and scavenger cells, all of the Agitair type. A six-inch Wilfley sand pump brings the ground pulp to the conditioners, a series of four cells, without partitions, in which the reagents are thoroughly mixed with the pulp and given time to act on the minerals. The pulp overflows a weir at the end of the last conditioner cell and passes to the bottom of the Agitair roughers which consist of four cells, each 48 inches square, in series. In each cell there is an impeller or agitator consisting of a steel cone with fingers extending vertically from its base and covered with rubber, at the bottom of a rotating vertical shaft. Air is introduced at the bottom of the cells at a pressure of 1.25 pounds per square inch. In the turbulence thus created the chalcopyrite rises to the surface in the froth and overflows the cells while the other minerals sink. The froth concentrates, which are impure, are conveyed by a two-inch Wilfley pump to the four cleaner cells, 36 inches square, the froth from which is delivered by a two-inch Morris pump to the recleaners. The final recleaner froth concentrates are pumped to the thickener. The tailings from the rougher cells pass to the scavenger cells, the froth concentrates from which, containing about five per cent copper go back to the conditioners and thence again through the series, while the tailings from the scavengers go to the tailings pond.

The froth concentrates from the recleaners contain about 40 percent of solids and go to the thickener for partial dewatering. The thickener is a large cylindrical wooden vat, 49 feet in diameter and 10 feet high. The solids settle

[1] For a fuller account of flotation see Richards and Locke's Text Book of Ore Dressing; McGraw-Hill Book Co., New York (1900).

to the bottom and are moved to the discharge opening at the center by a slowly moving raking mechanism driven from a central vertical shaft. Clear water overflows all around the periphery of the thickener. The thickened underflow, containing about 75 percent solids is then pumped to the Oliver filter for final dewatering.

This filter is a cylinder 12 feet in diameter and 12 feet long, slowly revolving on a horizontal axis. The surface of the filter is a wooden grid tightly covered with canvas as a filtering medium. The space below the canvas, to a depth of four inches, is divided into several sections and each section is connected by a pipe to the hollow central shaft. By means of an automatic valve the pipe is under suction while the cylinder is making about three-quarters of a revolution and under pressure for the remainder. The cylinder is partly submerged in the underlying tank of pulp which has come from the thickener. The cycle for any given section starts on the entrance of this section into the pulp. Since the section is now under suction a cake of solid material forms on the outside while the liquid is sucked through the canvas and discharged through the pipe. The section remains under suction until the valve reverses, when suction changes to pressure and the cake is loosened so that a scraper on the edge of the tank removes it from the canvas, whence it falls into the concentrate bin.

The pulp entering the flotation cells contains about 25 percent solids and 2.25 percent copper; the final concentrates carry some 92 percent solids and about 25 percent copper. The concentrates are trucked about ten miles to Kendall, Vermont, and shipped by rail to the Phelps Dodge smelter on Long Island, New York.

RESULTS

The mill is operated three shifts a day, except Sundays, and requires the services of fourteen men. It is designed to treat 15,000 tons of ore a month but, owing to the labor shortage, this figure has not yet been attained. About 9,000 tons of ore a month are being milled. Since January 1, 1944, the ore has averaged 2.2 percent of copper, 0.25 of an ounce of silver and a trace of gold. From 93 to 95 percent of the copper in the ore is being recovered.

As already stated the pyrrhotite in the tailings from the flotation cells is at present going to waste but can be recovered. This pyrrhotite has a high potential value in its sulphur content for the manufacture of sulphuric acid or the production of elemental sulphur; the residual iron would also be a valuable by-product. The problem is being studied.

LABOR

Mining, milling, and supplementary operations call for the services of about 180 men. Many of these workers live in South Strafford and neighboring villages while, owing to labor shortage, some fifty miners have recently been secured from Newfoundland.

Surface workers receive from 65 to 90 cents an hour, depending on the nature of the work. The mine is operated during two eight-hour shifts per

day, six days a week. Miners receive from 70 to 90 cents an hour for the first forty hours worked, with time and one-half for extra hours. The average pay is about $45.00 a week. Sickness and accident insurance are provided without charge.

HOUSING

To provide for the accommodation of workers the Federal Housing Authority has erected, at some distance from the mine, group housing to take care of forty families, and also a recreation building provided with games and a radio. The housing consists of forty apartments, varying from two rooms and bath to five rooms and bath, all furnished with modern kitchen equipment, electric refrigerators and other conveniences. Rents for these apartments vary from $23.00 to $29.50 a month, which include water, lights, garbage disposal and other necessities.

The writer gratefully acknowledges valuable information and assistance received from the officials of the Vermont Copper Company.

II

A Preliminary Report on the Geology of the Strafford Quadrangle, Vermont

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INTRODUCTION

The Strafford quadrangle is located in eastern Vermont, north of White River Junction and not far west of the Connecticut River Valley. The northern portion, comprising slightly more than two-thirds of the map area, lies in Orange County, while the remaining southern portion lies in Windsor County. The quadrangle is included between parallels 43° 45′ and 44° 00′ and meridians 72° 15′ and 72° 30′. It covers above 216 square miles.

SCOPE OF WORK

This paper is the result of field work carried on during a month of the summer of 1942 and the summers of 1943 and 1944. The purpose of this study was to map the geology of the Strafford quadrangle with the intention of showing the relationship of the geologic structures to ore deposits, which might possibly lead to the location of new ore bodies. The paper, therefore, describes the structural geology, stratigraphy, and geologic history of the area. In order to acquire an intelligent understanding of the metamorphic geology, it is, of course, important that the rock series be studied petrographically, and in this respect the problem of metamorphism is being investigated by Professor Jacobs, to be reported elsewhere. In some sections mapping was carried on with difficulty; hurricane timber and lumberman's slash made progress extremely slow and in some places impossible. It might also be mentioned that the map available to the writer was surveyed in 1896 by reconnaissance methods and contained inaccuracies which made it difficult to locate exposures.

ACKNOWLEDGMENTS

The writer wishes to express his sincere thanks to Mr. George A. Ellis, chairman of the Board of Directors of the Vermont Copper Company, whose generosity and interest in the problem has made the continuance of this study possible, and to Prof. Elbridge C. Jacobs, of the University of Vermont, State Geologist, under whom this work was begun and concluded.

The writer also wishes to thank Mr. Fred W. Snow, president of the Vermont Copper Company, for his kindly attitude toward the work. Mr.

Hector M. Kingsbury, geologist for the Vermont Copper Company, gave valuable counsel, especially concerning the geology in the mine.

PREVIOUS WORK

The Strafford quadrangle was first mapped by Prof. Charles H. Hitchcock of Dartmouth College and might be considered a general reconnaissance study done in the light of the geological field methods of the time (C. H. Hitchcock, 1912). He described the schists, limestones, amphibolites, and other rocks, the first two types under the names Goshen and Conway, respectively. The boundaries of the Green schist, Coos, and other formations mapped by him, in the extreme southeast corner of the quadrangle, were delineated with a fair degree of accuracy. Hitchcock observed the relation of bedding to cleavage, which is an important characteristic of the region.

Prof. Charles H. Richardson, late of Syracuse University, mapped the two most prominent formations as Bradford schist and Washington limestone in his studies of the geology of Orange County, Vermont (C. H. Richardson, 1902). Richardson also noted the relationship of cleavage to bedding (C. H. Richardson, 1902, p. 83).

There are, of course, numerous articles in the professional journals and bulletins, some of them touching upon the geology in the vicinity of the mines.

GEOMORPHOLOGICAL FEATURES

The two important drainage channels in the region are the Ompompanoosuc and West Branch Ompompanoosuc rivers, both, after confluence, emptying into the Connecticut River farther to the east. White River crosses the southwest corner of the area in a deep valley, and the First Branch White River traverses the northwest portion of the region. These rivers flow over limestones and schists alike, but have entrenched themselves more impressively in the schists. The courses of these rivers are determined, in part, by the structures.

The elevations in the Strafford quadrangle are determined both by rock composition and structures. The schist terrane is, in general, more rugged and abrupt than the softer limestone areas, which is reflected in the agricultural development of the respective regions. The curving range of hills beginning in the vicinity of Copperfield and including Patterson Mountain, Colton Hill (the highest elevation in the whole region), and Brocklebank Hill, is an example of topographic trend with rock structure. To a considerable degree, the hills on the Strafford anticline trend with the structures, as is well shown where they turn with the amphibolite around the south end of the anticline.

STRATIGRAPHY

GENERAL STATEMENT

Formation names appearing in this paper have been taken from local topographic features, and it is realized that some of them may sometime be abandoned in favor of preoccupied names, when more accurate correlations with adjacent areas have been made.

The vast majority of the rocks of the Strafford quadrangle consist of metamorphosed sediments and volcanics, and comprise a number of lithologic types. The formations range in age from middle Silurian to lower Devonian. It is possible that certain volcanics in the Durkee Hill greenstones (see map legend), presumably the equivalent of the Post Pond member of the Orfordville formation (J. B. Hadley, 1942), may be middle Ordovician in age. The writer considers the intrusives in the Durkee Hill greenstones to be either late- or post-Devonian in age, for reasons to be explained later in this paper.

Certain strata possess remarkably well-defined lithologic characteristics which enable them to be quite easily followed for considerable distances. These excellent horizon-markers reveal much of the complex structure of the region. An increase in the intensity of metamorphism has been noted in the schists from the Monroe fault westward.

MEMPHREMAGOG FORMATION

The Memphremagog formation was named by the writer from its occurrence in the region covered by the quadrangle of that name, in the northern part of Vermont. In this region the formation comprises a great variety of lithologic types, including limestones which have yielded fossils. The limestones are, therefore, considered a key horizon in the Memphremagog formation.

The limestones and schists.—The Memphremagog formation consists of arenaceous and micaceous dolomitic limestones and intercalated mica schists. The limestones are fine- to medium-grained, light- to blue-gray, and often possessing a noticeable luster imparted by mica flakes and the crystallinity of the lime content. Calcite commonly occurs in small veins and blotches, often displaying rhombohedrons. The thicknesses of the individual beds range from fissility to as much as three and four feet in the more massive layers. The thickness of the Memphremagog formation is difficult to obtain because of intense folding, but that portion occurring on the Strafford quadrangle has been estimated by the writer to be about 8,000 feet.

Upon approach to its contact with the schists, the Memphremagog formation becomes increasingly arenaceous and intercalated with greater amounts of rusty, coarse mica schists. Likewise limy layers occasionally occur in the area of siliceous schists to the east. These changes in the lithology of the beds suggest a transition zone between the calcareous formation to the west and the siliceous formation to the east. The eastern siliceous formation is believed, therefore, to lie conformably upon the western calcareous strata.

The age of the Memphremagog formation has been determined from fossil evidence discovered in the Waits River limestone member in the vicinity of Lake Willoughby to the north (C. G. Doll, 1943). These fossils indicate a middle Silurian age for the formation.

The Standing Pond amphibolite.—This is predominantly a needle amphibolite and an excellent horizon-marker. It has been named from the fine exposures impounding the waters of Standing Pond at its west end. It has been found to occur either entirely in the limestones or along their contact with the mica schists. Because of this stratigraphic relationship the Standing Pond amphibolite is considered a member of the Memphremagog formation.

The Standing Pond amphibolite is thought to be a metamorphosed volcanic or an altered sediment. It is commonly a fine- to medium-grained, greenish-gray or black rock, depending on the minerals present. Banded hornblende schists are frequently encountered with layers one-fourth to one-half inch thick. Occasionally this amphibolite becomes coarse at the contact with other rocks as well as away from them, where it often contains prominent amphiboles helter-skelterly strewn in a groundmass of basic feldspars. Orientation of the amphiboles parallel to the schistosity is much more prevalent in the fine-grained amphibolites and hornblende schists than in the coarse-grained amphibolites.

Among the other prominent minerals present in these amphibolites are garnets. They occur as porphyroblasts up to two inches in diameter for varying thicknesses at the borders of the amphibolite with the adjacent beds. Epidote is present irregularly and in veinlets occasionally continuing several feet along the schistosity or fractures. In places epidote is associated with light gray feldspathic areas often containing ilmenite. It is into these feldspathic areas that oriented amphiboles converge and bend.

Solution grooves and pockets are exhibited by many of the amphibolite exposures. These occur in the limy portions of the amphibolite, due to the weathering of calcite. Calcite is frequently developed along the schistosity, which accounts for the parallel orientation of these solution cavities in many instances. Calcite occurs irregularly in many of the quartz veins, sometimes composing the extension of these veins entirely where they pinch out. Where the amphibolite shows a great deal of contortion, the quartz veins are often mineralized, containing such minerals as ilmenite, magnetite, hematite, and pyrite.

The thickness of the Standing Pond amphibolite member varies from about 10 to 300 feet, due to thickening and thinning along the strike, probably caused by folding. Where it is not interrupted by faulting, this amphibolite has reasonably good continuity along its strike.

Mineral prospects are numerous in the Standing Pond amphibolite (see map legend). The majority of them, however, do not appear to be very encouraging, for, where present, the sulphides are sparsely disseminated, and the mineral chalcopyrite, desired for its copper content, is more often wanting.

The coarse garnet schist.—The coarse garnet schist is associated with the Standing Pond amphibolite and like the latter, it serves as an easily traceable horizon. It ordinarily accompanies the amphibolite along the contact with the limestones. However, in a few places it was observed to lie well out in the limestones, in which instances it appears to be absent from the amphibolite border. The coarse garnet schist seems to be restricted to areas exhibiting intense deformation, where the strata have been inverted and faulted. Schists in the structurally less complicated "oval" of the Strafford anticline, stratigraphically equivalent to the coarse garnet schist, do not carry the conspicuously large garnets, but instead, small garnets locally. These schists also possess thin layers colored pink by concentrations of extremely minute garnets, and disseminations of small iridescent magnetites.

The typical coarse garnet schist is highly micaceous, with large flakes of muscovite bending around the garnet porphyroblasts. Quartz, feldspar, and biotite are common constituents of the matrix which is strongly foliated. The garnet metacrysts are generally red, but in a few localities they are black. They are variable in size, but in any case they are quite conspicuous, averaging from one-half to three-fourths of an inch in diameter, rarely attaining a maximum of two and a half inches.

The garnets are often shattered and minutely fractured, some of the fractures filled with quartz. The quartz appears to be replacing the garnets, for it is not uncommon to see fragments of garnets or garnet nuclei in rust-stained saccharoidal quartz. Replacement is complete in many cases. In some exposures, occasional garnets are flattened out by pressures, to conform with the direction of schistosity.

A definite relationship appears to exist between the coarse garnet schist and the Standing Pond amphibolite, in that they are transitional into one another. Where in contact with the amphibolite the coarse garnet schist contains large amphiboles and darkens in color. It has already been noted that garnet porphyroblasts occur in the amphibolite at its contact with the coarse garnet schist.

Like the Standing Pond amphibolite which it adjoins, the coarse garnet schist also is variable in thickness, but nowhere approaching that of the amphibolite. In the inverted section of the recumbent fold on Grannyhand Hill, it is 12 feet thick, and at the Gove mine 18 feet. Generally, however, its thickness is in the neighborhood of 30 feet, thickening to 40 feet or more in folds.

GILE MOUNTAIN SCHISTS

The name Gile Mountain schists suggests itself from the excellent exposures on the mountain of that name in the southern part of the area. The Gile Mountain schists are light to dark gray, becoming black in certain graphitic schists. It consists principally of quartz-mica schists in which both oriented and unoriented biotite is a common constituent. Rocks in subordinate amounts are thin beds of massive and sheared quartzite, occasional coarse feldspathic schists, calcareous beds, and some graphitic layers. Porphyroblasts of garnet, staurolite, tremolite, kyanite, and sillimanite, appear to have a zonal distribution in the schist terrane west of the Monroe fault. There is an increase in metamorphism westward. Beginning with the prevailingly

sandy schists carrying staurolites, in the eastern part of the belt, the schis
become increasingly micaceous and coarser to the west, where they conta
kyanite and some sillimanite. Garnet increases both in size and quantity
the west, frequently staining the schists a reddish-brown due to weatherin

Bedding is generally absent, but is visible locally in contorted quartz vei
between thinly banded layers in the tightly compressed drag-folds, and occ
sionally in narrow layers differing in texture and color where the beds flatt
out (Plate IV, fig. 4). It is on the steeply dipping limbs of the minor folds th
the bedding practically coincides with the dip of the schistosity (Plate I
figs. 1-4).

The coarse amphibolites.—Predominantly coarse amphibolites conformab
with the schists become increasingly prevalent in the western portion of t
schist terrane. These amphibolites are ordinarily massive with black or dar
green amphiboles which are usually without orientation. The basic feldsp
matrix is sometimes quite calcareous.

The coarse amphibolites do not have the continuity of the Standing Po
amphibolite, but pinch out along the strike at varying distances. The d
continuity of these amphibolites may be due to folding and stretching. Laye
of quartzites have been observed to thin and finally pinch out along the strik
In many respects, the coarse amphibolite resembles the Standing Pond an
phibolite. The lithology of both types does not appear to differ radically, a
in several exposures near the western border of the schists the coarse amphib
lites are associated with needle amphibolites corresponding to the Standi
Pond amphibolites. It is possible that the coarse amphibolites and the Standi
Pond amphibolites had a similar origin, and that the differences in textur
generally is due to their association with different types of rocks, and the fa
that they lie in metamorphic zones of different intensities.

Measured from Gile Mountain to their contact with the Meetinghou
slates east of New Boston, the Gile Mountain schists have an estimated thic
ness of about 6,500 feet. The Gile Mountain schists are lower Devoni
in age, based upon fossil evidence. (C. G. Doll, 1943).

Meetinghouse slates.—Gray and black, micaceous slates which are grad
tional westward into the schists, comprise the Meetinghouse slates, a memb
of the Gile Mountain schists. The name comes from Meetinghouse Hill
the Strafford quadrangle, a part of which they occupy. Interbedded with t
slates are very thin quartzite layers, some of which are carbonaceous in appea
ance. The slates possess excellent cleavage which is sinuous along the stri
Much of the slate has a distinct brownish stain, due to the presence
weathered pyrite.

The Meetinghouse slates overlie the Gile Mountain schists. They a
isoclinally folded with a slight overturn to the east, and rest against the Monr
fault. Because these slates are transitional into the schists, they are correlat
with the schists and are, therefore, Devonian in age. The possibility of meas
ing the exact thickness of such intricately folded rocks is remote, but an es
mated thickness gives about 1,100 feet.

DURKEE HILL GREENSTONES

Between the Monroe and Ammonoosuc faults lies a tract of greenstones named Durkee Hill greenstones, after the highest elevation in the tract, known locally as Durkee Hill. The best exposures of these greenstones occur on this hill.

The Durkee Hill greenstones consist of a complex of basic and ultra-basic intrusives and volcanics. They range in color from gray through various shades of green to black. They are massive and schistose, fine- to coarse-grained. Prominent among them are chlorite schists with well-developed schistosity. The more or less massive chloritic rocks contain large, often well-formed crystals of pyroxene, feldspar, and amphibole, some of the pyroxenes an inch long. Feldspar inclusions are present in many of the pyroxenes. Streamers and irregular areas of epidote are fairly abundant. A light gray feldspathic gneiss occurs irregularly among the greenstones.

If the volcanic members in the Durkee Hill greenstones are to be considered the equivalent in age of the Post Pond member (J. B. Hadley, 1942, p. 119), then there are rocks representative of more than one geologic period composing the greenstones. However, the presence in the greenstones of inclusions of Meetinghouse slates, some of them huge folded blocks, is the evidence that places the greenstones in the late- or post-Devonian. These inclusions are confined to the western border of the greenstones and conform to the regional structure. Bedding is excellently preserved in some of them.

BROCKLEBANK GRANITE

The Brocklebank granite acquires its name from Brocklebank Hill four miles south-southeast of the village of Chelsea. It is a medium-grained, light gray, binary granite. Good exposures of the granite can be seen in several quarries in the vicinity of Brocklebank Hill, the largest opening being in the hill itself.

The granite in the quarry on the east side of Brocklebank Hill is traversed by sets of joints striking northeast and northwest and with dips to the southeast and southwest, respectively. Some of the joints are mineralized; one dipping 78° SE is coated with large biotites, and another dipping 44° SW shows a development of pyrite, ilmenite, and tourmalines in a layer of quartz. However, not all of the joints having these bearings are mineralized.

Granite dikes and sills are numerous in proximity to the Brocklebank exposure, and throughout the limestone area as well. They vary in thickness from a few inches to tens of feet, and are usually fine-grained to aplitic, occasionally ending in quartz veins. The granite is cut by pegmatite dikes and incloses areas of pegmatite. Granite dikes were observed to cut the Gile Mountain schists 1½ miles southwest of Standing Pond. They have been correlated with the Brocklebank granite because of similar lithology and structural evidence.

Because the Brocklebank granite intrudes rocks of lower Devonian age, it must be either late- or post-Devonian. The writer favors a late Devonian age on the basis of structural evidence.

BASIC DIKES AND SILLS

Several varieties of basic dikes and sills occur in both the Gile Mountain schists and the Memphremagog formation. They are black and fine- to medium-grained. Some of them carry sulphides. Those observed range from 3½ to 30 feet in thickness. A dike with a visible thickness of 7 feet cuts the Gile Mountain schists in an east-west direction, in the bed of Lord brook 1¼ miles south of the Elizabeth mine.

Since the youngest rocks they intrude are of lower Devonian age, they are considered younger. They appear not to have been affected by the late Devonian orogeny and have, therefore, been made post-Devonian. One dike could be traced along a straight course for a distance of 400 feet.

PEGMATITES

Pegmatites appear to be restricted to the area covered by the Memphremagog formation. They occur in irregular areas within the granites, and as dikes cross-cutting granite sills and the sediments, including quartz veins paralleling the schistosity. The pegmatites are the youngest of the acid rocks and were very likely intruded during the later stages of the late Devonian orogeny.

In thickness the pegmatites are usually under a foot and carry quartz, feldspar, and muscovite. In a few cases, accessory minerals are present, such as garnets and bundles of amphiboles.

QUARTZ

Quartz is present in all the rocks of the Strafford quadrangle. It occurs in veins, lenses, and irregular masses, which are mostly conformable with the schistosity and bedding. Some quartz veins cut across the beds. Undoubtedly, there are several generations of quartz present. Quartz parallel to the schistosity and bedding of the sediments is probably original with the sediments. Some quartz veins are pegmatitic, carrying small amounts of white feldspar and muscovite, and represent introduced quartz.

Many of the quartz veins are mineralized. Some of them contain ilmenite, others pyrite, not so often chalcopyrite, and still others carry tourmaline. The most conspicuous mineral in the quartz veins is kyanite. Blades of kyanite with its characteristic blue-white color occur in sheaves, of which individual blades sometimes attain a length of 5 inches or more.

STRUCTURE

GENERAL STATEMENT

The major structure in the Strafford quadrangle is the Strafford anticline. This anticline has been observed and described by C. H. Hitchcock (1912,

p. 113). However, the most striking and complex structural features on the quadrangle are, what the writer has chosen to call, the zig-zag folds. They are exhibited by the Standing Pond amphibolite near the village of Strafford and to the northeast. One can, perhaps, best imagine them by bending his outstretched arm part way toward the body, then rotating the forearm ostensibly through 180° to produce the inverted limbs.

With the exception of two prominent faults which cross the southeast corner of the quadrangle, faulting is subordinate to folding. Minor faulting occurs as small displacements to be measured in inches, often clearly shown by offset pegmatite dikes, quartz veins, and beds. Drag-folds plunging predominantly to the northeast are common throughout the whole region. Granite intrusions occur in the northwestern part of the region and mixed basics in the southeastern part.

THE STRAFFORD ANTICLINE

The dominant structure in the Strafford anticline is schistosity which is essentially parallel to the bedding, excepting where the bedding deviates from it in minor folds. The dip of the bedding is often less steep than that of the schistosity, but the reverse condition also has been noted. By and large, the dip of the schistosity is steeper where the beds trend north and northeast than where their trends are west and northwest. From the axial region of the Strafford anticline eastward, the dips of the schistosity increase, becoming vertical at the Monroe fault.

The Strafford anticline has a north-northeast trend in conformity with the regional trend, and plunges in this direction. It is deformed in its northward extension, as shown structurally, and by the course followed by the anticlinal axis. In the "oval" of the anticline, the axis lies slightly to the east of a center line, which, along with average steeper dips on the east than on the west limbs, reveals a slight overturn to the east. The crest of the anticline is more easily definable in the "oval" portion than it is north of Kibling Hill where the anticline broadens and gradually loses its identity. West of the village of South Strafford the anticlinal axis turns to the northwest and at Kibling Hill it resumes a northeasterly direction. This fold in the anticlinal axis suggests two periods of folding, further evidence for which will be discussed elsewhere in this paper.

The younger Gile Mountain schists flank the Memphremagog formation on both sides of the "oval" section of the anticline, but farther northward they lie only on the east and northeast flanks. The Gile Mountain schists are believed to have had a greater westward extension formerly, and to have since been eroded. The serrated northeast-trending contacts between the Gile Mountain schists and the Memphremagog formation northeast of the village of Strafford are due to folds plunging at low angles. Contacts along the strike of the formations are smooth. A glance at the accompanying geological map will show the Standing Pond amphibolite to be in the limestones farther from the schist border to the north than to the south of the village of Strafford.

This is so here because there is a smaller thickness to be eroded where the beds have gentler dips than where the dips are steep.

In the "oval" section of the Strafford anticline the minor folds are progressively more overturned toward the crest where many of them are practically recumbent, and north of this section strong overturning and recumbency are common in the folds. On the east limbs of the anticline the overturning is to the west and on the west limbs, to the east.

Bordering the "oval" segment of the Strafford anticline on the west is a syncline of Gile Mountain schists overturned to the east. The syncline gradually narrows northward and becomes structurally more complicated at its north end, where an extremely narrow, overturned appendage curves around to the northwest. The plan of this syncline opening to the south gives the impression that the syncline has a plunge to the south. However, the drag-folds indicate a plunge to the north. These observations seem to show that the structure is a syncline in which the plunge is inverted. Folds with inverted plunges have been discovered in other regions (M. P. Billings, 1937, p. 522).

THE ZIG-ZAG FOLDS

This type of folding so well displayed by the Standing Pond amphibolite and, to a lesser degree, the coarse garnet schist, appears to be restricted to the area in which the anticlinal axis of the Strafford anticline turns to the northwest. In fact, this change in the direction of the anticlinal axis and the axes of the zig-zag folds parallel to it are genetically related. The forces producing these intricate folds have broken up the original symmetry of the Strafford anticline by causing the migration of the crest of the major fold to the west, and, at the same time, flattening and broadening its nose.

The fact that the zig-zag folds increase in magnitude southwesterly, and plunge in a northeasterly direction, gives the impression that the major deforming pressures came from that direction. Faulting might be cited as added evidence giving credence to the above impression. Faults of small magnitudes along fractures striking northeasterly, occasionally displacing veins, occur within these folds. Moreover, the almost complete absence of Standing Pond amphibolite between the lower strip of Gile Mountain schist and the Memphremagog formation on the southwest slope of Grannyhand Hill leads to the supposition that a thrust fault concealing the amphibolite exists here. It is not difficult to conceive of thrusts accompanying folding of this type. The thrust plane, in this case, dipping to the northeast implies further that deforming pressures were directed from the northeast.

A possible origin of the forces which deformed the Strafford anticline and produced the associated zig-zag folds is suggested in the proximity of the thick granite sill at Brocklebank Hill. This sill lies conformably in the nose of the Strafford anticline and its plunge indicates the direction of intrusion to have been, in general, from the north. Judging from the location and attitude of this igneous body, it is difficult to resist the thought that the igneous masses intruded the sediments from the north or northeast, generating the pressures which ultimately resulted in the production of the zig-zag folds and the distortion of the Strafford anticline. The steep dips at the south end of the major anticline, in contrast with those to the north, are also suggestive of forces acting in a southerly direction. The fairly symmetrical oval shape of the southern half of the Strafford anticline causes the suspicion that it is underlain by an igneous body which was intruded from a northerly direction.

It has been suggested that a shearing couple applied in a northeast-southwest direction might have caused the formation of the zig-zag folds. This would fit the case very well and would appear to have support in the recorded minor faulting along northeast-southwest fractures, and in shear zones along which faulting and mineralization have taken place in the Elizabeth mine. That the rocks have undergone plastic flow is in evidence both in the schists and the limestones, especially in the latter. Intercalated schists and quartz are frequently seen ruptured and drawn apart along the strike, due to attenuation of the beds caused by plastic flow. Good examples of thinning along the limbs and thickening in the saddles of folds may be seen in the Elizabeth mine. The ore behaves structurally in the same way. It appears conceivable that a shearing couple active in rocks under a great load could have formed the zig-zag folds. For reasons cited above, the writer is inclined to favor the conception of unbalanced stresses applied from northeast and southwest directions, the greater stress coming from the northeast.

The manner in which the zig-zag folds were formed may be rather crudely explained by arching a conveniently wide strip of paper with its axis parallel to that of the Strafford anticline. Since it is conceived that the original trend of the anticlinal axis conformed with the regional structures and, therefore, had a presumably undistorted north-northeast and south-southwest trend, the arched strip of paper should have the same orientation. This stage in the analogy represents a section of the Strafford anticline as it appeared at the end of an earlier period of folding and before the formation of the zig-zag folds.

Now imagine stresses opposing each other from the northeast and southwest, respectively, or a shearing couple practically paralleling the axial trend of the anticline. Incidentally, the following sequence in the analogy of the folding can best be demonstrated by using paper with a great amount of flexibility. Forces acting in these directions constitute the second period of folding. The next procedure is to apply the northeast-southwest directed stresses, either simple compression or a shearing couple, to the properly oriented anticlinal section. If the stresses are correctly applied, the axis of the folded section soon will be seen to bend horizontally into a northwesterly direction. This cross folding is continued until the paper model has been brought into a position simulating that of the original fold. During the process of developing the northwesterly bend in the anticlinal axis, and especially if sufficient resistance is employed, either actual or imaginative, the stresses will produce the type of folds exhibiting a zig-zag pattern, herein named zig-zag folds.

The Standing Pond amphibolite and the coarse garnet schist already have

been referred to as excellent horizon-markers. This distinctive characteristic is especially valuable in disclosing the most complex structures in the region. North of Gilman Hill the Standing Pond amphibolite is concealed under the Gile Mountain schists, appearing to the north in a few places along the contact of the schists with the Memphremagog formation. From Gilman Hill southward to the first abrupt change in strike this amphibolite is in the original order of stratigraphic sequence, with the accompanying coarse garnet schist underlying it, but from this first abrupt turn northwestward to the sharp bend 1¾ miles northwest of the village of Strafford the stratigraphic sequence is overturned, with the coarse garnet schist overlying the amphibolite. The Gile Mountain schist also shows a reverse order along this limb. In their southwestward trend to Grannyhand Hill, the beds are again in normal stratigraphic sequence, but an overturn exists where they once more trend northwesterly to the north end of the village of Strafford.

Continuing from here northwesterly into the area of the limestones, the amphibolite appears to be concealed, but a few folded exposures of coarse garnet schist with variable dips have been recorded on the southwest slope of the spur trending southeasterly toward the village of Strafford. On the slope directly west of the village of Strafford the same inverted horizon continues its northwest strike in an overturned fold, returning southeasterly as beds right side up and terminating on the same slope just south of where they began. From this point along the schist-limestone contact on Grannyhand Hill to the brook about half a mile southwest of the summit of Whitcomb Hill, the Standing Pond amphibolite occurs in limited exposures in two places, the coarse garnet schist apparently being entirely absent.

This normal stratigraphic sequence continues around the "oval" of the Strafford anticline, but here the schist underlying the Standing Pond amphibolite does not carry the large garnet porphyroblasts. Slightly more than half a mile north of Standing Pond the underlying schists again carry the conspicuous garnets which are continuous into the Randolph quadrangle. Northward the horizon-markers continue in normal order until they return on the southwest side of the narrow, curving fold appended to the overturned syncline of Gile Mountain schists bordering the "oval" of the Strafford anticline on the west. For a short distance on the west side of the re-entrant between the syncline and its appendage fold the beds are right side up, but in rounding the north end of the syncline they become inverted again. They continue in this relationship southwesterly for about 3 miles when the structure becomes somewhat obscure. From the White River valley on, the coarse garnet schist appears again, but bordering the Standing Pond amphibolite on its southeast side.

It will be noted that the zig-zag folds on the northeast limb of the Strafford anticline are overturned to the southwest, and the narrow, arcuate, appendage fold on the southwest limb, to the northeast, and that these folds are more closely folded and overturned near the anticlinal axis. The plunges of the zig-zag folds are in the direction of dip of the beds, and if coincident with the dip of the beds and having equal values on both limbs of the fold, the beds will be parallel and will not meet when projected to restore their original extent. However, it is unlikely that such agreement in the dips and plunges in this type of fold exists, although it might be approximated, when the projection of the beds would have great length. The zig-zag folds on the Strafford quadrangle very probably were closed at one time in their history.

FAULTS

Two prominent faults cross the southeast corner of the Strafford quadrangle in a southwest direction. They are the Ammonoosuc thrust and the Monroe fault, the former extending about 1⅓ miles on the quadrangle and the latter about 3¾ miles. The Ammonoosuc thrust has been given detailed description by Billings (1937, p. 525-530) and Hadley (1942, p. 154-156).

On the Strafford quadrangle the Ammonoosuc thrust forms the contact between the Durkee Hill greenstones on the west and a narrow tract of quartz-mica schists and quartzites on the east, correlated here with the Gile Mountain schists farther to the west for reasons of lithologic similarities and structure. The beds southeast of and including much of the Meetinghouse slates dip to the northwest, the dips becoming gentler to the southeast. Northwest of the Meetinghouse slates the dips of the Gile Mountain schists are easterly. These contrary dips indicate a syncline to the southeast of the Strafford anticline. They also show an overturn to the southeast and the minor folds indicate a plunge to the northeast.

Bordering the narrow area of Gile Mountain schists on Blood Mountain are amphibolites closely resembling the Standing Pond amphibolites. Because of similar lithology and stratigraphic position, they have been correlated with the Standing Pond amphibolites. The writer is of the opinion that in pre-Ammonoosuc time the Gile Mountain schists on the east limb of the syncline extended farther to the northwest and that much of this formation is now concealed by the Ammonoosuc thrust. It appears, then, that the width of the syncline was much greater before the development of the Ammonoosuc thrust.

The Durkee Hill greenstones overlying the thrust are strongly contorted and sheared, and contain much quartz in proximity to the fault contact. Layers of quartz on cleavage and fracture surfaces are often slickensided. Minor faults trending athwart the strike of the cleavage, shown by quartz stringers, have been recorded with small displacements measured in inches. The underlying Gile Mountain schists are likewise sheared and contain slickensided quartz on the surfaces. The schists are not as contorted as the overlying greenstones. The Ammonoosuc thrust follows a straight course in depressions elongated with its strike, which is southwesterly.

The Monroe fault lies between the Meetinghouse slates on the west and the Durkee Hill greenstones on the east, and passes through Union Village where it crosses the Ompompanoosuc River. This fault is detected by a stratigraphic break and excessively steep dips, many of them vertical, along its trend. These steep dips extending for some distance away from the fault on both sides might perhaps be construed as evidence determining it as a gravity fault in which the western side has apparently gone down with respect to the east side. However, the Monroe fault, from evidence obtained elsewhere throughout its long extent, is considered a thrust fault. Like the Ammonoosuc thrust, the Monroe thrust crosses the area in southwest-trending depressions, along a trace almost equally straight. As shown by the attitudes of the rocks in the bordering formations, the dip of the Monroe fault is very steep to the northwest.

Minor faulting is not uncommon throughout the region, and a few faults more or less localized in the Standing Pond amphibolite have been observed. The gap in the Standing Pond amphibolite southeast of Gilman Hill and the sudden piling up of the beds in tight, overturned folds are indicative of a fault at this place.

GEOLOGIC HISTORY

The area represented by the Strafford quadrangle was once a part of an early Paleozoic geosyncline in which marine sediments were being deposited. The geologic history of this region begins with the middle Silurian when the sediments now constituting the Memphremagog formation were laid down. These sediments accumulated on the sea bottom as dolomitic muds and sands, with smaller amounts of calcareous muds. Toward the end of the epoch increasingly more sand was deposited, accompanied by some volcanics, attesting to a period of mild volcanism.

In lower Devonian time deposition was dominated by sands, with small amounts of limy and graphitic muds, now the Gile Mountain schists. As the lower Devonian advanced the depositional facies changed to mud, when the Meetinghouse slates were deposited. Sedimentation in the region was concluded with the deposition of the Meetinghouse slates.

Toward the end of the Devonian a major disturbance occurred. The sedimentary rocks were metamorphosed and compressed into folds with north-northeast trends. The Brocklebank granite was intruded into the strata from a northerly direction.

The Strafford anticline with an array of minor folds was the major structure to form at this time, and the rocks flanking it on the west and east were folded into synclines. It is the writer's belief that these folds were evolved during the early stages of the late Devonian orogeny and mark the end of the first period of folding. When the intrusion of the granites was well under way the second period of folding was initiated when the zig-zag folds were formed and the northern half of the Strafford anticline was deformed.

The major stresses generated in large part by the invading granite and active in a general southerly direction not only were instrumental in producing the zig-zag folds but quite likely caused a broad movement in a southerly direction, which finally culminated in the evolution of the Ammonoosuc thrust to the southeast. During this time shear planes, striking practically north and with very steep dips, developed in the region about the "oval" of the Strafford anticline. These shear planes gave rise to faults, along some of which ore mineralization has taken place.

The Monroe fault developed at approximately the same time as the Ammonoosuc thrust and, because of its steep dip, is believed to intersect the latter at depth. The dip of the Monroe fault is unusually steep, which is accounted for by folding. Basic intrusives probably accompanied the faulting along the Monroe fault, invading older volcanics (probably Post Pond of Hadley, 1942, p. 119), and rafting fragments of Meetinghouse slates of Devonian age.

Basic dikes and sills were intruded into the sediments throughout the eastern portion of the area sometime in the post-Devonian. After Devonian time, erosion became the dominant geologic agency and, continuing into the present, has exposed the rocks and their structures as we see them today.

CORRELATIONS

The Memphremagog formation appears not to be present among the formations of western New Hampshire, unless the middle Silurian Fitch (Billings and Cleaves, 1934, p. 415) represents a change in facies of the Memphremagog formation eastward. Both formations have yielded fossils of middle Silurian age. The overlying Gile Mountain schists strongly resemble the Littleton formation (Billings and Cleaves, 1934, p. 418) lithologically and, like the Littleton formation, rests upon beds of middle Silurian age. On the basis of fossils they both belong to the lower Devonian. Because of these relationships, the Gile Mountain schists are believed by the writer to be the equivalent of the Littleton formation.

The Albee formation and Ammonoosuc volcanics (Billings, 1937, p. 472, 475) are missing on the Strafford quadrangle. This appears to be due to the northeasterly plunge of the Durkee Hill greenstones which they would be expected to overlie.

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III

General Petrology in Strafford Township

ELBRIDGE C. JACOBS

Fifteen rocks collected by Professor Doll and the writer have been sectioned and studied. They are included in the region within five miles north of Copperas Hill, two miles southwest of the hill and also the vicinity of the Elizabeth Mine. They include two drill cores.

In these studies no attempt has been made to separate the constituent minerals and determine their optical constants; white garnets are called grossularite and red ones, almandite.

The rocks are wholly metamorphic. The lay reader is referred to a brief summary of metamorphism in the twenty-first Report of the Vermont State Geologist (1937-'38), page 26.

THE MEMPHREMAGOG FORMATION

THE STANDING POND AMPHIBOLITE[1]

Location CB-1; section No. 576; 3/8 mile north of Strafford village. The hand specimen is a finely-laminated dark green rock weathering dark brown. It is of schistose structure and folio-granoblastic texture with metacrysts (porphyroblasts) of many minerals.

Hornblende makes up probably 80 percent of the slide and occurs in prismatic sections up to 10 mm. long and 6 mm. wide, generally oriented and giving the schistose structure to the rock. It is much corroded and chloritized, the chlorites including diabantite and penninite, with their abnormal birefringent colors. Quartz, epidote, carbonate and magnetite have also been developed in the hornblende together with a small amount of biotite, giving the blastopoikilitic, or sieve, structure.

Sphene is very abundant with its characteristic idioblastic shapes, the largest 0.45 x 0.35 mm. Magnetite is extensively developed in irregular grains as well as in euhedral and subhedral crystals, the largest 1.2 x 0.90 mm. Epidote occurs in small, irregular grains, maximum 0.5 x 0.2 mm., and there are a good many small sections of clinozoisite. A few scattered grossularite garnets are noted in the chlorite. Faint patches of biotite have developed in the chlorite together with several small subhedral sections.

The sials[2] consist of orthoclase, including one or two Carlsbad twins, and plagioclase. All show strain shadows and are considerably altered to sericite, kaolin and other minerals. Plagioclase is subordinate to the orthoclase in

[1] See the geological map in the pocket of the Report.
[2] "Sials" include quartz and feldspar.

amount and is of the andesine-oligoclase variety. The whole section is "sprinkled" with fine mineral dust, mostly sulphides.

Considerable pyrrhotite, some including tiny rods of rutile, is found, fresh and unaltered to leucoxene. The pyrrhotite includes grains of the non-metallic minerals and was evidently introduced later. Chemical tests on the ground rock show titanium, manganese, and a trace of copper. The manganese belongs to the hornblende.

The rock is hornblende-schist: an amphibolite. Of all the slides studied this represents the lowest grade of metamorphism. Biotite zone (just emerging from the Chlorite zone).

A partial chemical analysis of the amphibolite gave:

SiO_2	47.15 percent
Combined oxides[1]	38.97 percent
CaO	7.52 percent
MgO	6.67 percent
	100.31

This analysis and the absence of free quartz in the section suggest a basic igneous rock as the progenitor of the amphibolite; it may well have been a lava flow as Professor Doll suggests.

Location CE-1; section 578; one-fourth mile north of Old City. The hand specimen is a dark-green, very fresh needle-amphibolite with a few fine grains of almandite garnet. It weathers black.

The slide is much like No. 576 but the amphibolite is probably actinolite, comprises perhaps 90 percent of the whole, is fresher and only slightly chloritized. It occurs in long, decussate prismatic sections, maximum 1.20 x 0.75 mm. There are no micas but a good many xenoblasts of grossularite including one "monster," 1.45 x 1.30 mm. in size, slightly chloritized and containing films of iron oxide in the cracks. Almandite is not seen in the slide but occurs in the hand specimen, as noted.

The sials include quartz, orthoclase, and plagioclase nearest to andesine. Accessory minerals are sphene, clinozoisite, a few grains of ilmenite somewhat altered to leucoxene, carbonate, a few apatite needles, and zircons.

Chalcopyrite grains are abundant and as large as 0.85 x 0.85 mm.; a smaller amount of pyrrhotite is present. The fine mineral dust noted in most of the other slides is lacking here. Much iron oxide has resulted from the oxidation of the sulphides; thin films of limonite are seen in the crystal boundaries.

The rock is a very pure actinolite-schist: a quartz-amphibolite.

Almandite zone.

THE COARSE GARNET SCHIST (*page 17*)

Location CD-2; section 577; McMaster Hill, near the contact with the amphibolite belt shown on the geological map (Plate III).

The hand specimen shows a sericite schist in contact with a dark schist containing red and black garnets which, in the field, reach 2.5 inches in diameter.

[1] Fe_2O_3, Al_2O_3, TiO_2, Mn_3O_4. Of course a large part of the iron (even the whole of it) may exist as FeO.

The slide reveals an exceedingly coarse garnet-quartz-biotite schist of grano-folioblastic texture containing very large metacrysts. The garnets include small grossularite grains and larger almandites (maximum 0.5 x 0.6 mm.). The garnets are much compressed, fractured, and contain inclusions of quartz and some zoisite. Some of the cracks are filled with pyrite and possibly chalcopyrite, which shows that these sulphides are younger than the garnet.

The quartz occurs in elongated grains showing strain shadows and inclusions. It is probably the second mineral in abundance; the grains are as large as 1.3 x 0.8 mm. Large sections of andesine-plagioclase, a small amount of sericite and a few grains of microcline also occur.

Biotite is large in amount and occurs as fairly well oriented laths, maximum 3.2 x 0.9 mm. Grains of clinozoisite with its abnormal birefringent colors, rutile, spinel, and zircon are noted. A good deal of graphite dust and a great deal of sulphide dust are scattered over the slide. More or less iron oxide has resulted from the oxidation of the sulphides. No hornblende is present; chlorite has been used up in the production of the garnets and biotite.

Almandite zone.

THE LIMESTONES AND SCHISTS (*page 16*)

Location CE-9; section 580. The specimen came from a location about five-eighths of a mile south of McMaster Hill, near the amphibolite belt. The hand specimen is a schistose limestone with gray and yellow bands and weathering dirty brown. It freely effervesces with cold, dilute hydrochloric acid. Its structure is schistose and its texture grano-folioblastic.

The section shows a mosaic of fine, irregular sial grains as large as 1.2 x 0.70 mm., much compressed and outlined by films of limonite. The mosaic is crossed by narrow, oriented laths of bleached biotite and a small amount of muscovite. Maximum biotite laths measure 1.8 x 0.90 mm. Calcite forms about 50 percent of the section.

The sials are: quartz with fine mineral inclusions, orthoclase about equal to it in amount, a subordinate amount of plagioclase and a few grains of microcline. A few small grossularite garnets, tourmalines, and possibly apatites are noted. Much pyrrhotite and magnetite occur in fine grains, stringers in the schistosity, and knots. Considerable graphite is noted.

The rock is a silicious biotite-calcite schist. It bears out Professor Doll's suggestion of "a transition zone between the calcareous formation (Waits River limestone) to the west and the silicious formations (Gile Mountain schist) to the east." The influence of the adjacent amphibolite is seen in the development of biotite and magnetite.

Grossularite-garnet zone.

Location SE-7; section 587, about 2¼ miles S.W. of Copperas Hill. The hand specimen is a light-gray gneiss with included mica foliations. It is full of fine sulphide grains.

The section shows a gneissose structure and grano-folioblastic texture, with metacrysts of mica, calcite and a few small grossularites. The sials greatly predominate and are quartz, orthoclase, and a small development of plagioclase. The sials are from 5.3 x 1.4 mm. to the finest grains in size; they are generally elongated and show strain shadows. The micas are small in amount and are prevailingly bleached biotite in fragmentary laths and larger masses. Narrow muscovite and biotite laths outline the sial grains. Calcite, maximum 0.68 x 0.53 mm., occurs in fragmentary grains some of which are twinned. A few small grossularites and smaller zircons are noted. No chloritization has taken place. As in CF-17 the section is full of sulphides, including chalcopyrite and pyrrhotite as large as 0.35 x 0.25 mm. and diminishing to the finest dust. Some of this dust occurs as sinuous trains in the quartz.

The rock is a quartz-orthoclase-mica gneiss.

Grossularite-garnet zone.

GILE MOUNTAIN SCHIST *(page 18)*

Location SD-27; section 588; near summit of Morrill Mountain; about 1½ miles west by south of Copperas Hill.

The hand specimen is a compact, silvery-gray, schistose rock with mica foliations, full of fine magnetite and sulphide grains, and weathering brown.

The section shows a schistose structure and grano-folioblastic texture with fragmentary metacrysts of mica and zoisite, and scattered small grossularites and opaques. The sials which enclose these minerals consist of quartz and orthoclase grains, as large as 0.55 x 0.25 mm., generally elongated and strained. The micas are biotite and sericite (maximum, 0.68 x 0.25 mm.) the former predominating, generally in thin laths outlining the sial grains. Grossularite garnets (0.08 x 0.05 maximum size) are scattered through the section in oval and elongated grains. One blastopoikilitic almandite appears, 1.7 x 1.3 mm. in size, much corroded, altered to quartz and orthoclase, and showing some retrogression to chlorite. Fragments of penninite are associated with the micas. Grains of rutile and zircon are also noted.

The sials are full of grains of magnetite much altered to hematite, and fine pyrrhotite and perhaps chalcopyrite dust.

From its silvery appearance the rock may be classified as a garnet-biotite-sericite schist.

Almandite zone.

Location CF-3a; section 584; south slope of Whitcomb Hill, in the small amphibolite belt.

The hand specimen is a gray, coarsely laminated rock, with fine, dark bands, studded with small almandite garnets; largest 5 mm. diameter. The section shows a gneissose structure and grano-folioblastic texture. The sials are made up of alternate bands of coarse and fine grains from 1.3 x 0.8 to 0.05 x 0.05 mm. in size, somewhat elongated and oriented and showing the usual strain shadows. Quartz predominates, orthoclase is present, and there is considerable plagioclase, nearest andesine.

The section contains many metacrysts of which those largest in amount are almandite garnets, the largest 4.4 x 1.2 mm. These almandites are largely skeletal but subhedral crystals are also seen. Some of the garnets are much altered to quartz and sheaves of penninite, thus showing retrogression. Considerable grossularite is also present in small oval grains.

Next in amount comes a very pale green hornblende in much corroded prismatic and basal sections, the largest, 2.8 x 1.2 mm. It is much altered to penninite small sheaves of which are included in it, and large sheaves, maximum 1.0 x 0.7 mm., are in contact with the amphibole.

Sphene occurs in scattered crystals (max. 0.75 x 0.35 mm.) and in small nests. Grains of rutile are present (max. 0.6 x 0.4) partly altered to ilmenite and this to leucoxene. Scattered grains of ilmenite altering to leucoxene are noted and more or less epidote. A small amount of pyrrhotite and resulting limonite, a good many grains of zircon and a very little carbonate complete the list of this very interesting mineral assemblage. The rock is a garnet-hornblende-quartz-gneiss.

Almandite zone.

Location CF-3b; section 585.

The specimen came from the south side of Whitcomb Hill, somewhat north of CF-3a, at elevation 1650. It is a light-gray, fine-grained massive quartzite with fine grains of almandite garnet and spangles of white mica.

The section shows a mosaic of irregular sial grains (maximum 0.70 x 0.40 mm.) with quartz predominating and showing strain shadows and with much fine mineral dust. Almandite garnets are next in extent and exist as blastopoikilitic grains as large as 1.65 x 1.15 mm.; some are almost entirely altered to chlorite (probably clinochlorite), quartz and dendritic hematite. The garnets thus show retrogression. There are also scattered grossularite grains. Muscovite comprises most of the micas and appears in the cracks of the sial grains and as chubby laths, maximum 0.80 x 0.18 mm. Narrow laths of biotite are much chloritized and show retrogression. There is much olive-green chlorite (clinochlorite?), occuring in sheaves in the almandites and also as thin fragments in the cracks; it represents the complete chloritization of former biotite grains. Small zircons and one or two grains of tourmaline are seen. Grains of magnetite and pyrrhotite are scattered through the section and a very few grains of chalcopyrite.

The rock is a garnet-mica-quartzite.

Almandite zone.

Location CF-17; sections 586 a, b, c, d; about five-eights of a mile northwest of CF-3 and considerably removed from the surrounding amphibolite belt.

The hand specimen is a dark, brownish-black, thinly foliated schist, weathering dirty brown, and containing red garnets as large as eight mm., and radiated fibers of a dark mineral.

The sections show that the rock is a sillimanite-kyanite-biotite-garnet schist. The structure is schistose, the texture prevailingly folioblastic.

Broad laths of biotite extend across the slide, interlaminated with clinozoisite and fibers of sillimanite—in some of the slides large metacrysts of sillimanite are seen, slightly pleochroic from contained biotite. Elongated quartz and orthoclase and narrow bands of graphite are also included.

The garnets are chiefly almandite and a few small grossularites. The almandites are as large as 2.3 x 2.1 mm.; some are much cracked and corroded while others have suffered less alteration. The kyanite occurs in aggregates, maximum 1.4 x 1.2 mm.

For accessory minerals, a few small rutiles, a small amount of magnetite and pyrrhotite and some fine grains of (probably) gold occur. Very fine sulphide dust is scattered over the slides. It might be well to assay this rock for gold.

Sillimanite zone.

Location SR-43, section 589; about one-half mile southwest of Copperas Hill.

The hand specimen is a silvery-gray schist enclosing dark granular material which includes garnets, fine sulphide grains and mica flakes.

The section shows a schistose structure and folio-granoblastic texture with metacrysts of fresh, brown biotite making up nearly half the total area. The sials comprise quartz, orthoclase (the former in excess), maximum 0.90 x 0.57 mm., albite-plagioclase, maximum 0.60 x 0.60 mm., and a few grains of microcline. The sials show the usual strain shadows but are not so much elongated as in other slides. The biotite occurs in prismatic and basal sections, maximum 1.70 x 0.50 mm., generally oriented with the schistosity. It is much corroded and altered, chiefly to quartz. A good many grossularite garnets are scattered through the slide singly and in nests, maximum 0.25 x 0.20 mm.; some of them are somewhat anisotropic. There are possibly a few apatite needles. The opaques are difficult to determine but appear to consist of magnetite and pyrrhotite—and possibly chalcopyrite. They are not very numerous.

The rock is a biotite-garnet-sericite schist.

Grossularite-garnet zone.

Location SD-51; section 590; a few rods northwest of SD-43. The hand specimen is a dark, silvery-gray schistose rock with included red garnets. There are reticulated fibers on the surface as in section 586. These are probably kyanite.

The section resembles 589 in its structure but the biotite is bleached and less in amount, and new minerals appear. The structure is schistose, the texture grano-folioblastic with meta crysts of almandite, kyanite and clinozoisite.

The sials are quartz and sericite and vary in size from 0.70 x 0.55 mm. to very fine grains. The few large almandite garnets are subhedral or xenoblastic, much corroded and altered to biotite, sericite and limonite, thus showing retrogression; maximum size 1.75 x 1.15 mm. A few small grossularites occur. A very small amount of kyanite is seen in small, elongated aggregates; maximum 0.55 x 0.13 mm. Considerable clinozoisite occurs in small, prismatic sections, much corroded; maximum size 0.35 x 0.10 mm.

The section also contains a few tourmalines and many zircons. The opaques are ilmenite grains considerably altered to leucoxene, pyrrhotite and possibly chalcopyrite. Fine mineral dust is scattered through the section.

The rock is an almandite-kyanite schist.

Kyanite zone.

Specimen collected by the writer from the Elizabeth mine open cut; section 591.

The specimen shows a dark, granular, very impure limestone freely effervescing with dilute hydrochloric acid.

This was originally a silicious, aluminous, ferruginous sediment in which metamorphism produced crystalline calcite, much of it twinned, maximum grain size 1.5 x 1.5 mm.; average, 0.85 x 0.50 mm., with about an equal amount of sials: quartz and orthoclase (quartz predominating) and much plagioclase, nearest andesine; laths and basal sections of very pale brown mica, probably phlogopite; many small grossularite garnets; a good deal of clinozoisite with its ultra-blue interference color; a considerable amount of kyanite; many grains of rutile; and large and small grains of sphene, maximum 0.43 x 0.36 mm.

As was to be expected from its proximity to the mine, the slide shows many irregular grains of chalcopyrite and some pyrrhotite; the grains have a maximum size of 2.9 x 1.25 mm. Some of the grains include non-metallic minerals and therefore the sulphides are younger.

Although kyanite occurs in slides 586, 590, and 591 in relatively small amounts, there is a large development northeast of Copperas Hill, on Gove Hill, where specimens several inches long can be collected.

The rock is an impure, crystalline limestone.

Kyanite zone.

Specimen collected by the writer some distance west of the open cut, on the border of the dump; section 592.

The hand specimen is a dark-gray, compact, foliated rock weathering light brown.

Structure gneissose; texture grano-folioblastic with metacrysts of garnet and mica.

The sials are much compressed, show the usual strain shadows, and are outlined with thin laths of mica and limonite; they consist of quartz, orthoclase, and plagioclase too faint to determine.

The micas are seen on broad bands of interlaminated muscovite and biotite laths, oriented, some 0.9 mm. wide and running the length of the section

(26 mm.); narrow biotite laths and some muscovite laths have also formed in the sial boundaries, as noted above.

The garnets consist of small grossularites and a few large blastopoikilitic almandites, maximum 2.6 x 2.4 mm., much corroded, altered to quartz and orthoclase, and showing slight chloritization.

There are a few small grains of sphene, maximum 0.36-0.12 mm., and a few tourmalines, maximum 0.1 x 0.05 mm. A few tiny zircons and considerable fine mineral dust are noted.

The rock is a garnet-biotite gneiss.

Almandite zone.

DRILL CORES

Diamond drill cores being available, the writer thought it would be interesting to compare their mineralogy near the surface with that at depth. The cores selected were from the Bureau of Mines drill hole No. 18, at the south end of the Elizabeth vein zone, between the old South Mine and the main opencut, 1800 feet south of coordinate "10,000 feet N" (Plate I).

Section 594 was cut from a core seven feet below the surface. It shows a biotite-feldspar schist. Brown biotite occurs as long, oriented laths in broad bands running the length of the slide, some interlaminated with elongated sials; others in larger laths somewhat corroded and altered to quartz. The biotite is fresh and shows no chloritization; some of it is interlaminated with muscovite.

The sials are quartz (predominating), orthoclase, and plagioclase nearest andesine; they are much elongated, show strain shadows, and are covered with sulphide dust. They are generally fresh but some show alteration to sericite and muscovite. Their average grain size is 0.87 x 0.44 mm.

For the accessory minerals, a few small grossularite garnets, zircons and tourmalines are scattered through the slide. No carbonate is seen.

Chalcopyrite and less pyrrhotite occur in small grains and elongated stringers, the largest 1.7 x 0.50 mm., lying in the schistosity.

Grossularite-garnet zone.

Section 595, from 190 feet below the surface, shows about the same mineralogy but the biotite has a coarser grain size. It occurs mostly in large, fragmental prismatic and also basal sections, showing less orientation than 594. It is much corroded and chloritized—some of it is entirely altered to chlorite, thus showing retrogression.

The sials are quartz (predominant), orthoclase, and andesine-oligoclase, about equal in amount to the biotite.

The grains are generally elongate, cracked, show the usual strain shadows and contain a great deal of sulphide dust. The orthoclase is much sericitized and the plagioclase somewhat altered to a fine, flaky mineral, possibly saussurite. The average grain size of the sials is 0.77 x 0.48 mm. For the accessory minerals: Much carbonate (calcite or dolomite) occurs as small grains and elongated stringers; grossularite garnets are somewhat more numerous, scattered zircons and tourmalines also are seen.

There is much more chalcopyrite than in 594. It occurs in elongated grains and stringers, maximum 2.9 x 0.60 mm., in the schistosity; some include biotite and other minerals and so are younger. Pyrrhotite is subordinate to the chalcopyrite in amount. The rock is also a biotite-feldspar schist.

Grossularite-garnet zone.

The chief points of difference in the two sections are: the larger and coarser development of biotite, the greater alteration of the biotite and feldspars, and the greater amount of sulphides with increasing depth. The average grain sizes of the sials is about the same.

Of course a larger number of slides should be studied and also sections from greater depth in order to arrive at more definite conclusions.

CONCLUSIONS

Vermont is a state very largely of regional and dynamic metamorphism. The rocks of the Strafford area are made up of assemblages of high-temperature, stress minerals, formed in the meso- and kata-zones, at great depths below the present surface, before peneplanation took place.

Staurolite was not found in the sections but Professor Doll discovered it in the eastern part of the Gile Mountain schist belt. With this included, metamorphism has run the whole gamut of the metamorphic zones, from the practically Chlorite zone of the amphibolite belt to the Sillimanite zone of the aluminous schists in the Gile Mountain belt.

In a traverse across the Green Mountains,[1] from west to east, in the latitudes of Chittenden County, the rocks on the western border of the massive are found to belong to the Chlorite zone. The Biotite zone begins in the Underhill valley and continues across the Main and Worcester ranges where it is retrogressive to chlorite and is followed by the Almandite zone. Almandite appears in the Westford schist and increases in amount in the Green Mountain complex, reaching its greatest development on Mount Hunger, in the Worcester Range. Here much retrogression to chlorite has taken place. No metamorphism higher than the Almandite zone was found in the traverse. Thus metamorphism increases in intensity across the State from west to east, culminating in the Sillimanite zone on Whitcomb Hill.

The hydro-thermal influence of hidden magmatic bodies is seen in the presence of tourmalines in the thin sections and, indeed, in the sulphide ore itself.

[1] 21st Rep. Vt. State Geologist (1937-38).

IV

Vermont Mineral Industries

Elbridge C. Jacobs

These industries have been variously affected by the war.

ASBESTOS

The Vermont Asbestos Mines, Division of the Ruberoid Company of New Jersey, is engaged in developing its new property in Lowell, on the southeast flank of Mt. Belvidere where a large amount of long-fibered asbestos has been discovered, together with the short-fibered mineral in which Mt. Belvidere abounds. This deposit was first worked by the Lowell Lumber and Asbestos Company, about 1900. An aerial tramway 5,000 feet long, built by the Interstate Equipment Company and having a capacity of 100 tons of rock per hour, has been constructed to carry the asbestos-bearing rock to the old mill in Eden, on the south side of Belvidere, where it is finely crushed and the fiber recovered. Asbestos is classed as a "critical mineral" by the War Production Board and is in great demand. Unfortunately the company is so handicapped by labor shortage that only one shift per day can be maintained. The company was out of production for several months while the tramway was being constructed and the new quarry opened.

COPPER

See The Vermont Copper Company.

GRANITE

Owing to the acute labor shortage the granite companies are unable to supply the demand for monumental granite. The active companies are, in the Barre district: the J. K. Pirie Estate, Rock of Ages Corporation, E. L. Smith, Wells-Lamson Quarry Company, and Wetmore and Morse Granite Company; at Hardwick, the Woodbury Granite Company. No structural granite is being produced.

LIMESTONE

The chief demand is for agricultural lime. The active companies are: the Champlain Valley Lime Company, at Winooski; the Green Mountain Lime Corporation, at New Haven Junction; the Swanton Lime Works; the Vermarco Lime Company, at West Rutland; and the Vermont Associated Lime Industries, at Leicester Junction.

MARBLE

About 80 percent of the Vermont Marble Company's activities are in iron work for the war effort. The marble produced is very largely for monumental purposes.

SLATE

Owing to building restrictions and other causes the slate industry is probably at the lowest point in its history: less than five percent of normal. The active slate companies at present are: the Hinchy Consolidated Slate Company, of Hydeville; the Landscape Slate and Roofing Company, of Poultney; Pedro Brothers, of Fair Haven; the Staso Milling Company, of Castleton; the Vermont Slate Flooring Corporation and the Vermont Structural Slate Company, Inc., of Fair Haven.

TALC

There is an active demand for ground talc for its varied purposes, and for talc crayons. Companies engaged in the talc business are: the Eastern-Magnesia Talc Company, of Burlington, with mines at Johnson and Moretown; the Vermont Mineral Products Company, of Chester Depot, with its new mine in Reading; and the Vermont Talc Company, of Chester Depot, with its mine in Windham County.

MINERAL INVESTIGATIONS

During the last biennium the U. S. Bureau of Mines, the State Geologist, or both these agencies have examined a considerable number of mineral deposits in the State to see if they could be used in the war effort. These examinations have included graphite in Ripton, galena and zinc in Leicester (Lyon Hill); galena in Brandon, mica in Sherburne, Rochester and Woodbury; manganese in Lincoln and South Wallingford (the old Kinney Cobble mine once worked by the Carnegie Steel Company); molybdenum at Cuttingsville; the old pyrite-chalcopyrite deposit at Copperas Hill, Shrewsbury; and many old iron ore deposits.

Of these only the mica deposit in southwest Rochester, where a fairly promising deposit of muscovite mica is being worked in a small way by Mr. H. J. Fuller, of Chester Depot, and the old Burden iron ore bed in West Bennington seem to have any promise.

IRON ORE DEPOSITS

Iron production was a thriving industry in Vermont in the nineteenth century, in one instance as late as about 1880. Deposits were worked in Rutland, Windham and Bennington counties and today the remains of old stone, cold-blast furnaces which used charcoal for fuel are found in East Pittsford, Plymouth, Forestdale and East Bennington. The Conant furnace at Forestdale is the best preserved and is shown on Plate V but the air-blast pump

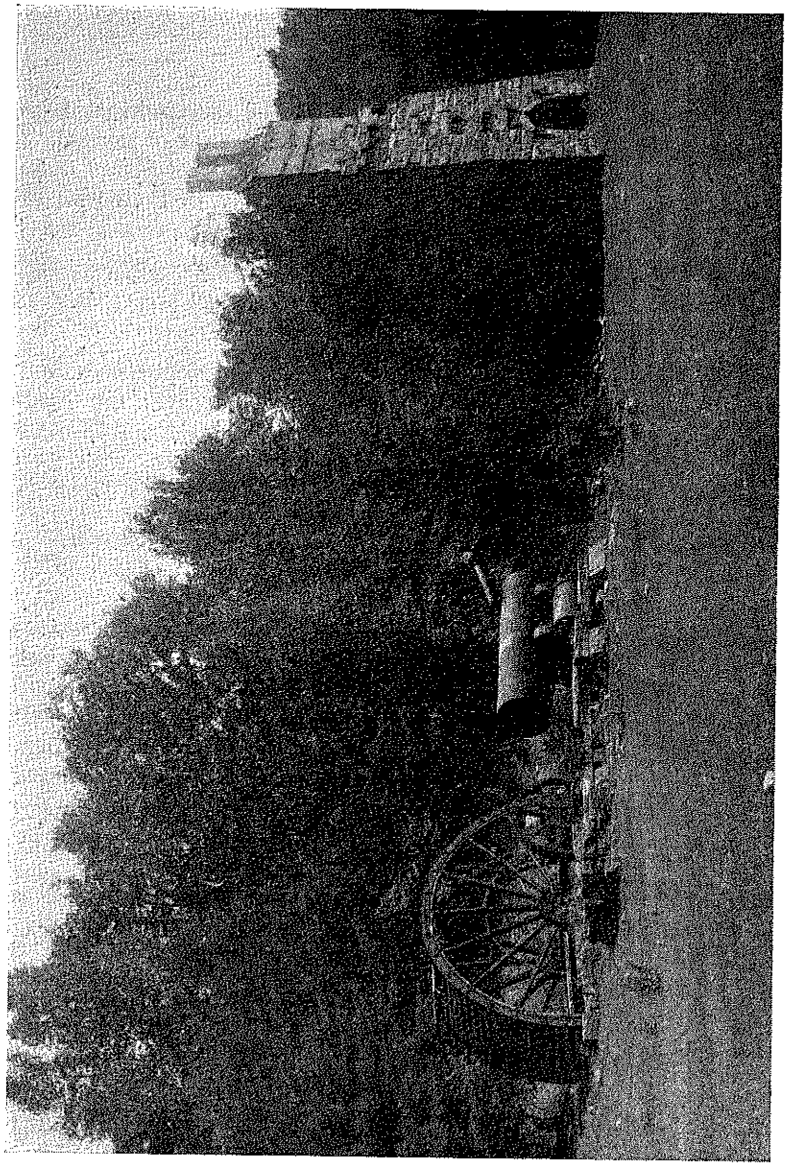


Plate V. Old Iron Furnace at Forestdale

and waterwheel and the stacks at the top of the furnace are missing. The furnace was originally about 35 feet high and was last in blast about 1853.

The ores appear to have been thinly bedded deposits of bog iron and hematite often associated with manganese minerals and kaolin. The ores in some instances contained so much manganese that they could not be used for the production of soft pig iron. Such was the case in East Bennington, along the Walloomsac River where those parts of the deposit rich in manganese were not mined, with the result that some manganese ore still remains but probably not in commercial quantities. Since the deposit is very near the river and not much above it, flood waters would interfere seriously with mining operations, as they probably did in the past.

The iron furnaces seem to have exhausted the iron deposits near them for no traces of ore are to be found in their vicinity, except at East Bennington.[1] The deposits more removed from the smelting centers may still contain ore but the old shafts are caved in and it probably would not pay to reopen them.

The most promising deposits today are the old Burden beds in West Bennington near the New York State line. These were mined years ago to supply the Burden blast furnace at Troy, New York, but operations were discontinued in favor of the magnetite deposit at Mineville, New York, so that commercial amounts of ore probably remain. This property has been acquired by Mr. Ferdinand Mayer, of Bennington, and some exploratory work has been done by Prof. T. T. Quirke of the University of Illinois. This work has been suspended and will be undertaken anew by the District Engineer of the Bureau of Mines when time permits. The Bureau has produced samples of good sponge iron from the deposit.

KAOLIN

The only company producing kaolin is Frank E. Bushey and Sons, of East Monkton; post office address, Bristol, Vermont.

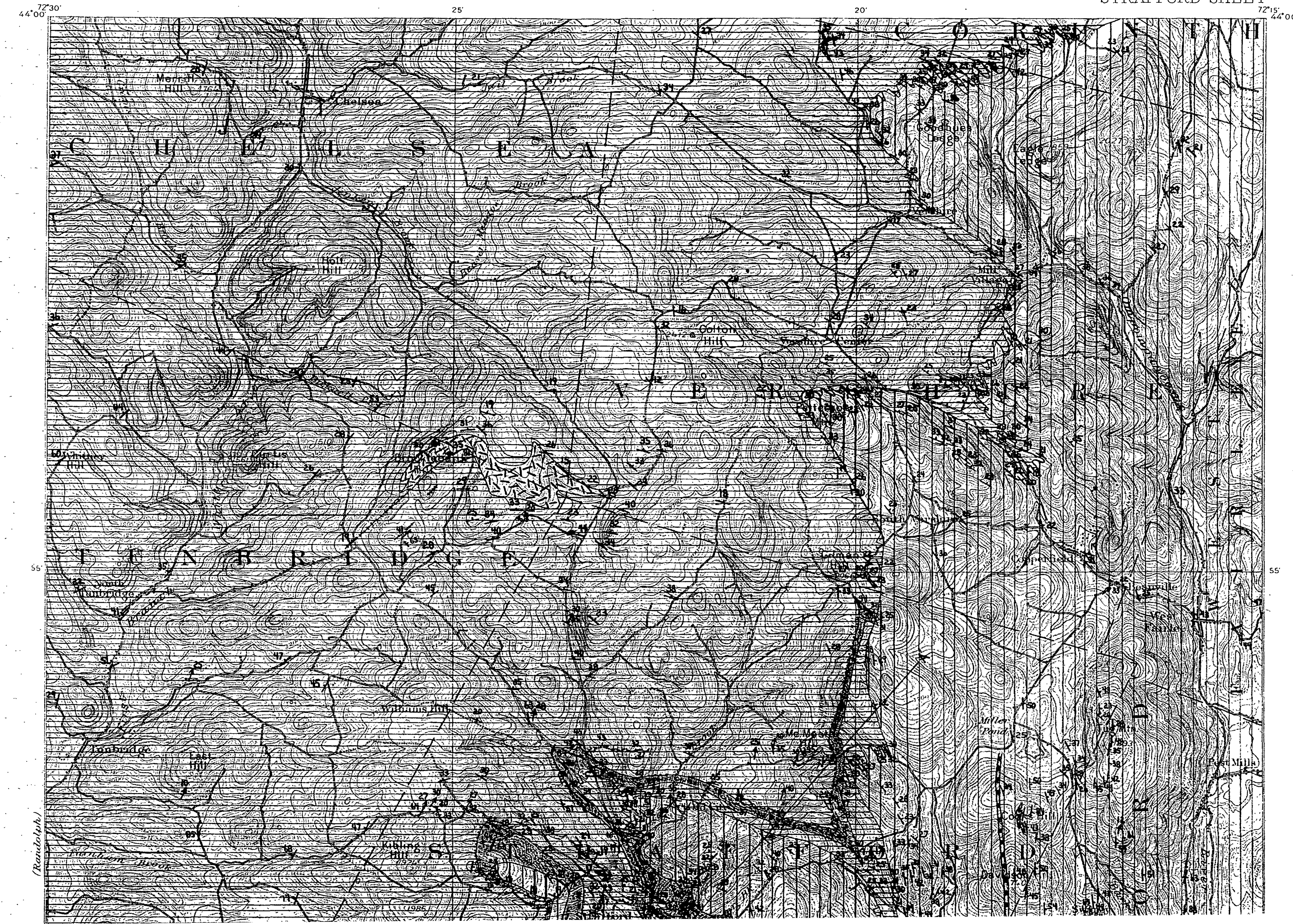
[1] See Iron Mining and Smelting in Bennington, Vermont; John Spargo, Bennington Historical Museum (1938).

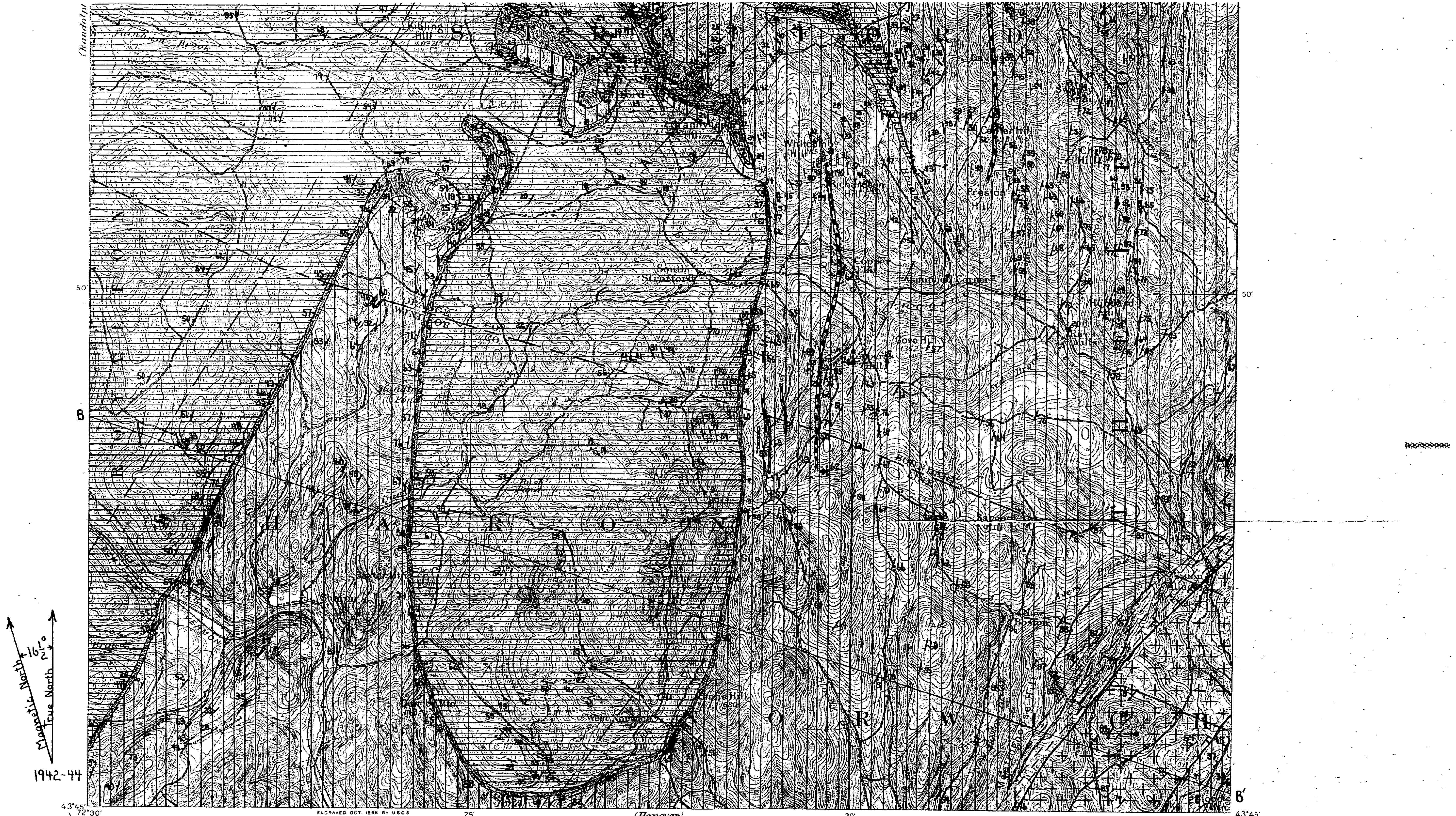
GEOLOGIC MAP AND STRUCTURE SECTIONS OF THE STRAFFORD QUADRANGLE, VERMONT

SHEET NO. 2

DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

VERMONT
STRAFFORD SHEET





Henry Gannett, Chief Topographer.
H.M. Wilson, Chief Geographer in charge.
Triangulation by U.S. Coast and Geodetic Survey.
Topography by G.E. Hyde and Jas. McCormick.
Surveyed in 1894.

ENGRAVED OCT. 1896 BY U.S.G.S.

Hyde | J.McC.

Scale $\frac{1}{62500}$

1 ½ 0 1 2 3 4 Miles

1 ½ 0 1 2 3 4 5 Kilometers

Contour Interval 20 feet
Datum is mean Sea level

Edition Dec. 1896, reprinted 1937

Polyconic projection. North American datum

This area surveyed by reconnaissance methods. Maps of adjacent areas surveyed by modern methods may not join this sheet exactly

VT.
STRAFFORD

Geology by Charles G. Doll, 1942, 1943, 1944

GEOLOGIC MAP AND STRUCTURE SECTIONS OF THE STRAFFORD QUADRANGLE, VERMONT

SHEET NO. 1

Figures 1 - 4, Showing Bedding—Schistosity Relationships

LEGEND FOR GEOLOGIC MAP

SHEET NO. 2

Post-Devonian

Basic diKes and sills

Late or Post-Devonian

DurKee Hill Greenstones

BrocKlebanK granite and associated diKes and sills

Lower Devonian

— Mhs
— ca

Gile Mountain schists

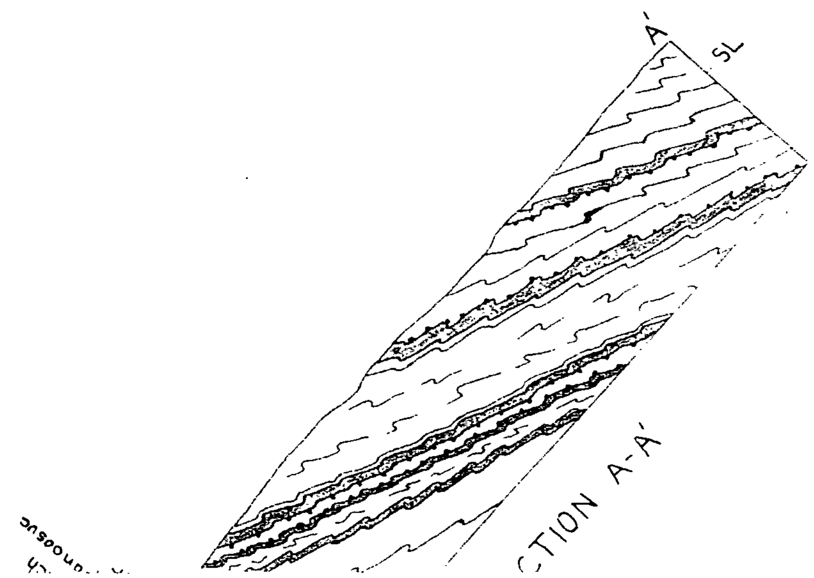
Mica schist, quartz-mica schist, garnet-mica schist, biotite schist graphitic schist, arenaceous schist, quartzite, some staurolite, kyanite, and sillimanite schists. ca, coarse amphibolite. Mhs, Meetinghouse slate, gray to black.

Middle Silurian Probably Lower Devonian

- gs
- SPa

Memphremagog formation

Arenaceous, micaceous, dolomitic limestones and mica schists. SPa, Standing Pond amphibolite (needle amphibolite conspicuous) gs, coarse garnet schist occurring with amphibolite



Middle Silur Probably Lower Devoni

SPa

Memphremagog formation

Arenaceous, micaceous, dolomitic limestones and mica schists.
SPa, Standing Pond amphibolite (needle amphibolite conspicuous)
gs, Coarse garnet schist occurring with amphibolite

Contacts

Special Symbols

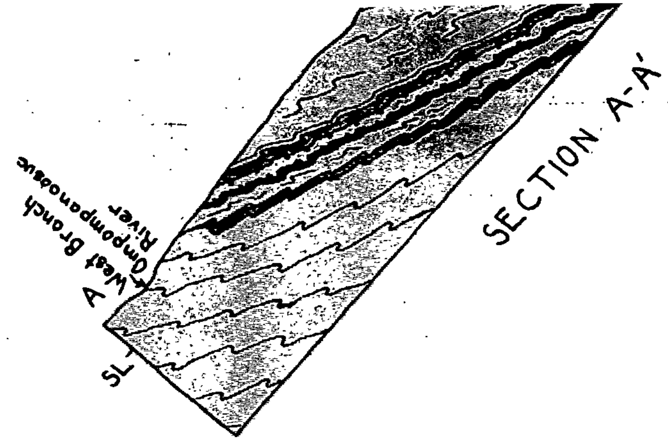
60
Dip and strike of bedding and schistosity including inverted beds

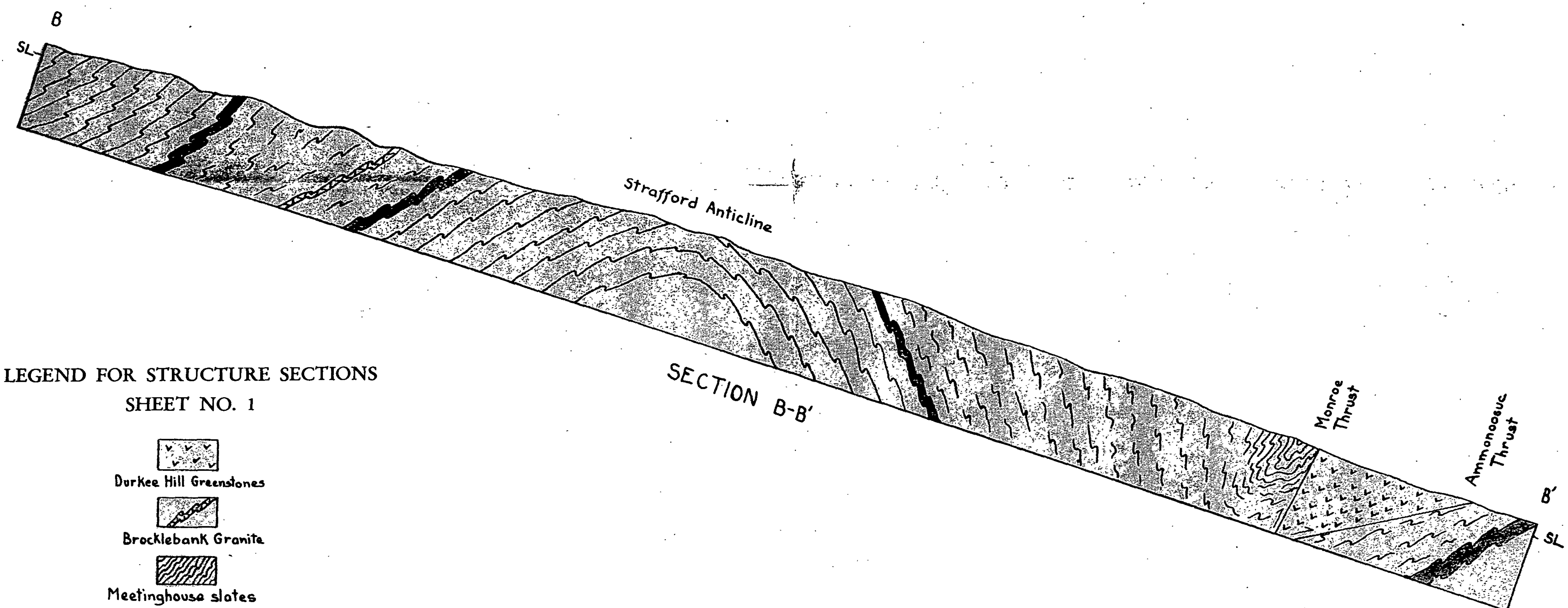
Strike of vertical beds

20
Plunge and trend of fold axes

Overthrust side of thrust faults

Mines, prospects, and quarries





LEGEND FOR STRUCTURE SECTIONS
SHEET NO. 1

Durkee Hill Greenstones

Brocklebank Granite

Meetinghouse slates

Gile Mountain schists

Memphremagog formation

Relationship of Structure Sections to Geologic Map is shown by placing Sheet No. 1 over Sheet No. 2. (See A - A', B - B'.)

0 1/2 1 2 3
Scale in Miles