

A SYMPOSIUM  
on  
THE SANDHILL DEEP WELL  
WOOD COUNTY,  
WEST VIRGINIA

Including papers presented at the joint meeting of the Appalachian Geological Society and the Pittsburgh Geological Society, at Blackwater Falls Lodge, Tucker County, West Virginia, October 11-12, 1956, Assembled and collated by Herbert P. Woodward, acting for an informal Committee on the Hope Well, with Dr. Paul H. Price and Dr. Ralph L. Miller as co-chairmen.

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Report of Investigations No. 18

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Published by the West Virginia Geological Survey,  
Morgantown  
West Virginia

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LETTER OF TRANSMITTAL

*Hon. Cecil H. Underwood,  
Governor of West Virginia and President,  
Geological and Economic Survey Commission  
Charleston, West Virginia*

DEAR SIR:

Following the completion of the first well ever to penetrate all the sedimentary rocks in the deep portion of the Appalachian Basin, drilled to a depth of 13,331 feet by the Hope Natural Gas Company and others, the 2,868 feet of the core recovered from the lower section of the well, was divided longitudinally and made available to specialists in some ten State and Federal institutions for detailed study. Our own Survey does not have all the technical skills that were available for these studies. One complete section of the core remains with the State Geological Survey (a National repository) for permanent storing and possible further study.

The studies by the specialists at several institutions are now completed and technical reports, based on their many findings have been written. Probably few wells, certainly not one in the Appalachian area, has received the critical analysis given by specialists to the Sandhill Well. Even though each report represents a complete study in itself, their consolidation under one cover was required to tell the entire story.

It has always been the policy of the West Virginia Geological Survey to publish reports resulting from investigations that will aid us in the more efficient techniques of discovery, recovery and use of our State's natural resources. The knowledge gained from the detailed study of the records of this well has provided us with information that was never before available to man and will be of inestimable value to us, not only for use in drilling other wells, but in adding to our knowledge of the composition and structure of our State. It is for this reason that I submit and recommend it for publication.

Respectfully,

PAUL H. PRICE,

Director and State Geologist

Morgantown, West Virginia  
June 30, 1959

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## HISTORY OF INVESTIGATIONS

The Hope Natural Gas Company (in 1955) with the South Penn, United Fuel, Manufacturers Light and Heat, and Columbian Carbon Gas Companies drilled the first well in West Virginia to penetrate the entire Paleozoic section from the Coal Measures to the Pre-Cambrian basement rocks. This well is located near the crest of the Burning Springs Anticline in Wood County. The well reached a total depth of 13,331 feet, a record for the Appalachian Basin. Some 2868 feet of the well was cored, mostly near the bottom of the hole in rocks of Ordovician and Cambrian age, which had never before been seen in or near this part of the Appalachian Basin.

Although the well was not successful in obtaining commercial quantities of oil or gas, it did provide an unequalled stratigraphic record of the formations of middle and early Paleozoic age, and it also brought to light unsuspected structural complications of interest to all geologists working in the Appalachian region.

Realizing the great significance of this well in furthering the geologic knowledge of the important oil and gas producing regions of the northeast, the officials of the Hope Natural Gas Co. agreed to make the core and cuttings available for study by qualified specialists. This was done in the interests of obtaining as much scientific information as possible on the rocks penetrated by the well, and particularly of the previously unknown rocks cored near the bottom of the well.

A "core party" was held by the Hope Natural Gas Company August 19, 1955, at which the core was inspected by many petroleum geologists. Subsequently officials of the West Virginia Geological Survey, Ohio Geological Survey, Pennsylvania Geological Survey, and the U. S. Geological Survey were given an opportunity to inspect the core.

As the result of the interest generated by these "core parties", an informal committee was formed at the time of the annual convention of the American Association of Petroleum Geologists in New York April 1, 1955. This organizing meeting was attended by about 35 representatives of state and federal geological surveys, universities, and the petroleum industry. The purpose of the committee was to promote, organize, direct, and arrange for the publication of appropriate geological, geophysical, and geochemical studies of the unique core from the Sandhill, Wood County, well. During this meeting Paul H. Price and Ralph H. Miller agreed to co-chairman the committee.

The first product of the Committee's work was a detailed log of the cuttings and core of the well prepared by Robert E.

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Bayles and William H. Henry of the Hope Natural Gas Company, the late Prof. Charles R. Fettke of Carnegie Institute of Technology, Russell R. Flowers and Oscar L. Haught of the West Virginia Geological Survey, and Leonard D. Harris of the U. S. Geological Survey. Harris and Flowers prepared the detailed log of the core. This valuable complete log of the well was published promptly by the West Virginia Geological and Economic Survey as **Report of Investigations No. 14.**

Simultaneously more exhaustive and time-consuming researches on the sample and core material were undertaken by the authors of this Bulletin. It is of interest to note that affiliations of the authors from the time the work started to the present include the Hope Natural Gas Company; the West Virginia, Ohio, and Pennsylvania Geological Surveys; the U. S. Geological Survey; the Pennsylvania State University; the Newark Branch of Rutgers; the University of Pittsburgh; Michigan State University; Northwestern University; and Stanford University. Thus, the talents and facilities of eleven top-level geologic research organizations have been brought to bear on the material and the data provided by the Wood County well.

Preliminary results of the investigations were reported by the researchers at a symposium at Blackwater Falls State Park in October 11, 12, 1957, jointly sponsored by the Appalachian Geological Society and the Pittsburgh Geological Society. The present publication presents the final results of these investigations.

It will be noted by the careful reader that the various authors are not always in complete agreement. Particularly is this true in interpreting the stratigraphic significance of some features observed in the core, and stratigraphic correlations of these formerly unknown rocks with known sequences at the surface in distant regions. This is not at all surprising. The alternative interpretations presented should assist other workers in solving similar correlation problems for deep wells that may be drilled in the future in the northern Appalachian Basin.

From the beginning, the cooperative effort directed toward obtaining the maximum amount of useful scientific information from the Sandhill, Wood County, deep well has been quite unique. The well itself is unique, the scope of the investigations and the range of interests of the investigators is unusual, the number of research institutions represented by this series of studies on only one well is likewise exceptional, and the informality of the loose organization known as the "Hope Well Committee" has been extraordinary, but quite effective. The Committee was self-generating and has been

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self-perpetuating. With the appearance of this publication of the results of the scientific studies on the Sandhill, Wood County well, the Committee goes out of existence.

Special credit for the success of this effort should go to Robert E. Bayles of the Hope Natural Gas Co. who first envisioned and proposed the project; and to Dean Herbert P. Woodward of the Newark Branch of Rutgers University, whose enthusiasm for the project and unremitting efforts have assisted the work of the Committee from start to finish.

PAUL H. PRICE

State Geologist of West Virginia

RALPH L. MILLER

U. S. Geological Survey

Co-Chairman, Hope Well Committee



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## FOREWORD

By H. P. Woodward

At a meeting in June 1954 at White Sulphur Springs, West Virginia, of the Eastern District American Petroleum Institute, Division of Production, the writer advised that:

“The Appalachian basin presents an ideal area where the pooling and recataloging of all available information are likely to have great practical value. While many writers have published their findings and conclusions regarding the basin, its rocks and its structures, and while various State Surveys have devoted much space, time, funds, and effort to the study and description of the region, there is still a vast store of information in company files and in unpublished notebooks that ought to be made available to the profession as a whole. It is strongly urged that some effort be made to collect, coordinate, classify, and broadly disseminate this information to those concerned, and it can almost confidently be predicted that geologic knowledge will generally be increased and that advantages will accrue to all those operating the oil and gas industry in the region.”

Later that fall at the October meeting of the Appalachian Geological Society at Marietta, Ohio, the writer reiterated the same idea and suggested that the Appalachian Geological Society might well undertake such a cooperative project as one of its goals.

Unknown to him, such a venture had already commenced. Started in May 1951, the Hope Natural Gas Company Well No. 9634 was completed to a depth of 4,322 feet in April 1952, where it was unproductive and drilling was discontinued.

Officials of the Hope Company recognized the advantage of extending this well to the Pre-Cambrian basement, and drilling was resumed in July 1954 on a cooperative basis agreed upon by the Hope Natural Gas Company, the South Penn Natural Gas Company, the United Fuel Gas Company, the Manufacturers Light and Heat Company, and the Columbian Carbon Company. Thus, the completion of this project was a cooperative venture of the type recommended.

As predicted, the well revealed a great deal of new and valuable information. Mr. Robert E. Bayles, chief geologist of the Hope Company, decided to explore an extension of the cooperation already achieved, and arranged for a conference to be held in the office of Dr. Ralph L. Miller, of the United States Geological Survey, to pursue the cooperative study of the well log and other data.

This meeting took place on January 12, 1956, at which time Dr. Paul H. Price, State Geologist of West Virginia, and Dr. Miller were selected as cochairmen of a permanent

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committee on the well. A program of research was laid out to deal with various aspects of the well and the writer was asked to serve as an editorial coordinator for the project. In the meantime, the West Virginia Geological Survey published the excellent preliminary report on the well entitled "Report of Investigations No. 14," released early in 1956.

The committee met again in November 1956 and in May 1957 and arranged a symposium meeting of the Appalachian Geological Society and the Pittsburgh Geological Society to be held in October 1957 at Blackwater Falls Lodge, Tucker County, West Virginia, at which time papers resulting from the several research projects were presented.

The symposium meeting was well attended and the committee agreed that the papers presented should be assembled in a symposium volume to be published as speedily as possible. A dead-line was set for completion of the manuscripts for the spring of 1958 and it was hoped that the published volume could be issued during the summer of 1958.

Various unavoidable delays interfered with the plans and the individual manuscripts were not finally delivered to the writer until May 1959 by which time the West Virginia Geological Survey had agreed to undertake publication of the volume. Inasmuch as the Survey maintains its own editorial staff, the role of the present writer has been chiefly to serve as a coordinating office in assembling the manuscript for submission to the Survey.

Despite the long delay in getting the volume into print and the fact that another but shallower well has been drilled near the first hole, it is believed that the present volume is a valuable record of the original deep well and that many aspects of the information discussed herein concern problems of the Appalachian region in general.

Herbert P. Woodward,

May 5, 1959

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## INTRODUCTION

By Paul H. Price<sup>1</sup> and O. L. Haught<sup>2</sup>

This symposium is devoted entirely to the discussion and evaluation of data obtained from a single well. Publication of a sizable group of papers about one well is unusual, but is felt to be justified in the present case by the amount of important and absolutely new information that we have obtained from this well.

The well has received the name "Sandhill well" from the locality at which it was drilled. It is the Hope Natural Gas Company well No. 9,634, drilled under the permit number WOO-351, and is located 14 miles east of Parkersburg, W. Va.

The location was chosen for a deep test by the geologists of the Hope Natural Gas Company, and the well was drilled with cable tools to a depth of 4,338 feet, at which point strong flows of heavy brine were encountered, making further progress with cable tools very slow and expensive. As it was now extremely doubtful that the well could ever be drilled to the planned depth with cable tools, operations were suspended at this point for over two years—from April 1952 to July 1954. During this time an agreement was made between the Hope Natural Gas Company on one hand and the South Penn Natural Gas Company, the United Fuel Gas Company, the Manufacturers Light and Heat Company, and the Columbian Carbon Company on the other, for deepening the well to basement if possible. Under the terms of the agreement, the Hope Natural Gas Company was to have full charge and control of the drilling, while the other companies were to help defray the costs and to receive complete information of the results of drilling—lithology, stratigraphy, tests, and so on. The Hope Company then contracted with the Falcon Seaboard Drilling Company for the deepening operation, which began July 17, 1954 and was completed on Feb. 18, 1955.

This was the first well in the central part of the Appalachian basin to be drilled entirely through the Paleozoic sequence of sedimentary rocks and into presumably Pre-Cambrian metamorphics. It has provided us, for the first time, with samples of the Cambrian and early Ordovician rocks of this region. In fact, the composition of the entire lower Paleozoic section, including the Silurian, Ordovician, and Cambrian, found in this well is of great scientific and economic interest.

Previous publications about the Sandhill well include, besides many notices in newspapers and trade journals, an article entitled "Appalachian Test Goes to Basement," by

<sup>1</sup>Director of the Geological and Economic Survey and State Geologist of West Virginia.

<sup>2</sup>Petroleum Geologist, W. Va. Geological and Economic Survey.

Dr. Paul H. Price, which was published in the April 2, 1956 issue of the "Oil and Gas Journal," and "Wood County Deep Well" by several writers, published as "Report of Investigations No. 14" by the West Virginia Geological and Economic Survey. The material of most of the papers of this symposium was discussed and preliminary papers read at a joint meeting of the Appalachian Geological Society and Pittsburgh Geological Society held at Blackwater Falls State Park near Davis, W. Va., in October 1957. All papers have subsequently been more or less rewritten or revised, so that none appears in this symposium exactly as presented at that meeting.

These papers are the results of independent work by the several writers on various aspects of the data—cores and drilling samples—obtained from the well. Consequently, entire agreement on the deductions that can be made from such data has not been required. The advantages of presenting conclusions, even when contradictory, made from various viewpoints and through various methods of study are felt to outweigh those of a superficial harmony, obtainable only through ignoring uncertainties. Essential agreement on the data, including the distinguishable rock units found in the cores, has been obtained, but agreement in detail on deductions made from the data can not be expected.

Drilling samples were collected throughout the section of the well drilled with cable tools, but no cores were taken. Complete samples were also taken through the section drilled with rotary tools, and much coring was done with excellent recovery, especially below the depth of 9,400 feet. The total cored section amounts to 2,559 feet. Each of the cores was sawed longitudinally into three slices, of which the middle is now stored for possible future study with the West Virginia Geological Survey at Morgantown, W. Va. The other parts have been made available for study by the writers of the papers presented here.

Three successful drill-stem tests were made during the drilling of this well. Each recovered gas and gas-cut mud. The most interesting was the deepest, which tested the interval between depths of 11,190 and 11,274 feet, and recovered a considerable amount of salt water besides gas. An attempt to test the interval between 11,884 and 11,920 feet failed, and some difficulty was experienced in pulling the tools. No subsequent drill-stem tests were attempted. The exact procedure and the results of tests made after completion of drilling have not been made public, but casing was set and cemented at a depth of 9,126 feet, and interesting intervals above this point were tested by means of perforating the casing. The tests of the 4,200 feet of open hole below the casing seem to have been rather sketchy, but no exact information is available about

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them, beyond the clause "observing no results," and the fact that the tests were made by displacing the drilling mud with fresh water, then bailing or swabbing this out of the hole. It seems strange that gas or salt water did not enter the hole under these conditions. The writers would venture to guess that permeability throughout the exposed section had been effectively destroyed immediately around the hole through the continued presence for several months of a column of rather heavy mud extending to the surface.

#### GENERAL GEOLOGICAL SETTING

A short description of the regional and local geological environment of the Sandhill well is felt to be appropriate here, introductory to a series of papers that treat in detail various aspects of local geology as revealed by the data obtained from this well.

The wide Allegheny synclinorium, a part of the Appalachian basin which extends northwestward from the folded Appalachians across all of western Pennsylvania, western West Virginia, and eastern Ohio, is occupied by a thick section of Paleozoic sedimentary rocks, in which all the Paleozoic systems are represented, up to and probably including early Permian. The upper part of this great belt of Paleozoic rocks, down to the bottom of the Devonian, has long been known as the main oil and gas producing region of the eastern United States. Early in the present century, discovery of commercial accumulations of gas in the early Devonian Oriskany Sandstone stimulated drilling through the Devonian, although, in fact, the beds of this system are even to-day far from completely prospected. The Silurian, Ordovician, and Cambrian Systems are still virtually untested throughout the Allegheny synclinorium, though they make up a mass of unmetamorphosed marine sedimentary rocks well over a mile thick in most of the basin.

Structurally, the Allegheny synclinorium is characterized almost everywhere by nearly horizontal rocks and very gentle, even obscure, folds, which are approximately parallel to those of the Appalachian Mountains, just southeast of this synclinorium. In the western part of central West Virginia however, this succession of gentle structures is abruptly broken by a single strong, much-faulted, fold—the Burning Springs Anticline—which, unlike the Appalachian structures in general, strikes due north, rather than northeast. The deep well, the results of which provide the subjects for the present group of papers, is located upon the surface axis of this structure, about 14 miles east and a trifle south of Parkersburg, W. Va.

As yet, not much has been published about the deeper parts of this remarkable structure, though its superficial ex-

pression is fairly well known, through careful and assiduous work by a succession of competent geologists. Details have been hard to determine, since the exposed rocks contain few easily recognized key horizons, and good exposures are none too common, on account of the lack of recent active downward erosion in this part of the Ohio Valley. Large faults are certainly present underground. At the surface, many of these are probably represented in the main by bedding-plane displacements, hard to find since they do not produce stratigraphic offsets. Nevertheless the presence of several faults is clearly indicated by exposed geological features.

On the surface, the Burning Springs Anticline is remarkably sharply bounded. As we approach the structure from either east or west, we find the attitude of outcropping beds to change quite abruptly from almost horizontal to steeply dipping,  $45^{\circ}$  or even more. Between the steep flanks, the crest of the structure lies in a belt of nearly horizontal beds, about a mile wide through most of the length of the anticline. The ends of the structure are almost as sharp as the flanks. Just south of the Ohio River near Belmont, as on the Little Kanawha southwest of Creston, the structure plunges so rapidly that it disappears from the surface within a mile or two. Attempts to extend its axis farther north into Ohio and farther south or southeast in West Virginia have not been markedly successful. In fact, there seems to be little doubt that the ends of the Burning Springs Anticline, as a distinctive and well-defined structure, lie in the areas just mentioned. Whatever structure may extend beyond these areas, in apparent continuity with the Burning Springs Anticline, belongs rather in the category of the gentle folds characteristic of the Allegheny synclinorium in general.

The structure as just described is thirty miles long by about two to three miles wide. Dr. Woodward, who spent considerable time in detailed study of this structure, states that surface closure is about 1,600 feet. Conclusive evidence of the presence at depth of faults of large displacement renders unsafe the projection to any great depth of surface structure. In fact, the structure found while drilling the Sandhill well was by no means exactly as had been expected, though the geologists of the Hope Natural Gas Company had available the results of detailed geophysical investigations, besides all data obtainable from surface work.

As truncation of the Burning Springs structure has exposed productive Pennsylvanian sandstones, seepages of oil and gas exist here, and were early discovered. Consequently, drilling began in this area almost immediately after the completion of the Drake well at Titusville, Pa., and soon led to the development of West Virginia's first oil field, during and

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shortly after the Civil War. Small amounts of oil are still produced here, from wells many of which are over sixty years old.

The fact that the Burning Springs Anticline was by far the strongest positive feature to be found towards the middle of the Allegheny synclincium rendered it the obvious first choice for the location of a well intended to test the hitherto unprospected lower Paleozoic rocks of this region, though it was realized that the section encountered in drilling upon so strong and anomalous a structure might not be entirely representative of the basin as a whole.



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# GENERAL STRATIGRAPHY OF THE LOCALITY<sup>1</sup>

By Herbert P. Woodward<sup>2</sup>

## THE ANTICLINE ITSELF

The Burning Springs Anticline is indelibly engraved on a geologic map of the Eastern Interior and the Ohio Valley, for it nearly bisects the Permian outcrop into two parts. (Figure 1). Known also as the "Eureka" Anticline from the river town of Eureka in Pleasants County, West Virginia, and sometimes called the "Volcano" Anticline from a small town of that name in eastern Wood County, the Burning Springs axis is a significant and conspicuous fold of northern West Virginia.

Its general strike is north-south, and it wavers but little from this trend from the point where the fold emerges on the bank of Ohio River near Belmont, to the southeastern corner of Wirt County, West Virginia, where it forks into two axes, one continuing south, the other swerving to the southeast. North of the Ohio, the anticline trends northeastward in Newport Township of Washington County, but its ultimate termination is not at all clear. The length of the fold is nearly 40 miles and for all of that distance it dominates the structure of four West Virginia counties—Pleasants, Wood, Wirt, and Ritchie. Its southernmost fork extends into Roane County; the southeastern fork passes into Calhoun County<sup>3</sup>.

In a general region where most of the bed-rock looks entirely flat, the Burning Springs Anticline is a conspicuous interruption with some side dips as steep as 70° and many between 30 and 60 degrees. The crest of the fold is relatively flat for a lateral distance of more than a mile. It pitches gently southward from Sandhill (where the Washington Coal is con-

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<sup>1</sup>This report and its companion paper (titled Structural Interpretations of the Burning Springs Anticline) are taken essentially intact from a manuscript prepared by the present author early in June 1957 and informally distributed in mimeograph form to twenty-five geologists concerned either with the well in question or with this symposium. Both papers were presented at the meeting at Blackwater Lodge in October 1957.

<sup>2</sup>Dean, and Professor of Geology, Newark College of Rutgers University.

<sup>3</sup>For a general description of these counties, and particularly for their geologic and structural maps of the anticline, see County Reports, published by the West Virginia Geological Survey, as follows: Pleasants, Wood, and Ritchie Counties, by G. P. Grimsley, 1910; Wirt, Roane, and Calhoun Counties, by Ray V. Hennen, 1911.

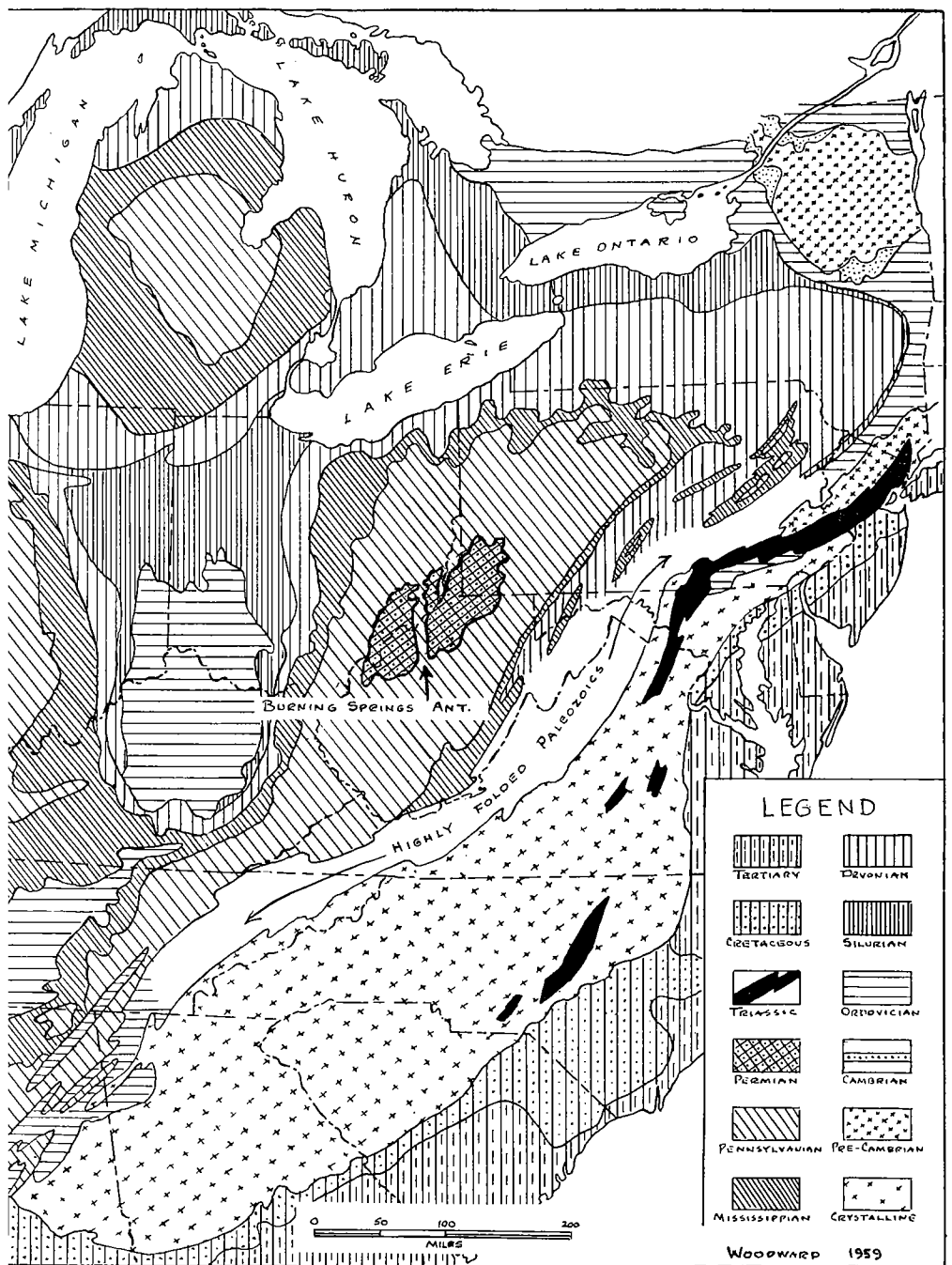


FIGURE 1.—Generalized geologic map showing location of the Burning Springs Anticline.

toured at 2,400' A.T.) to the Wirt-Roane-Calhoun tri-county boundary 25 miles south, where the coal horizon stands 1,000' above tide. The north end of the high dome pitches more steeply, dropping 1,000 feet in the ten miles to the Ohio River.

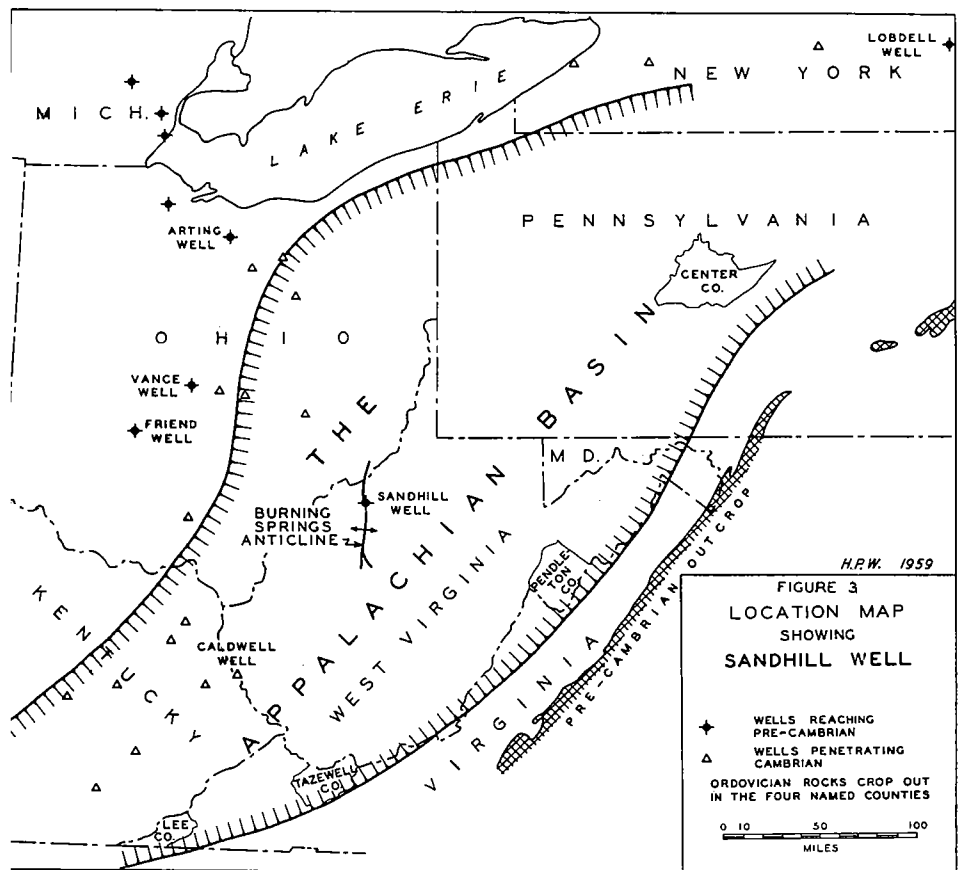
Although the anticline is approximately symmetrical, its west flank is a little steeper than the east flank; indeed, the general level of equivalent surface beds east and west of the arch is discordant by about 300 feet, the lower basin lying west of the fold. As delineated by structure contours drawn on the Washington Coal, the fold has an estimated closure of about 1,650 feet, the highest point occurring near Sandhill. (Figure 2). Surface elevations of interstream divides along the crest of the arch stand about 1,000' A.T., and the streams themselves are entrenched 300 or more feet below the upland surface.

Surface faulting is clearly implied and in places is visible along both flanks of the structure. There is a definite offset at the north end of the fold, separating a subsidiary dome in western Pleasants County whose axis is at least one mile west of the main anticline at Sandhill. It seems likely that this offset has resulted from faulting that flanks the east side of the northern dome and the west side of the main structure. There is some surface evidence of this faulting both along Cow Creek east of the northern dome and along Walker Creek west of the Sandhill axis. Similar indications are seen west of the main dome along Hughes River. Still farther south in east-central Wirt County, probable surface faulting is indicated along the east side of the main arch.

The well in question is officially known as the Hope Natural Gas Company No. 9634 Well, drilled on the Power Oil Company tract in Walker District of Wood County, West Virginia. It is situated some 14 miles east of Parkersburg, about 300 yards west of a crossroads locally known as Sandhill, Ritchie County. For these reasons, the well will be called the "Sandhill well" or the "Hope well" in this symposium.

From the ground surface to the Oriskany Sandstone, this well is matched by thousands of other wells in the region. A hundred or more wells also continue down to the Tuscarora Sandstone. But as yet no other well in the entire central Appalachian basin has been drilled into the crystalline basement, and for the lower part of the rock column, the Hope well is unique. (Figure 3). If it provided no commercial oil or gas, it did unearth a continuous record of more than two and one-half miles of sedimentary rocks, and the present series of reports is an attempt to interpret that unusual record. As a producing well, the hole was dry; but as an exploratory well into unknown territory, it was geologically successful,





sediments do not quite reach the surface. The flanks of the fold are formed by sloping Conemaugh and Monongahela rocks, and the basins on either side contain Dunkard beds of Permian age. Several coal seams—the Upper Freeport, Brush Creek, Harlem, Little Clarksburg, and Pittsburgh—can be traced around or along the anticline, and there are several tough sandstones—Mahoning, Buffalo, Saltsburg, Grafton, Morgantown, and Connellsville—that are useful horizon markers for surface field work.

The exposed surface formations vary considerably in thickness in short lateral distances, and the intervals are not the same along Ohio River as those along Hughes River, 16 to 18 miles farther south. Figures given below may be regarded as practical approximations.

## Surface Section Near the Sandhill Well

	Feet
LOWER PERMIAN OR WASHINGTON SERIES -----	447±
Upper Washington siliceous Limestone -----	5
Interval of sandy shale -----	16
Hundred massive sandstone -----	40
Shaly interval -----	35
Upper Marietta Sandstone -----	45
Creston red shales and sandstones -----	50
Lower Marietta Sandstone -----	35
Washington Coal -----	3
Washington fire clay and yellow shale -----	3
Interval of shale -----	35
Mannington Sandstone -----	40
Interval of shale and sandy shale -----	60
Waynesburg Sandstone -----	50
Interval of shale, red shale, coal, and limestone (?) -----	30
PENNSYLVANIAN SYSTEM -----	1363±
Monongahela Series -----	292±
Gilboy Sandstone -----	35
Interval of shale -----	40
Uniontown Sandstone -----	30
Uniontown Coal -----	2
Interval mainly of red shale -----	50
Uniontown Limestone -----	10
Arnoldsburg Sandstone -----	30
Lower Uniontown Coal and slate -----	1
Interval of red limy beds -----	30
Sewickley coarse pebbly Sandstone -----	25
Upper Pittsburgh Sandstone -----	35
Pittsburgh Coal -----	4
Conemaugh Series -----	527±
Lower Pittsburgh Sandstone -----	50
Shaly interval -----	35
Interval of shale and sandy shale -----	20
Connellsville Sandstone -----	20
Interval of shale and sandstone -----	10
Little Clarksburg Coal -----	1
Interval of shale and sandstone -----	80
Morgantown Sandstone -----	25
Shaly interval, mainly red -----	60
Elk Lick Limestone -----	6
Birmingham red shale, with basal sandstone -----	70
Ames Limestone -----	2
Shaly interval -----	20
Harlem Coal -----	2
Pittsburgh Red Shale -----	60
Saltsburg Sandstone -----	40
Shaly interval -----	20
Hughes River Chert, or Brush Creek Limestone -----	5
Black fossiliferous shale -----	10
Brush Creek Coal -----	1
Allegheny Series -----	324±
Mahoning Sandstone -----	35
Shaly interval -----	15
Upper Freeport Coal -----	2
Interval of sandy shale -----	16
Upper Freeport (Burning Springs) Sandstone -----	45
Lower Freeport Sandstone -----	50

Kittanning Coals and shaly interval .....	115
Vanport fossiliferous Limestone .....	2
Clarion Sandstone .....	40
Clarion Coal .....	tr
Pottsville Series .....	200±

A stratigraphic location of the top of the hole is important. Sandhill, Ritchie County, West Virginia, near which the well is located, takes its name from a coarse white friable sandstone that lies about 160 feet below the Upper Freeport Coal and is probably the Clarion Sandstone at the base of the Allegheny Series. The well starts a short distance across the county boundary from the crossroads at Sandhill and its mouth must be just above the top of the Pottsville Series.

#### BED-ROCK FORMATIONS IN THE SANDHILL WELL

Much of the valuable information to be derived from the Sandhill well is the stratigraphic section penetrated by the deeper part of the hole. An excellent description of the sample and core studies, together with a brief stratigraphic analysis by Haught, has already been published by the West Virginia Geological and Economic Survey.<sup>4</sup>

Using the published information plus his own observations, the present writer prepared and distributed in mimeograph form in June 1957 a somewhat more detailed stratigraphic analysis of the bed-rock stratigraphy. Later at the request of the cochairmen for this symposium, the writer revised his listing of the various lithic units penetrated by the well and distributed this in mimeograph form to the authors of this symposium for their criticism and comments. In addition, he prepared a rough correlation chart of the various stratigraphic interpretations at the Mid-Ordovician level and this was also submitted to the other authors in two editions, all in the late fall of 1957.

The following descriptive log enumerates all of the lithic units required by the other authors to make plain their stratigraphic or descriptive correlations, with units numbered from 1 through 155 in descending order. As notes to this list, the writer had added his own interpretation of the stratigraphy, essentially or originally phrased by him in the mimeographed manuscript of June 1957 referred to above.

Thus the following resume of the bed-rock formations of the Sandhill well contains lithic units agreed to by all authors of this symposium. But the descriptive notes and stratigraphic interpretations are those of the present writer who has indicated, so far as practical where he disagrees from the inter-

<sup>4</sup>Bayles, Robert E., et al., Wood County Deep Well; Report of Investigations No. 14, West Virginia Geol. Survey, 1956, 62 pp.

pretations of other persons. Finally, Plate I is a graphic representation of the following log of the well.

### BED-ROCK FORMATIONS IN THE SANDHILL WELL

Generalized lithologic section for the Hope Natural Gas Company No. 9634 Well, known also as the Sandhill well, drilled in 1951-55 near Sandhill, in Walker District of Wood County, West Virginia. The lithic units listed below have been established from sample and core studies, both those reported in Report of Investigations No. 14, "Wood County Deep Well," West Virginia Geological Survey, 62 pp., 1956, and others to be referred to in this symposium. Elevation 1,050' A. T.

Descriptive notes are those of H. P. Woodward. See also Plate I for a graphic representation of this log.

Unit No.	Depth	Lithologic Description	Thickness Feet
<b>PENNSYLVANIAN SYSTEM (0-220')</b>			220±
<b>Lower Pennsylvanian or Pottsville Series (0-220')</b>			220
1.	0-14	No samples	14
2.	14-20	Medium-grained, light-gray, micaceous sandstone	6
3.	20-57	Siltstone and gray shale	37
4.	57-106	Fine- to coarse-grained, brown-gray sandstone	49
5.	106-155	Same, with quartz pebbles	49
6.	155-175	Gray siltstone and shale	20
7.	175-220	Fine to coarse sandstone, very pebbly	45
(NOTE: Probably Beds 4 and 5 are the two Con- noquenessing Sandstones and Bed 7 the Sharon Conglomerate).			
<b>MISSISSIPPIAN SYSTEM (220-762')</b>			542
<b>Upper Mississippian Series (absent by erosion)</b>			
<b>Middle Mississippian Series</b>			18
<b>"Greenbrier" Limestone (220-238')</b>			
8.	220-238	Very sandy oolitic buff limestone	18
(NOTE: There is an erosional unconformity at the base of the "Greenbrier" Limestone, as well as a major unconformity below the Pottsville sandstone. No beds customarily assigned to the Mauch Chunk or Upper Mississippian are present in this well, although they occur erratically in other wells in the general area. The so-called "Keener" Sand underneath the "Greenbrier" also appears to be absent).			
9.	238-255	Fine- to medium-grained pebbly sand- stone and shale	17
10.	255-268	Gray to dark-gray shale and siltstone	13
11.	268-367	Fine- to medium-grained pebbly sand- stone, some shale	59
(NOTE: These beds are at the level of the "Big In- jun Sands" of the driller).			

12. 367-739 Gray to medium-gray shale and siltstone -----372  
 13. 739-762 Dark-gray pyritic shale, a thin sand and pebble zone at the base ----- 23

(NOTE: This is the horizon of the Sunbury Shale, and the sandy basal zone probably stands for the Berea Sandstone).

**DEVONIAN SYSTEM (762-6215'), totaling 5453' corrected to 3880'**  
**Upper Devonian Series (782-3842') 3080'**

(NOTE: The topmost beds of the Upper Devonian are described as fossiliferous in the wells, a character incompatible with the red Catskill facies of the Devonian. Hence, although some of these beds have a reddish cast, they can not be assigned to the Catskill facies or to the Hampshire Formation).

14. 762-1249 Greenish-gray to reddish-brown siltstone with interbedded gray shale; fossiliferous -----487  
 15. 1249-1494 Same -----245  
 16. 1494-1592 Same ----- 98  
 17. 1592-1745 Gray shale with a little interbedded siltstone -----153  
 18. 1745-2055 Essentially the same as Bed 17 -----310  
 19. 2055-2137 Gray to greenish-gray siltstone and darker shale ----- 82  
 20. 2137-2186 Gray shale with some siltstone ----- 49  
 21. 2186-2292 Gray to greenish-gray siltstone and gray shale -----106  
 22. 2292-2430 Same; fossiliferous -----138  
 23. 2430-2535 Gray to dark-gray shale, a little siltstone -----105  
 24. 2535-2593 Slightly pyritic dark-gray shale ----- 58  
 25. 2593-2635 Gray fossiliferous shale, a little siltstone ----- 42  
 26. 2635-2923 Gray to dark-gray shale, very little siltstone -----288  
 27. 2923-3400 Shale with interbedded gray siltstone 477  
 28. 3400-3535 Same, darker -----135  
 29. 3535-3600 Gray to dark-gray shale ----- 65  
 30. 3600-3779 Shale, dark to medium dark gray ---179  
 31. 3779-3842 Same ----- 63  
 32. 3842 Trace of dark calcareous shale ----- 0

(NOTE: It is not feasible to differentiate this series into formational units of either the eastern outcrop or western exposures. One may make generalized facies determinations as follows, but beyond these approximations it is unwise to proceed:

Beds 14-22 (762-2430') have the lithology of the "Chemung" facies of the eastern outcrop (1668 feet).

Beds 23-28 (2430-3535') resemble the "Portage" facies or Brallier Shale to the east (1105 feet).

Beds 29-31 (3525-3842') resemble the black Harrell (Naples) Shale of the eastern outcrop (307 feet).

Bed 32, at depth 3842', is probably the "Tully" horizon.

The above portion of the section is entirely analogous in thickness and character to the sequence encountered in hundreds of other wells in western West Virginia; there is no reason to consider it unusual in volume or quality. These beds are the general horizon of the Ohio Shale).

	Mid-Devonian Series (2842-?) .....	est. 400
	Hamilton-Marcellus equivalents (3842-4022')	
33.	3842-4012 Dark to black shale, evidence of minor deformation .....	170
34	4012-4022 Fine dense argillaceous limestone with metabentonite .....	10

(NOTE: Bed 33 is probably the Marcellus Shale, or a unit of similar lithology and position. The thin limestone, Bed 34, containing the Tioga metabentonite, is widely found above the Huntersville Chert in this general region. Lacking any more reliable correlations, one may regard it as an eastern equivalent of the Delaware Limestone (Hamilton-Marcellus) of Ohio. It is above and distinctly separate from the Huntersville Chert of Onondagan age).

Huntersville Chert (4022'-?) ..thickness uncertain..est. 185

(NOTE: At depth 4022' the well leaves Devonian shales and limestones and penetrates Huntersville Chert, a dense, fine-textured siliceous and very cherty rock. The chert is bluish-gray to brown-gray and much brecciated. The well continues through chert of Huntersville type to depth 4,306', at which point it enters sandstone. This thickness of Huntersville, totaling 294 feet, could be interpreted as a normal section, dipping about 30° from the horizontal and correspondingly thickened. Below depth 4,306' occur sandstone, chert, and limestone in a jumbled succession suggesting several faults that are also attested by shear zones and related phenomena. The disturbed section extends down to depth 5,865' where the Oriskany Sandstone again occurs, overlying beds that appear to be undisturbed and in normal sequence. It is possible that a shear zone occurs below the sandstone at depth 5,940'; but, if so, it seems not to have seriously interfered with the normal sequence or normal thicknesses. The present writer, therefore believes that the entire lower portion of the well below depth 5,865' is undisturbed and in proper position, save for the possible occurrence of a minor shear at depth 5,940'. By comparison with regional relations and with near-by wells, the Huntersville Chert is estimated to be about 185 feet thick at this location. This means that the interval in question contains 1658 more feet of bed-rock than the true stratigraphic interval requires).

In consequence, the following units, Nos. 35-46 inclusive, are not regarded as part of a continuous stratigraphic section normal for the locality of this well. The description of such a true section continues at depth 5,865' with unit No. 48.

GENERAL STRATIGRAPHY OF LOCALITY

19

35.	4022-4306	Limestone and chert .....	294
36.	4306-4345	Fine to coarse sandstone .....	39

(Depth corrected twice from 4345' to 4322' and then from 4322' to 4333', resulting from shift from old to new hole)

37.	4333-4538	Medium to fine, buff to gray sandstone .....	190
38.	4538-4515	Brown cherty limestone .....	285
39.	4815-4870	Same, some coarse crystalline limestone, some sand .....	55
40.	4870-4930	Brown cherty and silty limestone .....	60
41.	4930-4990	Brown silty glauconitic limestone .....	60
42.	4990-5445	Brown cherty glauconitic sandstone .....	455
43.	5445-5575	Gray partly calcareous sandstone .....	130
44.	5575-5620	Brown sandy cherty limestone .....	45
45.	5620-5625	Fine to medium brown gray calcareous quartzitic sandstone .....	5
46.	5625-5640	Cherty brown limestone .....	15
47.	5640-5865	Brown fossiliferous cherty limestone .....	225

(NOTE: The presence of the above-noted deformed zone separates the stratigraphic succession into three structural units as follows:

A. An upper section, from the well-mouth to depth 4,022' in which the rocks are essentially level on the flat crest of the anticline, whose steep sides and level summit are determinable from surface exposures. The closure of the anticline here is 1,650 feet as mapped by the Washington Coal.

B. A middle deformed section extending from depth 4,022' to 5,865' but including 1,658 feet more than the normal stratigraphic thickness.

C. A lower section below depth 5,685' in which the rocks are entirely horizontal where cored with no indication of the presence of the surface-visible anticline).

	<b>Lower Devonian Series (5,865-6,150')</b> .....	285	
	<b>Oriskany Sandstone (5,865-5,940')</b> .....	75	
48.	5865-5940	White, fine-grained, well-sorted sandstone, with some glauconite; probable fault at 5940' .....	75

(NOTE: As mentioned above, the Oriskany was encountered at least three times in the interval between 4,022' and 5,910', but in this position at 5,865' it appears to be undisturbed and part of an underlying normal succession).

	<b>Helderberg Group (5,940-6,150')</b> .....	210	
49.	5940-5955	Dark brown-gray fossiliferous limestone .....	15
50.	5955-6045	Dark cherty fossiliferous limestone, including some argillaceous and cherty zones .....	90
51.	6045-6065	Light-colored calcareous very fine sandstone .....	20
52.	6065-6150	Brown-gray fossiliferous limestone, partly silty, partly cherty, partly argillaceous .....	85

(NOTE: At 6,150' the section changes from limestone to dolomite, which is the customary lithologic criterion of the descent from the Helderberg to the Tonoloway. A thin sandstone at the top of the Tonoloway in certain eastern exposures may correspond to the sand of Bed 54. Probably it is unwise to match the Helderberg units of this well with outcrop formations, although Bed 50 could be the Port Ewen-Port Jervis (Shriver) Formation and Bed 51, the Healing Springs-New Scotland Sandstone).

**SILURIAN SYSTEM (6,150-7,811')** (See Figure 4) -----1661  
**Upper Silurian or Cayuga Series (6,150-7,015')** ----- 865  
**Tonoloway and Wills Creek Formations (6,150-6,980')** 830

53.	6150-6187	Light-brown to buff calcareous dolomite, partly argillaceous	37
54.	6187-6215	Fine-grained brown calcareous sandstone	28
55.	6215-6315	Fine to dense, brown argillaceous dolomite with much anhydrite	100
56.	6315-6325	Same, with green-gray argillaceous dolomite	10
57.	6325-6350	Brown sugary dolomite, trace of anhydrite	25
58.	6350-6475	Essentially the same as Bed 55	125
59.	6475-6610	Brown to dark-gray dolomite, only trace of anhydrite	135
60.	6610-6640	Brown-gray oolitic dolomite	30
61.	6640-6715	Same as Bed 59	75
62.	6715-6820	Dark to brown-gray argillaceous dolomite	105
63.	6820-6880	Same, plus a little green-gray shale and traces of light-colored fine dolomite sandstone	60
64.	6880-6980	Dark to brownish-gray argillaceous shaly dolomite	100

(NOTE: It seems unwise to separate Tonoloway and Wills Creek members in this sequence; regional relations suggest that their contact might occur near the base of Bed 59, with the Tonoloway having a probable thickness of 365 feet. The nearest exposure where these beds can be firmly separated is too far east for interpolation to be very reliable. Bed 63 resembles the Williamsport Sandstone and is so correlated by Bayles. Woodward believes that it is a younger and higher horizon. A similar sand is also found in the Gribble and Endress Hartman wells in north-central West Virginia, where it occurs more than 200 feet above the true Williamsport Sand. The same sand, or one similarly placed, is also known in the eastern outcrop area 100 or more feet above the base of the Wills Creek Formation).

	<b>Williamsport horizon (6,980-7,015')</b>	-----	35
65.	6980-6995	Dark-brown sandy oolitic dolomite and shale	15
66.	6995-7015	Same with some fine-grained dolomitic sandstone	20

(NOTE: Woodward regards Beds 65-66 as the Williamsport or Newburg Sandstone. Shearrow fixes the Williamsport in the interval between 6820' and 6880', but regards Bed 64 as more Cayugan Limestone. He places Beds 65-66 in the McKenzie).

**Middle Silurian or Niagaran Series (7,015'-7,215') ----- 200**  
**McKenzie-Lockport Formation (7,015'-7,215')**

67.	7015-7060	Brown-gray sugary dolomite, with some oolitic dolomite and a little sandstone -----	45
68.	7060-7067	Dark brown-gray argillaceous dolomite -----	7
69.	7067-7148	Dark argillaceous, shaly, partly oolitic limestone; fossils -----	81
70.	7148-7158	Light-colored sugary dolomite -----	10
71.	7158-7168	Medium-textured, dark, partly oolitic limestone -----	10
72.	7168-7215	Gray-brown oolitic fossiliferous limestone -----	47

(NOTE: On the basis of insoluble residues, Beds 71 and 72 are dolomite rather than limestone).

**Lower Silurian Series (7,215-7,811') ----- 596**  
**Keefer Sandstone (7,215-7,256') ----- 41**

73.	7215-7256	Very fine grained, light-gray, slightly calcareous or dolomitic sandstone and siltstone -----	41
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**Rose Hill-"Clinton" Formation (7,256-7,679') ----- 423**

74.	7256-7502	Variegated gray, greenish, and grayish-red shales with scattered sand and siltstone interbeds -----	256
75.	7502-7520	Light coarsely crystalline dolomite, with minute veins of hematite -----	18
76.	7520-7595	Variegated shale, green and red -----	75
77.	7595-7625	More dolomitic; fine siltstone seams -----	30
78.	7625-7640	Coarse gray dolomite, cherty; tiny veins of hematite -----	15
79.	7640-7667	Variegated gray and red shale; silty sandstone beds -----	27
80.	7667-7679	Transitional to material below -----	12

(NOTE: Shearrow regards Beds 75 and 76 as representative of the Dayton Limestone; Beds 77-79 as equivalent to the Brassfield Limestone; and he includes Bed 80 with the Tuscarora Sandstone; next below).

**Tuscarora Sandstone (7,679-7,811') ----- 132**

81.	7679-7739	Very fine grained to white quartzitic sandstone, many dark shaly streaks and interbedded shale laminae; with <b>Arthropycus</b> -----	60
82.	7739-7760	Same, slightly darker, more numerous shale laminae, base slightly conglomeratic -----	21

83. 7760-7765 Very fine grained quartzitic sandstone ----- 5  
 84. 7765-7811 Dark shale with numerous sandstone lenses; reworked basal zone at bottom 46

(NOTE: There is a strong regional disconformity below the Tuscarora Sandstone, separating the Silurian and Ordovician Systems. The fact that the Tuscarora here is about 40-50 feet thinner than in near-by wells strongly suggests a local erosional break at its top. This could represent erosion on the anticline itself).

**ORDOVICIAN SYSTEM (7,811-11-684') -----3873**

(NOTE: From this point downward, differences of stratigraphic interpretation increase among the various authors who have contributed to this symposium. Thus Woodward and Shearrow place the base of the Ordovician System at depth 11,684'; Prouty et al. use the figure 11,637'; Harris places the boundary at 11,737').

**Upper Ordovician Series (7,811-9,065') -----1254**  
**Juniata Formation (7,811-8,270') -----459**

85. 7811-8270 Reddish-brown siltstone, shale, and thin sandstone interbeds, character generally shaly, gradational boundaries above and below -----459

(NOTE: The Juniata is more of a facies than a true formation; it is of Richmond age, approximately equivalent to the Sequatchie Formation of the southern outcrops and to the Queenston Red Shale of the Lake Ontario region. The base of the unit is fixed at depth 8,270' because samples in the interval next below contain gray shale alien to the true Juniata. It is possible that Bed 86 and 40' of Bed 87 should be regarded with the Juniata).

**Martinsburg, or Cincinnati, Shales (8,270-9,065') -----795**

86. 8270-8330 Greenish-gray shale and siltstone, a little gray shale, and rare limestone fragments ----- 60  
 87. 8330-8380 Somewhat calcareous, red-brown to gray, silty shale; the lower 10 feet is fossiliferous ----- 50

(NOTE: The lower part of this member can almost certainly be identified as the Orthorhynchula horizon of the Maysville portion of the upper Martinsburg Shale. It is ubiquitous in the eastern outcrop area.

88. 8380-8425 Essentially the same, considerable red-brown shale ----- 45  
 89. 8425-8525 Gray-green shale with some interbedded greenish fossiliferous calcareous siltstone -----100

NOTE: Beds 86-89 totaling 255 feet, are assigned to the Maysville Division of the Martinsburg).

90.	8525-8760	Slightly calcareous green-gray shale with thin fossiliferous limestone and siltstone interbeds	235
91.	8760-9065	Same, somewhat grayer	305

NOTE: Beds 90-91, totaling 540 feet, are assigned to the Eden Division of the Martinsburg. Lower shaly beds, although still part of the Martinsburg Shale, are not truly Cincinnati but are of Trenton age).

Middle Ordovician Shales (9,065-9,265')	200
---	-----

NOTE: While there is general agreement that the section from 9,065' to 10,706' represents Trenton, Black River, and Chazy horizons, the several authors of this symposium do not agree upon the precise boundaries or names of the individual units into which the rocks can be separated. In addition, Prouty places the top of the Beekmantown at depth 10,537').

See also Figure 5.

92.	9065-9115	Gray to dark-gray calcareous shale with fossiliferous interbeds of limestone and siltstone	50
93.	9115-9265	Medium dark-gray calcareous fossiliferous shale; fewer siltstone and more limestone interbeds	150

NOTE: Beds 92 and 93, totaling 200 feet, are chronologically assigned to the upper Trenton, but because of their shaly character, they are retained within the Martinsburg Shale. The same can nearly be said for the five next lower members (Beds 94-98), but these are sufficiently calcareous to warrant inclusion in what is here grouped together as "Mid-Ordovician limestone." Probably Beds 92 and 93 correspond to the Coburn Formation of central Pennsylvania, and to the Cynthia-Million Formations of central Kentucky).

Mid-Ordovician Limestone (9,265-10,706')	1441
Mid-Trenton Horizons (9,265-9,528')	263

94.	9265-9345	Dark fossiliferous shale with limestone interbeds	80
95.	9345	Trace of metabentonite	0
96.	9345-9416	Dark fossiliferous shale with limestone lenses	71
97.	9416-9523	Mainly dark to black calcareous shale	107
98.	9523-9528	Transitional to next underlying unit	5

(NOTE: These beds pass northeastward into the Salona Limestone of central Pennsylvania, and southwestward into the Lexington Limestone of Kentucky. The horizon is unnamed in most of the Eastern Interior region. Indeed, in many wells, these beds lie above the top of the drillers' "Trenton Limestone." The bentonite bed 80 feet below the top of this unit is matched by a similarly placed zone in the Salona of central Pennsylvania).

<b>Lower Trenton Horizons (9,528-9,899')</b>		371
99.	9528-9580 Medium-dark, shaly to coarse fossiliferous limestone	62
100.	9580-9608 Essentially as above	18
101.	9608-9670 Dark to dark-brown limestone, some shale	62
102.	9670-9680 Same; trace bentonite at top and bottom	10
103.	9680-9730 Dense dark argillaceous limestone	50
104.	9730-9739 As above; some brown-gray subcrystalline limestone	9
105.	9739-9742 Same; 10-15% soft metabentonite	3
106.	9742-9790 Dense subcrystalline brown - gray limestone	48
107.	9790-9803 Dense medium-dark limestone, wavy bedding	13
108.	9803-9806 Limestone; irregular patches of coarse calcite	3
109.	9806-9873 Fine dense brown-gray stylonitic limestone; <b>Tetradium</b>	67
110.	9873-9895 Same, lenticular chert in lower 4 feet	22
111.	9895-9899 Same	4

(NOTE: Beds 99-106 represent the "Trenton Limestone" of the driller, but Woodward believes that they are entirely Lower Trenton in age. He correlates them with the Oregon-Tyrone Limestone of Kentucky and with the Witten-Nealmont Limestones of central Pennsylvania. Probably they represent the Woodway, Ben Hur, and Hardy Creek sequence of Lee County, Virginia, which became part of the Moccasin Formation of Tazewell County, Virginia).

<b>Black River Horizons (9,899-10,154')</b>		255
112.	9899-9928 Dark fossil limestone, alternately dense and siltsize	28
113.	9928-10040 Dark stylonitic limestone; <b>Tetradium</b> ; vertical joints	112
114.	10040-10064 Dense medium to olive-gray partly shaly limestone	24
115.	10064-10154 Dark argillaceous limestone and shale	90

(NOTE: Woodward regards beds 112-115 as of Black River age, approximately equivalent to the Wardell-Gratton-Ben Bolt sequence of Tazewell County, Virginia, and to the Hurricane Bridge Formation of Lee County, Virginia. He also believes that there are regional unconformities at top and bottom of the Black River Series).

<b>Chazy Horizons (10,154-10,706')</b>		552
116.	10154-10218 Dense olive to medium-gray limestone, some shales	64
117.	10218-10278 Onterbedded limestone and shale; some <b>Tetradium</b>	60
117.	10218-10278 Interbedded limestone and shale; limestone; some dolomite	113

119.	10391-10429	Dense dark wavy-bedded limestone; some shaly streaks -----	38
120	10429-10468	Styolitic fine dark dense limestone; some <b>Tetradium</b> -----	37
121.	10468-10490	Dense fine limestone, some shale and dolomitic bands -----	22
122.	10490-10497	Dark limestone, dense to fragmental	7
123.	10497-10523	Limestone and dark dolomite, intraformational conglomerate at top ---	26
124.	10523-10537	Same, with gray-black shale partings -----	14
125.	10537-10541	Dark dolomite, partly argillaceous --	4
126.	10541-10552	Same -----	11
127.	10552-10642	Mainly dark dolomite and shale --	90
128.	10642-10673	Same, lighter colored; siltstone at base -----	31
129	10673-10688	Silty dolomite, partings of dolomite shale -----	15
130.	10688-10706	Light-colored basal sandstone; interbedded with dolomite and light shale -----	18

(NOTE: Beds 116-130 comprise the Chazy Group but it seems unwise to attempt its further subdivision. In a general way these beds correspond to the Clifford Formation of Tazewell County, Virginia; to the Martin Creek, Rob Camp, Poteet, and Dot Formations of Lee County, Virginia (in descending order); and to the so-called "Camp Nelson" Formation of the Eastern Interior. The basal units Nos. 129-130 correspond to what is called "St. Peter" Sandstone in eastern Kentucky, and to the conglomerate zone at the base of the Blackford member of the Clifford Formation in the eastern outcrop. Probably they also represent the 22 feet of sand at the base of the Hockenberry well in Butler County, Pennsylvania, and the "Bellefonte" Sandstone that crops out near Bellefonte and Dale Summit, Center County, Pennsylvania. If the latter correlation is valid, then the higher portion of the Bellefonte Dolomite of Pennsylvania is actually Chazyan.

Bed 130 forms the base of the Mid-Ordovician. Note that Prouty regards Beds 125 through 130 as uppermost Beekmantown).

#### Lower Ordovician Horizons (10,706-11,684') ----- 978

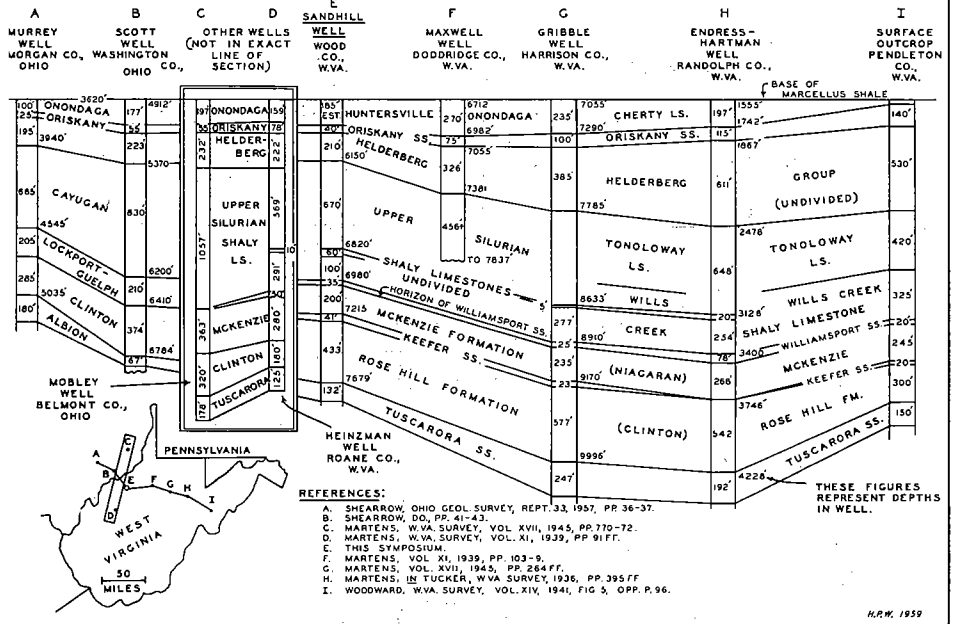
(NOTE: Despite its unexpected presence, all authors in this symposium unequivocally identified the next 900 feet and more as Beekmantown. There was not agreement, however, where or how it should be divided into units. One suggestion was that an equivalent of the Bellefonte Dolomite of Pennsylvania might extend down to about 11,037', the Nittany equivalent down to about 11,500', and the bottom portion might represent Stonehenge equivalents. Viewed from the Ohio region, the section down to depth 11,319' resembles the Shakopee; the sandstone next below could be the New Richmond; and the beds from 11,328' to the base could be the Oneota Dolomite. Prouty regards the top of the Beekmantown as commencing at depth 10,537'.

131.	10706-11037	Fine- to medium-textured dolomite; shale partings; very vuggy -----	331
132.	11037-11318	Fine to coarsely crystalline dolomite -----	281
133.	11318-11329	Fine to coarse dolomitic sandstone	10
134.	11329-11418	Fine, medium to light dolomite; cherty near top, partly oolitic ----	89
135.	11418-11500	Same; many vugs; light to dark chert -----	82
136.	11500-11633	Essentially the same -----	133
137.	11633-11637	Fine to medium crystalline sandy dolomite -----	4
138.	11637-11639	Same -----	2
139.	11639-11684	Sandstone and sandy dolomite ----	45
<b>CAMBRIAN SYSTEM (11,684-13,272')</b> -----			1588
<b>Upper Cambrian Series</b>			
<b>Trempealeau Formation (11,684-12,265')</b> -----			581
140.	11684-11737	Fine sandstone, some dolomitic, some calcareous -----	53
141.	11737-11740	Glauconitic dolomite -----	3
142.	11740-11923	Fine crystalline silty dolomite with some silty limestone interbeds; top 18 feet with fossils -----	183
143.	11923-12114	Fine to finely crystalline mottled dolomite; some dolomitized oolites; fossils -----	151
144.	12114-12220	Medium to coarse dolomite; light colored -----	106
145.	12220-12265	Same, darker; calcareous, oolitic --	45
<b>Franconia-Dresbach Sandstone (12,267-12,485')</b> -----			220
146.	12265-12280	Silty and sandy dolomite; fossiliferous -----	15
147.	12280-12290	Dolomitic sandstone and sandy dolomite -----	10
148.	12290-12410	Fine crystalline dark sandy dolomite; (this unit is actually only 104' thick because of a depth correction) -----	120
149.	12410-12465	Medium-fine light-gray dolomitic sandstone -----	55
150.	12465-12485	Finely crystalline oolitic dolomite --	20
<b>Eau Claire Formation (12,485-12,990')</b> -----			505
151.	12485-12985	Fine to finely crystalline light to dark dolomite with many silty, sandy, or argillaceous streaks; zones of dolomitized oolites; red strains at base -----	500
152.	12985-12990	Dolomitic sandstone, much as below	5
<b>Mt. Simon Sandstone (12,990-13,272')</b> -----			282
153.	12990-13272	Medium to coarse poorly sorted sandstone, some shale and dolomitic streaks; some zones of intraformational pebbles; pink, brown-red, gray and orange colors -----	282
<b>Middle and Lower Cambrian Series absent by non-deposition</b> -----			0

PRE-CAMBRIAN SYSTEM (13,272-13,327') -----

- 154. 13272-13310 Residual soil ("granite wash"); fragments of micaceous gneiss, rounder pebbles, sand, and erosional debris ----- 38
- 155. 13310-13327 Banded granite gneiss; penetrated to depth of 17 feet ----- 17
- Total depth of well ----- 13,327 feet
- Corrected to ----- 13,331 feet

FIGURE 4  
SILURIAN CORRELATIONS, SANDHILL WELL



EARLY PALEOZOIC CORRELATION CHART

		W. KENTUCKY AND OZARKS	EASTERN KENTUCKY	MICHIGAN OHIO	SAND HILL WELL	SOUTHWEST VIRGINIA	SHENANDOAH VALLEY	CENTRAL PENNSYLVANIA
		CATHEYS	CYNTHIANA	TRENTON	AFTER WOODWARD	LEE COUNTY	VALLEY	ANTES SH.
ORDOVICIAN	UPPER	CANNON	LEX - PERRYVILLE	9065' UPPER TRENTON	REEDSVILLE	REEDSVILLE	ORANDA FM.	COBURN L.S.
	MIDDLE	BIGBY	ING - HERMITAGE	9265' SALONA FM.	SH. (INCLUDED IN THE MARTINSBURG SHALE)	SH. (INCLUDED IN THE MARTINSBURG SHALE)	CHAMBERSBURG	SALONA L.S.
MIDDLE	LOWER	HERMITAGE	TYRONE	9525' NEALMONT L.S.	EGLESTON L.S.	EGLESTON L.S.	"LOWVILLE"	NEAL - RODMAN
	LOWER	TYRONE	TYRONE HIGH BRIDGE	9899' BLACK RIVER	HARDY CREEK L.S.	HARDY CREEK L.S.	"LOWVILLE"	MONT CENTRE HALL
MIDDLE	BLACK RIVER	LEBANON	OREGON	10154' (UNDIVIDED)	WOODWAY	WOODWAY	OTSEGO	L.S. OAK HALL
	BLACK RIVER	LEBANON	OREGON	9899' BLACK RIVER	HURRICANE BRIDGE	HURRICANE BRIDGE	WATSON	VALENTINE L.S.
LOWER	CHAZY	"STONES RIVER GROUP"	"CAMP NELSON"	10706' (UNDIVIDED)	WARDLELL	WARDLELL	HOLSTON	VALLEY VIEW L.S.
	CHAZY	"STONES RIVER GROUP"	"CAMP NELSON"	10154' CHAZY L.S.	MARTIN CREEK	MARTIN CREEK	"HOLSTON"	BENNER
LOWER	BEEKMAN-TOWN	POWELL	SHAKOPEE DOL.	10706' (UNDIVIDED)	CHAZY L.S.	CHAZY L.S.	"LENOIR"	STOVER
	BEEKMAN-TOWN	POWELL	SHAKOPEE DOL.	10706' (UNDIVIDED)	CHAZY L.S.	CHAZY L.S.	"LENOIR"	SNYDER
UPPER	UPPER	JEFFERSON CITY	NEW RICHMOND	11684'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	HATTER
	UPPER	JEFFERSON CITY	NEW RICHMOND	11684'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	HOSTLER
UPPER	UPPER	ROUBIDOUX	ONEOTA DOL.	11684'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LEYER
	UPPER	ROUBIDOUX	ONEOTA DOL.	11684'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	CLOVER L.S.
UPPER	UPPER	GASCONADE	TREMPALEAU	11684'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	CLOVER L.S.
	UPPER	GASCONADE	TREMPALEAU	11684'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
UPPER	UPPER	EMINENCE	FRANCONIA SS.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	UPPER	EMINENCE	FRANCONIA SS.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
UPPER	UPPER	POTOSI	DRESBACH SS.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	UPPER	POTOSI	DRESBACH SS.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
UPPER	UPPER	DOE RUN-DERBY	EAU CLAIRE FM.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	UPPER	DOE RUN-DERBY	EAU CLAIRE FM.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
UPPER	UPPER	DAVIS FM.	MT. SIMON SS.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	UPPER	DAVIS FM.	MT. SIMON SS.	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
UPPER	UPPER	BONNETTERE	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	UPPER	BONNETTERE	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
UPPER	UPPER	LA MOTTE SS.	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	UPPER	LA MOTTE SS.	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
MIDDLE	MIDDLE	"SPEARS SAND"	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	MIDDLE	"SPEARS SAND"	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
LOWER	LOWER	"SPEARS SAND"	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	LOWER	"SPEARS SAND"	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
PRE-CAMBRIAN	PRE-CAMBRIAN	"SPEARS SAND"	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.
	PRE-CAMBRIAN	"SPEARS SAND"	"SPEARS SAND"	12265'	ST. PETER SS. 33'	ST. PETER SS. 33'	"MOSHIM"	LOYSBURG L.S.

GRANITES AND OTHER CRYSTALLINE ROCKS REACHED AT DEPTH 13272' H.P.W. 1959



berg is 2,135 feet or approximately five times the normal thickness. Due to faulting, parts of the Onondaga, Oriskany, and Helderberg are repeated several times. Recognized horizons such as the glauconitic chert zone of the Onondaga are found at five different positions. Although all shear zones could not possibly be recognized in the cuttings, breaks in the sequence were noted at 4,530, 4,610, 4,840, 4,930, 4,990, 5,310, 5,345, 5,625, 5,640, and 5,935 feet. The sedimentary sequence is normal and undisturbed below the depth of 6,150 feet.

The Onondaga residues consist of white, blue, gray, and brown mottled chert; white, dead or dull finely porous chert; and gray and brown translucent and smooth chert. Minor amounts of sandy chert and glauconite are present. The percentages of insolubles range from 50 to 80%.

The Oriskany Sandstone, which is repeated three times in the Hope well, consists of very fine to medium grains of quartz which are angular and rounded. Both siliceous and calcareous cements are found in the Oriskany.

The insoluble residues in the Helderberg consist of brown finely porous shale and chert, minor amounts of white and brown rough chert, pyrite, and euhedral quartz crystals. The percentages in a normal or undisturbed section range from 60 to 90% for the upper two thirds of the section. The lower part of the Helderberg has residues which range from 10 to 20%.

### SILURIAN

The Cayugan Series extends from 6,150 feet to 6,980 feet. This differs from Bayles et al. (1956) who interpretates the Cayugan Series to extend from 6,150 feet to 6,880 feet. The writer interprets the interval from 6,880 feet to 6,980 feet as equivalent to the Greenfield of western Ohio. The change in residues and percentage break is at 6,980 feet. The residues of this one hundred foot section consist of gray and brown shale, brown finely porous shale, and anhydrite. This is typical of most of the Cayugan Series. At the top of the series minor amounts of brown finely quartzosed chert are found. The sandstone that extends from 6,190 feet to 6,220 feet is not present in Ohio wells. At 6,820 feet, where Bayles et al. (1956) mark the top of the Williamsport Formation the residues consist of brown and green shale and traces of very fine sand and pyrite. This zone can be found in many of the wells in eastern Ohio.

The Lockport has a smaller volume of residues compared to the Cayugan and is differentiated in central and western Ohio by the abrupt change in color of the dolomites. To the southeast where color is not a diagnostic feature in the subsurface, the residues are relied upon for correlation.

The Lockport extends from 6,980 feet to 7,215 feet. The residues range from 5% to 25% and generally are less than 10%. They consist of gray, black and brown shale, brown finely porous shale, gypsum sand and traces of pyrite. Pyrite and sometimes sphalerite are found at the top of the formation. Near the base of this 235-foot interval the residues consist of a very fine grained aggregate quartz sand.

The top of the Clinton Group is marked by the Keefer Sandstone at 7,215 feet. The Keefer, a dolomitic, very fine grained aggregate sand is 40 feet thick. The remainder of the Clinton Group extends downward to 7,605 feet, and consists of red and green shales with a dolomitic shale appearing at 7,500 feet to 7,520 feet. This dolomitic shale unit is interpreted as the eastern equivalent of the Dayton Formation of western Ohio. Below this dolomitic shale is a red shale that occupies the position of the disconformity at the base of the Dayton in the outcrop area of western Ohio.

The Medina Group extends from 7,605 feet to 7,811 feet and includes what is believed to be the Brassfield equivalent and the "Clinton Sandstones" of Ohio. The Brassfield equivalent is a dolomitic shale with minor amounts of brown and gray smooth and rough chert. The "Clinton Sandstones," the equivalent of the Tuscarora of West Virginia, are very fine grained aggregate quartz sands.

Although Bayles et al. (1956) include part of the Clinton Group and the Medina Group in the Rose Hill, the Dayton and Brassfield are recognized in the subsurface of eastern Ohio and are identified in the Hope well. For this reason the writer has used the terms Clinton and Medina Groups for correlation.

#### ORDOVICIAN

The Cincinnati Series extends from 7,811 feet to 9,523 feet. The top of the series is marked by the Juniata or Queenston Shales. The disconformity at the top of the series was observed in the core rather than being distinguished with the aid of insoluble residues. The disconformity occurs within the grayish-green shale rather than at the contact with the underlying reddish-brown shale. Residues are of little value in subdividing the Cincinnati.

The Mohawkian Series extends from 9,523 feet to 10,706 feet which includes the Trenton, Black River, and the Glenwood-St. Peter section.

The Cynthiana-Lexington Formation extends from 9,523 feet to 9,803 feet. The residues in the top 70 feet, consisting of gray and brown shale and brown, finely porous shale, range in percentage from 25% to 70%. The Lexington portion of the formation extends from 9,590 feet to 9,803 feet and has

a smaller volume of residues consisting of silicified fossil fragments, mottled chert, traces of very fine grained sand and brown finely porous shale.

The Black River Group is predominantly a lithographic limestone and extends from 9,803 feet to 10,642 feet. The residues range in percentage from 5% to 90% and consist of brown and gray finely porous shale. In addition to the shale, traces of barite were noted from 10,150 feet to 10,495 feet. Between 10,945 feet and 10,642 feet, where the carbonate rock is a dolomite, an appreciable amount of anhydrite and brown finely porous shale was noted in the residues.

The Glenwood-St. Peter Formations, extending from 10,642 feet to 10,706 feet are described as a unit because of the interfingering of the sandstones with the shale. This unit has residues ranging in percentage from 85% to 100%. The shale residue is white to gray and finely porous. The sand, rounded and frosted, is very fine to coarse-grained.

The Lower Ordovician and Cambrian nomenclature of this report bears names for units first described in the Upper Mississippi Valley. The terminology was applied to Ohio stratigraphy by Fettke (1948). With the exception of the upper part of the Lower Ordovician, the remaining sediments are represented in the deeper wells located in Ohio. Although the thicknesses, lithologies, and some insolubles are slightly different, certain characteristic residues found in the Hope well are present in well cuttings from southern Ohio.

The Prairie du Chien Group, in descending order, is composed of the Shakopee, New Richmond, and Oneoto Formations, and extends from 10,706 feet to 11,684 feet.

The interval from 10,706 feet to 11,319 is identified as Shakopee. The major constituents of the residues are dolocastic, smooth, and finely quartzosed chert, brown finely porous shale, and silicified oolites.

The New Richmond, 11,319 feet to 11,328 feet, is a fine- to medium-grained dolomitic sandstone. The percentage of insolubles range from 70 to 90 per cent.

The interval of the Oneoto is 11,328 feet to 11,684 feet. The Oneoto has a higher percentage of chert and less shale than the Shakopee. The residues consist of dolocastic and finely quartzose chert with minor amounts of brown finely porous shale. At the base of the Shakopee is a quartzitic sandstone and is interpreted as being transported and re-deposited on the Cambrian surface.

### CAMBRIAN

The Cambrian extends from 11,684 feet to 13,272 feet and includes, in descending order, the Trempealeau, Franconia, Dresbach, Eau Claire, and Mt. Simon Formations.

The Trempealeau, extending from 11,684 feet to 12,265 feet, has small residues which range from 5% to 40%. The sandstone at the top of the Trempealeau is distinguished from the basal sandstone of the Oneota by the shale content. Shales are characteristic of the residues in the Trempealeau. The shales found in the residue are gray, brown, and red. Minor amounts of chert and sand also are present in the residues.

The Franconia-Dresbach interval is from 12,265 feet to 12,484 feet. No attempt was made to separate these formations. The percentage of the residues range from 5% to 60% and consist of gray and brown shale and very fine to fine-grained quartzitic sand.

The Eau Claire Formation, extending from 12,484 feet down to 12,985 feet, has residues consisting of gray, brown, and red shale, and very fine to fine-grained quartzitic sand with traces of gypsum. The residues range from 5 per cent. and increase with depth to a maximum of 60 per cent. near the base. Sand is noted to increase in depth thus accounting for the larger residues in the lower half of the Eau Claire.

The Mt. Simon Sandstone extends from 12,985 feet to 13,272 feet. The residues are irregular in percentage and range from 5% to 100% but average above 60% for the entire unit. The residues are primarily a very fine to medium-grained quartzitic sand but thin partings of shale are noted in the section. The arkosic sandstone at the base of the Mt. Simon is 15 feet thick. Thin partings of arkosic material were noted in several other places in the interval between 13,000 feet and 13,100 feet.

#### PRE-CAMBRIAN

Since no carbonates are present in the Pre-Cambrian section which extends from 13,272 feet to 13,331 feet, the writer made no attempt to describe the section.

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- Grohskopf, John G., and McCracken, Earl, 1949, Insoluble residues of some Paleozoic formations of Missouri, their preparation, characteristics, and application: Mo. Div. Geol. Survey & Water Resources, Rept. Invest. No. 10.
- Shearrow, George G., 1957, Geologic cross section of Paleozoic rocks from northwestern to southwestern Ohio: Ohio Div. Geol. Survey, Rept. Invest. No. 33.

The following sample log describes in detail only the insoluble residues. The carbonate portion has been described

by Bayles et al. (1956). The largest percentage whether insoluble residue or carbonate is recorded first, followed by the lesser amounts of the rock types found in the samples.

### INSOLUBLE RESIDUES DESCRIPTION

Hope Natural Gas Company No. 9634	Elevation: Original 1039'
Power Oil Company Farm	Elevation: D. D. 1050'
Walker District	Drilling Commenced 5/3/51
Wood County	Drilling Completed 4/11/52
West Virginia	D. D. Commenced 7/17/54
Marietta S. E. Quadrangle	D. D. Completed 2/18/55
1.14 mi. W. of 81° 15'	Original Total Depth 4322'
5.4 mi. S. of 39° 20'	Drilled Deeper T.D. 13331'
	Production: Dry Hole

0	4338	Samples not examined
<b>DEVONIAN SYSTEM</b>		
<b>Oriskany Sandstone</b>		
4338	4375	Sandstone, buff to gray, very fine to fine-grained aggregate
4375	4380	Sandstone, buff to gray, very fine to fine-grained aggregate with fragment of blue and brown mottled chert
4380	4405	Sandstone, buff to gray, very fine to fine-grained aggregate with traces of black shale and carbonates
4405	4430	Sandstone, buff to gray, fine-grained aggregate
4430	4445	Sandstone, buff, very fine grained aggregate, 10 to 15% carbonates
4445	4455	Sandstone, buff, very fine to fine-grained aggregate
4455	4465	Sandstone, buff to gray, very fine grained aggregate
4465	4500	Sandstone, gray, carbonaceous, very fine grained aggregate
4500	4510	Sandstone, brown, very fine grained aggregate
4510	4525	Sandstone, brown to gray, carbonaceous, very fine grained aggregate
4525	4530	Sandstone, brown to gray, carbonaceous, very fine grained aggregate, 20% carbonates
<b>Onondaga Limestone</b>		
4530	4560	Chert, brown dead finely porous, brown and blue mottled, 20 to 40% limestone
4560	4575	Chert, brown and blue mottled, 40% limestone
4575	4585	Chert, brown and blue mottled, brown dead finely porous 40% limestone
4585	4610	Chert, brown and blue mottled, brown dead finely porous, minor amounts of glauconite and very fine grained aggregate sand, 40% limestone
4610	4680	Chert, brown dead finely porous, brown and blue mottled 40 to 50% limestone
4680	4690	Limestone, 30 to 35% brown and blue mottled and brown dead finely porous chert
4690	4735	Limestone, 40-50% brown and gray mottled and brown dead finely porous chert.
4735	4740	Chert, brown dead finely porous, 20% limestone
4740	4765	Chert, brown mottled and dead finely porous, 40 to 50% limestone

4765	4800	Chert, brown smooth, mottled, and dead finely porous, 40 to 50% limestone
4800	4840	Limestone, 35 to 60% brown fine quartzosed, smooth, mottled and finely dolocastic chert with traces of barite
4840	4855	Chert, brown mottled and smooth, traces of fine-grained aggregate sand, 35 to 40% limestone
4855	4860	No sample
4860	4870	Limestone, 35 to 40% brown mottled and smooth chert, 5 to 15% fine-grained aggregate sand
4870	4885	Chert, brown mottled and smooth, traces of fine to medium subangular grained sand, 40% limestone
4885	4890	Chert, brown mottled and dead finely porous, 20% fine- to medium-grained sand, 40% limestone
4890	4905	Chert, brown mottled and dead finely porous, traces of fine-grained subangular sand, 40 to 50% limestone
4905	4930	Chert, brown rough dead and dead finely porous, traces of fine-grained subangular sand, 30 to 40% limestone
<b>Helderberg Group</b>		
4930	4940	Limestone, 20 to 40% brown finely porous shale, 10 to 20% rough dead chert
4940	4955	Shale, brown finely porous, 35 to 45% limestone.
4955	4975	Shale, brown finely porous, traces of brown smooth chert, 30 to 35% dolomitic limestone
4975	4990	Shale, brown finely porous, traces of glauconite, 15 to 20% limestone
<b>Onondaga Limestone</b>		
4990	5020	Chert, gray, brown and blue mottled, minor amounts of brown finely porous shale, 40 to 70% limestone
5020	5030	Chert, blue and brown mottled, traces of brown finely porous shale, 40 to 50% limestone
5030	5040	Limestone, 40% blue and brown mottled, traces of brown finely porous shale and fine-grained aggregate sand
5040	5065	Limestone, 40 to 50% light gray to buff mottled chert, traces of very fine to fine-grained subangular sand
5065	5080	Chert, brown and gray mottled, 40 to 50% limestone
5080	5120	Limestone, 40 to 45% brown and gray mottled chert, traces of very fine grained subangular sand
5120	5125	Limestone, 40% gray and brown translucent chert, 5% very fine grained subangular sand
5125	5135	Limestone, 20% gray and brown translucent chert, traces of very fine grained subangular sand
5135	5140	Chert, gray and brown translucent, 40% limestone
5140	5155	Limestone, 40 to 45% gray and brown translucent and white dead finely porous chert
5155	5225	Chert, gray and brown mottled and white dead finely porous, 40 to 50% limestone
5225	5260	Chert, brown mottled and dead finely porous, 35 to 45% limestone
5260	5275	Chert, brown dead finely porous and sandy, traces of glauconite, 20 to 30% limestone
5275	5285	Chert, brown mottled and dead finely porous, 40% limestone

5285	5300	Chert, white, gray to buff mottled, 35% limestone
5300	5310	Limestone, 35 to 45% brown and gray mottled and dead finely porous chert
5310	5345	Limestone, 45% brown smooth and finely quartzosed chert, few euhedral quartz crystals
5345	5380	Chert, brown mottled and dead finely porous, 40% limestone
5380	5405	Chert, brown mottled and dead finely porous, traces of glauconite, 40 to 50% limestone
5405	5415	Limestone, 25 to 40% brown mottled and dead finely porous chert, traces of glauconite
5415	5425	Limestone, 50% brown and gray mottled and brown dead finely porous chert
5425	5445	Chert, brown and gray mottled and brown dead finely porous, 35% limestone

#### Oriskany Sandstone

5445	5452	Sandstone, fine to medium grained aggregate, 30% limestone
5452	5459	Core No. 1. Cored 7 feet, recovered 7 feet
5452	5459	Sandstone, gray fine-grained aggregate, carbonaceous
5449	5475	Sandstone, gray very fine to fine-grained aggregate, carbonaceous
5475	5495	Sandstone, buff very fine grained aggregate
5495	5535	Sandstone, buff very fine to medium-grained sub-angular
5535	5545	Sandstone, gray very fine grained aggregate, carbonaceous
5545	5580	Sandstone, buff very fine grained aggregate
5580	5585	Sandstone, brown very fine grained, aggregate traces of brown finely porous shale, 35% limestone
5585	5590	Sandstone, brown very fine grained aggregate, 20% limestone
5590	5600	Sandstone, brown very fine grained aggregate, minor amount of brown finely porous shale, 45 to 50% limestone
5600	5605	Sandstone, brown very fine grained aggregate, traces of finely porous shale, 20% limestone
5605	5610	Sandstone, brown very fine grained aggregate, traces of finely porous shale, 40% limestone
5610	5615	Sandstone, brown very fine grained aggregate, 10% finely porous shale, 20% sandy chert, 35% limestone
5615	5625	Sandstone, brown quartzitic, minor amounts of brown quartzosed chert and limestone

#### Helderberg Group

5625	5640	Chert, brown rough dead, 50% limestone
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#### Onondaga Limestone

5640	5660	Limestone, 30% gray and brown mottled chert, 5% brown finely porous shale
5660	5680	Limestone, 45% gray and brown mottled and dead finely porous chert, minor amounts of brown finely porous shale
5680	5690	Chert, white, gray to buff mottled and brown dead finely porous, 35 to 45% limestone

5690	5710	Chert, white, gray to buff mottled and brown dead finely porous, 20 to 30% limestone
5710	5715	Chert, brown rough dead, 45% limestone
5715	5760	Chert, light gray to brown mottled and brown finely dolocastic, 40% limestone
5760	5780	Limestone, 45% gray and brown mottled and brown rough dead finely porous chert
5780	5790	Chert, gray and brown mottled and brown finely dolocastic, 35 to 45% limestone
5790	5810	Chert, gray and brown mottled and brown dead finely porous, 35 to 45% limestone
5810	5820	Chert, gray and brown mottled and brown dead finely porous, traces of glauconite and very fine grained aggregate sand, 30 to 40% limestone
5820	5845	Limestone, 45% gray and brown mottled and brown dead finely porous chert
5845	5865	Chert, gray and brown mottled and brown dead finely porous, traces of very fine grained aggregate sand, 30% limestone
<b>Oriskany Sandstone</b>		
5865	5870	Sandstone, white to gray very fine to fine-grained aggregate, 10% brown mottled and dead finely porous chert, 30% limestone
5870	5875	Sandstone, white to buff very fine to fine-grained aggregate, 20% limestone
5875	5890	Sandstone, white to buff very fine to fine-grained aggregate, 5% limestone
5890	5895	Sandstone, white to buff very fine to fine-grained aggregate, 35% limestone
5895	5910	Sandstone, white to buff very fine to fine-grained aggregate, carbonaceous, traces of brown mottled chert, 10 to 20% limestone
5910	5925	Sandstone, white to buff very fine to fine-grained aggregate
5925	5935	Sandstone, buff very fine grained aggregate
5935	5940	Sandstone, brown very fine grained aggregate, 20% limestone
5940	5950	Sandstone, brown very fine grained, subangular, 10 to 15% brown finely porous shale, 20% limestone
<b>Heiderberg Group</b>		
5950	5955	Limestone, 40% brown very fine subangular grained sand
5955	5960	Limestone, 25% very fine grained, aggregate sand, 20% brown rough dead chert, traces of brown finely porous shale
5960	5965	Limestone, 30% brown finely porous shale, 20% brown rough dead chert
5965	5975	Shale, brown finely porous, 5 to 10% brown rough dead chert, 25% limestone
5975	6000	Shale, brown finely porous, 5 to 10% dolomitic limestone
6000	6025	Shale, brown finely porous, traces of brown and gray mottled chert, 10% limestone
6025	6035	Shale, brown finely porous, traces of brown mottled chert, 25 to 35% limestone
6035	6045	Chert, brown rough dead, 20% limestone
6045	6065	Chert, brown rough read and sandy, 10 to 15% very fine grained, aggregate sand, 20 to 30% limestone

6065	6075	Chert, brown rough dead and sandy, 30 to 35% limestone
6075	6085	Chert, brown dead finely porous, and rough dead, 20 to 30% limestone
6085	6095	Shale, brown finely porous, minor amount brown rough chert, traces of pyrite, 40 to 50% limestone
6095	6120	Limestone, 20 to 25% brown finely porous shale, traces of brown rough chert, pyrite, very fine subangular grains of sand and euhedral quartz crystals
6120	6150	Limestone, 10% brown finely porous shale, traces of white and brown rough chert, pyrite, very fine subangular grains of sand and euhedral quartz crystals

**SILURIAN SYSTEM**  
**Cayugan Series**

6150	6170	Dolomite, 10 to 15% brown finely quartzosed, mottled, and rough chert, 5% brown finely porous shale
6170	6175	Dolomite, 35% brown shale
6175	6180	Shale, brown, 30% dolomite
6180	6185	Shale, brown, 10% dolomite
6185	6190	Shale, brown, 15% very fine, subangular-grained sand, 30% dolomite
6190	6200	Sandstone, white, very fine, subangular-grained aggregate sand, 45 to 50% dolomite
6200	6215	Sandstone, white, very fine, subangular-grained aggregate sand, 20 to 30% dolomite
6215	6220	Dolomite, 35% white, very fine, subangular-grained aggregate sand and 15% gray and brown shale
6220	6230	Dolomite, 25 to 30% fine anhydrite with traces of gray and brown shale
6230	6250	Dolomite, 35% to 45% anhydrite
6250	6255	Dolomite, 20% anhydrite with traces of gray and brown shale
6255	6260	Dolomite, 30% brown shale, 10% anhydrite
6260	6300	Dolomite, 30% to 40% anhydrite
6300	6305	Anhydrite, 25% brown quartzosed chert, 30% dolomite
6305	6310	Dolomite, 30% anhydrite with traces of brown quartzosed chert and shale
6310	6315	Dolomite, 10% anhydrite, and traces of gray shale
6315	6330	Dolomite, 10% anhydrite, 10% gray and brown shale
6330	6335	No sample
6335	6340	Dolomite, 10% anhydrite and traces of gray shale
6340	6345	No sample
6345	6355	Dolomite, 10 to 15% gray and brown shale and traces of anhydrite
6355	6360	Dolomite, 35% brown and gray shale and minor amount of anhydrite
6360	6370	Shale, gray and brown, minor amount of anhydrite, 35 to 40% dolomite
6370	6375	Dolomite, 50% anhydrite, minor amount of brown shale
6375	6380	Dolomite, 30% anhydrite, 30% brown shale
6380	6390	Anhydrite, minor amount of brown shale, 10% to 20% dolomite
6390	6405	Shale, brown, minor amount of anhydrite, 25 to 30% dolomite

## CORRELATION OF SANDHILL DEEP WELL

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6405	6415	Anhydrite, minor amount of brown shale, 30% dolomite
6415	6425	Shale, brown, 10 to 25% anhydrite, 25 to 30% dolomite
6425	6450	Dolomite, 30 to 40% brown shale, minor amount of anhydrite
6450	6455	Dolomite, 10% anhydrite, 5% brown shale
6455	6475	Dolomite, 30 to 45% brown and gray shale, minor amount of anhydrite
6475	6565	Dolomite, 15 to 25% gray and brown shale, minor amount of anhydrite
6565	6660	Dolomite, 5% brown and gray shale and anhydrite
6660	6695	Dolomite, 20% brown finely porous shale, minor amount of anhydrite
6695	6720	Dolomite, 10 to 20% anhydrite, minor amount of brown shale
6720	6750	Dolomite, 25% brown shale, minor amount of anhydrite
6750	6760	Dolomite, 15% brown shale, 10% anhydrite
6760	6770	Dolomite, 10% anhydrite, minor amount of brown shale
6770	6775	Dolomite, 15% brown and gray shale, minor amount of anhydrite
6775	6820	Dolomite, 20 to 30% brown and gray shale, minor amount of anhydrite
6820	6830	Dolomite, 30% brown and green finely porous shale, traces of pyrite and very fine grained aggregate sand.
6830	6850	Dolomite, 50% gray green, and brown shale
6850	6870	Dolomite, 50% brown and gray shale
6870	6880	Shale, brown and gray, minor amount of very fine to fine, rounded and frosted grained sand, 35 to 45% dolomite
6880	6900	Dolomite, 30% gray and brown shale
6900	6950	Dolomite, 35 to 40% gray and brown shale
6950	6980	Dolomite, 20 to 25% gray shale and brown finely porous shale, minor amount of anhydrite

## Niagaran Series

## Lockport-McKenzie Formation

6980	7000	Dolomite, 5 to 10% gray and brown shale, minor amount of very fine grained gypsum sand and traces of pyrite
7000	7020	Dolomite, 5% gray and brown shale, and very fine grained gypsum sand
7020	7030	Dolomite, 5% gray shale, very fine grained gypsum sand, gray smooth chert and traces of sphalerite
7030	7055	Dolomite, 5% gray and brown shale, very fine grained gypsum sand, gray and brown smooth chert
7055	7065	Dolomite, 20% gray and brown finely porous shale
7065	7085	Limestone, 15 to 25% gray shale and brown finely porous shale
7085	7105	Limestone, 5 to 10% gray shale and brown finely porous shale
7105	7140	Limestone, 5 to 10% gray shale, brown finely porous shale, very fine grained gypsum sand, and brown rough chert

7140	7150	Limestone, 5% gray shale, brown finely porous shale and brown rough and finely quartzosed chert
7150	7160	Dolomite, 5% gray shale, brown finely porous shale, brown rough and finely quartzosed chert, and a few crystals of celestite
7160	7175	Limestone, 5 to 15% gray shale, brown finely porous shale, brown rough and finely quartzosed chert, a few euhedral quartz crystals
7175	7180	Limestone, 25% very fine grained aggregate sand, and 5% brown finely porous shale
7180	7185	Limestone, 10% gray shale and brown finely porous shale, minor amount of very fine subangular sand
7185	7190	Limestone, 10% very fine subangular grained sand, minor amounts of gray shale and brown finely porous shale
7190	7210	Limestone, 25 to 30% very fine subangular grained aggregate sand, and a minor amount of gray shale
7210	7215	Limestone, 20% brown shale, 10% very fine subangular grained sand

**Clinton Group  
Kefer Sandstone**

7215	7255	Sandstone, buff very fine grained aggregate, 10 to 30% dolomitic limestone
<b>Rose Hill Shale</b>		
7255	7275	Shale, gray, 10 to 15% very fine grained aggregate sand, 5 to 10% dolomite
7275	7290	Shale, gray, 10 to 15% dolomite
7290	7295	No sample
7295	7350	Shale, red, minor amount of grayish-green shale, 10 to 15% dolomite
7350	7420	Shale, red
7420	7445	Shale, gray, minor amount of red shale
7445	7495	Shale, green, minor amounts of red shale and dolomite
7495	7500	Shale, green, minor amount of red shale, traces of glauconite and very fine grained aggregate sand

**Dayton Limestone**

7500	7515	Shale, green, minor amount of red shale, traces of glauconite very fine grained aggregate sand, brown rough chert and fossil casts, 10 to 30% dolomite
7515	7520	Shale, red, minor amount of gray shale, 35% dolomite
7520	7550	Shale, red, minor amounts of green and gray shale
7550	7570	Shale, red, minor amounts of green and gray shale
7570	7590	Shale, red, minor amounts of gray and green shale and very fine grained aggregate sand
7590	7605	Shale, gray, minor amount of red shale, 15 to 20% very fine grained aggregate sand

**Medina Group  
Brassfield Limestone**

7605	7620	Shale, gray, minor amounts of red shale and very fine grained aggregate sand, 10 to 15% dolomite
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7620	7640	Shale, gray, traces of gray and brown smooth chert and very fine grained aggregate sand, 20 to 40% dolomite
7640	7650	Shale, gray, minor amount of red shale, traces of very fine grained aggregate sand, 20% dolomite (base of Brassfield)
7650	7667	Shale, gray, minor amounts of red shale and very fine grained aggregate sand

**Clinton-Tuscarora Sandstone**

7667	7680	Sandstone, grayish-green and pink very fine grained aggregate
7680	7692	Sandstone, gray to buff very fine grained aggregate
7692	7699	Shale, gray
7699	7712	Sandstone, gray to buff very fine grained aggregate
7712	7719	Shale, gray
7719	7725	Sandstone, white, very fine to fine-grained aggregate, 20% gray shale
7725	7728	Shale, gray
7728	7739	Sandstone, white to gray very fine grained aggregate
7739	7746	Sandstone, gray, very fine grained aggregate, 40% shale
7746	7754	Shale, gray, 20% gray very fine grained aggregate sand
7754	7765	Siltstone, dark-gray
7765	7775	Shale, gray
7775	7782	Shale, dark-gray, 40% dark-gray siltstone
7782	7802	Shale, dark-gray, traces of dark-gray siltstone
7802	7811	Siltstone, gray, minor amount of gray shale

**ORDOVICIAN SYSTEM**

**Cincinnatian Series**

7811	7813	Shale, gray and green
7813	7910	Shale, red
7910	7915	Shale, red, 20% red siltstone
7915	7925	Shale, red, 40% red siltstone
7925	7940	Siltstone, red, 40% red shale
7940	7950	Shale, red, 20% red siltstone
7950	7955	Siltstone, red, 40% red shale
7955	7960	Shale, red, 40% red siltstone
7960	7965	Siltstone, red, 20% red shale
7965	7970	Shale, red, 40% red siltstone
7970	8010	Siltstone, red, 20% red shale
8010	8020	Shale, red, 20% red siltstone
8020	8055	Siltstone, red, 20% red shale
8055	8060	Siltstone, red, 40% red shale
8060	8070	Shale, red, 25% red siltstone
8070	8080	Siltstone, red, 40% red shale, considerable cavings
8080	8095	Shale, red, 20% red siltstone, considerable savings
8095	8125	Shale, red, 40% red siltstone, considerable cavings
8125	8145	Siltstone, red, 40% red shale, considerable cavings
8145	8270	Shale, red, minor amounts of red siltstone, considerable cavings
8270	8335	Shale, red, minor amounts of green shale, some cavings
8335	8370	Shale, red
8370	8400	Shale, light-gray, 20 to 40% red shale
8400	8430	Shale, red, 20% gray shale

8430	8470	Shale, light-gray, 10 to 20% red shale
8470	8535	Shale, light-gray, 20 to 40% red shale
8535	8545	Shale, gray, 20% light-gray siltstone, 15% limestone
8545	8600	Shale, medium-gray, 15 to 20% limestone
8600	8640	Shale, medium-gray, 10 to 15½ light-gray siltstone, 20 to 30% limestone
8640	8675	Shale, medium-gray, 20 to 30% limestone
8675	8715	Shale, medium-gray, 10 to 15% light-gray siltstone, 20 to 30% limestone
8715	8750	Shale, medium-gray, 10% light-gray siltstone, 30 to 40% limestone
8750	8855	Shale, medium- to dark-gray, 20 to 25% limestone
8855	8925	Shale, medium- to dark-gray, 10 to 20% limestone
8925	8995	Shale, dark-gray to black, 10 to 20% limestone
8995	9115	Shale, dark-gray to black, 10 to 25% limestone
9115	9120	No sample
9120	9160	Shale, dark-gray to black, 25 to 30% limestone
9160	9275	Shale, medium-gray, 10 to 15% limestone
9275	9345	Shale, medium- to dark-gray, 20 to 25% limestone
9345	9410	Shale, medium- to dark-gray, 10 to 20% limestone
9410	9416	No sample
9416	9480	Shale, dark-gray and brown
9480	9496	Shale, black
9496	9500	Shale, dark-brown
9500	9518	Shale, black
9518	9523	Shale, black and dark-brown

**Mohawkian Series****Trenton Limestone**

9523	9527	Shale, gray and brown finely porous, 30% limestone
9527	9530	Shale, dark-gray to black finely porous, 40% lime- stone
9530	9534	Limestone, 20% brown finely porous shale
9534	9550	Limestone, 30 to 50% brown finely porous shale
9550	9577	Shale, brown and gray finely porous, 30 to 50% limestone
9577	9590	Shale, black, mostly cavings and 5% limestone
9590	9611	Limestone, 20 to 35% brown finely porous shale.
9611	9618	Limestone, 10% brown finely porous shale, traces of rough chert
9618	9624	Chert, blue and gray mottled and brown rough chert, 25% limestone
9624	9665	Limestone, 15 to 25% brown and gray finely porous shale, traces of very fine grains of sand
9665	9785	Limestone, considerable shale cavings, residues not calculated
9785	9790	No sample
9790	9803	Limestone, 5% brown finely porous shale, trace of brown rough chert and pyrite

**Black River Group**

9803	9813	Shale, gray finely porous, 40 to 55% lithographic limestone
9813	9834	Limestone, 15 to 35% brown finely porous shale
9834	9838	Shale, brown finely porous, 20% limestone
9838	9848	Limestone, 10 to 35% gray and brown finely porous shale
9848	9857	Shale, brown finely porous, 30 to 50% limestone
9857	9861	Limestone, 10% gray and brown finely porous shale

9861	9865	Limestone, 45% brown finely porous shale
9865	9879	Limestone, 10 to 25% gray shale and brown finely porous shale
9879	9894	Limestone, 5% gray shale and brown finely porous shale
9894	9898	Limestone, 20% brown and gray rough chert
9898	9916	Limestone, 5% gray and brown finely porous shale
9916	9932	Limestone, 20% brown finely porous shale
9932	9946	Limestone, 5% brown finely porous shale
9946	9950	Shale, brown finely porous, 40% limestone
9950	9957	Limestone, 30% brown finely porous shale
9957	10008	Limestone, 5 to 10% brown finely porous shale
10008	10027	Limestone, 5% brown finely porous shale and very fine grained sand
10027	10042	Limestone, 5% brown finely porous shale
10042	10065	Limestone, 5 to 15% gray shale and brown finely porous shale
10065	10067	Shale, brown finely porous, 30% limestone
10067	10102	Limestone, 20 to 50% brown finely porous shale
10102	10108	Limestone, 5% brown finely porous shale
10108	10112	Limestone, 45% brown finely porous shale
10112	10130	Limestone, 10 to 25% brown finely porous shale
10130	10133	Shale, brown finely porous, 20% limestone
10133	10136	Shale, brown finely porous, 50% limestone
10136	10148	Limestone, 20 to 30% brown finely porous shale
10148	10169	Limestone, 5% brown finely porous shale, traces of barite and pyrite
10169	10180	Shale, brown finely porous, 20 to 50% limestone
10180	10187	Limestone, 30 to 40% brown finely porous shale
10187	10191	Shale, brown finely porous, 10% limestone
10191	10208	Limestone, 20% brown finely porous shale
10208	10237	Limestone, 5% brown finely porous shale, traces of pyrite and barite
10237	10242	Shale, white to gray finely porous, 30% limestone
10242	10249	Limestone, 5 to 10% brown finely porous shale
10249	10252	Shale, brown finely porous, 10% limestone
10252	10256	Limestone, 30% brown finely porous shale
10256	10260	Limestone, 5% brown finely porous shale
10260	10267	Shale, brown finely porous, 10 to 30% limestone
10267	10283	Limestone, 5% brown finely porous shale
10283	10287	Shale, brown finely porous, 15% limestone
10287	10307	Limestone, 5 to 15% brown finely porous shale
10307	10312	Shale, brown finely porous, 30% limestone
10312	10315	Limestone, 5% brown finely porous shale
10315	10319	Shale, brown finely porous, 10% limestone
10319	10432	Limestone, 5% gray shale and brown porous shale, traces of barite
10432	10465	Limestone, 5 to 10% brown finely porous shale and brown rough and quartzosed chert.
10465	10469	Limestone, 35% brown rough and quartzosed chert
10469	10477	Limestone, 5 to 10% brown finely porous shale and brown rough and quartzosed chert
10477	10484	Limestone, 25% brown finely porous shale and brown rough quartzosed chert
10484	10487	Limestone, 5% brown finely porous shale
10487	10492	Limestone, 45% brown finely porous shale
10492	10495	Limestone, 5 to 10% brown rough and quartzosed chert
10495	10503	Dolomite, 5 to 10% brown finely porous shale
10503	10507	Shale, brown finely porous, 30% dolomite

10577	10512	Dolomite, 5% brown finely porous shale
10512	10513	Shale, brown finely porous, 25% dolomite
10513	10516	Dolomite, 5% brown finely porous shale
10516	10519	Shale, brown finely porous, 10% dolomite
10519	10523	Dolomite, 5% brown finely porous shale
10523	10526	Dolomite, 40% brown finely porous shale
10526	10531	Shale, brown finely porous, 20% dolomite
10531	10532	Dolomite, 20% brown dead finely porous chert
10532	10533	Shale, brown finely porous, 20% dolomite
10533	10537	Dolomite, 45 to 50% brown finely porous shale and anhydrite
10537	10540	Shale, brown finely porous, 15% dolomite
10540	10543	Dolomite, 5% brown finely porous shale and anhydrite
10543	10550	Shale, brown finely porous, traces of anhydrite, 15 to 30% dolomite
10550	10562	Dolomite, 5 to 10% brown finely porous shale and anhydrite
10562	10574	Shale, brown and gray finely porous, 10 to 20% dolomite
10574	10579	Dolomite, 35% brown finely porous shale
10579	10582	Shale, brown finely porous, 40% dolomite
10582	10586	Dolomite, 15% anhydrite
10586	10592	Shale, brown finely porous, traces of anhydrite, 30 to 40% dolomite
10592	10598	Dolomite, 5% brown finely porous shale and anhydrite
10598	10602	Shale, brown finely porous, 10 to 20% dolomite
10602	10606	Dolomite, 5% anhydrite
10606	10610	Shale, brown finely porous, 5% dolomite
10610	10614	Dolomite, 40% anhydrite
10614	10618	Anhydrite, 40% dolomite
10618	10620	Shale, gray and brown finely porous
10620	10629	Anhydrite, 45 to 50% dolomite
10629	10634	Dolomite, 20% anhydrite and brown finely porous shale
10634	10635	Dolomite, 40% anhydrite and brown finely porous shale
10635	10639	Dolomite, 5% anhydrite and brown finely porous shale
10639	10642	Dolomite, 40% anhydrite and brown finely porous shale

**Glenwood-St. Peter Formation**

10642	10673	Shale, white to gray finely porous and doloclastic, few scattered rounded frosted sand grains, 10% dolomite
10673	10674	Sandstone, quartzitic
10674	10683	Shale, white to gray finely porous, 15% dolomite
10683	10686	Sandstone, very fine grained aggregate, 15% gray shale, 10% dolomite
10686	10691	Shale, white to gray finely porous, 10% dolomite
10691	10694	Sandstone, very fine grained aggregate
10694	10695	Shale, white to gray finely porous
10695	10696	Sandstone, very fine grained aggregate
10696	10701	Sandstone, coarse rounded frosted grained aggregate
10701	10703	Sandstone, very fine grained aggregate
10703	10706	Sandstone, medium rounded frosted grained aggregate

**Prairie du Chien Group  
Shakopee Dolomite**

10706	10710	Dolomite, 20% green finely doloclastic shale
10710	10713	Shale, brown finely porous, 30% dolomite
10713	10727	Dolomite, 5% gray and brown shale, traces of pyrite and very fine grained sand
10727	10731	Dolomite, 30% brown finely porous shale
10731	10754	Dolomite, 5% brown shale, very fine grained sand, traces of pyrite and brown quartzosed chert.
10754	10760	Shale, brown and white to gray, 15 to 30% dolomite
10760	10763	Dolomite, 5% gray and brown shale, traces of pyrite
10763	10767	Shale, brown finely porous, 25% dolomite
10767	10783	Dolomite, 5% gray shale, very fine grained sand and trace of pyrite
10783	10794	Dolomite, 25 to 30% gray finely porous shale
10794	10799	Dolomite, 5% brown finely porous shale
10799	10802	Shale, brown finely porous, 10% dolomite
10802	10805	Dolomite, 5% brown shale and very fine grained sand
10805	10812	Dolomite, 30 to 50% brown finely porous and green finely doloclastic shale
10812	10816	Dolomite, 25% very fine subangular grained sand
10816	10819	Shale, white to gray finely porous, 10% dolomite
10819	10822	Dolomite, 10 to 30% white, brown, and gray smooth chert
10822	10836	Shale, brown finely porous, 10% dolomite
10836	10840	Dolomite, 30% brown finely porous shale
10840	10848	Shale, brown and gray finely porous, 10 to 30% dolomite
10848	10851	Dolomite, 20% brown quartzosed chert, 5% brown finely porous shale
10851	10855	Dolomite, 35% brown finely porous shale, 5% brown quartzosed chert
10855	10859	Siltstone, gray, 10% dolomite
10859	10861	Chert, blue, gray and brown smooth, 10% dolomite
10861	10866	Dolomite, 10 to 15% brown finely porous shale
10866	10870	Shale, brown finely porous, 10% dolomite
10870	10876	Dolomite, 50 to 15% brown finely porous shale, minor amount of gray quartzosed chert.
10876	10878	Dolomite, 35% gray siltstone
10878	10893	Dolomite, 5% gray shale and brown finely porous shale
10893	10897	Dolomite, 30% gray finely porous shale
10897	10900	Dolomite, 5% brown finely porous shale
10900	10904	Shale, white to gray, 15% gray smooth and brown quartzosed chert, 10% dolomite
10904	10905	Chert, white and gray quartzosed, 10% dolomite
10905	10907	Shale, brown finely porous, 10% dolomite
10907	10914	Dolomite, 5% brown finely porous shale.
10914	10918	Dolomite, 20% brown finely porous shale
10918	10921	Dolomite, 30% gray siltstone, 20% gray shale
10921	10926	Dolomite, 40% brown finely porous shale
10926	10941	Dolomite, 5% brown finely porous shale, traces of pyrite
10941	10944	Shale, brown finely porous, 20% dolomite
10944	10948	Dolomite, 5% brown quartzosed chert and brown finely porous shale
10948	10952	Dolomite, 20% brown finely porous shale
10952	10956	Shale, brown finely porous, 50% dolomite
10956	10960	Dolomite, 5% brown shale

10960	10962	Dolomite, 40% brown and blue smooth chert, 10% brown finely porous shale
10962	10967	Dolomite, 5% brown finely porous shale
10967	10971	Dolomite, 35% brown finely porous shale
10971	10975	Dolomite, 5% white to gray finely porous shale
10975	10986	Shale, brown finely porous, 20 to 25% dolomite
10986	10993	Dolomite, 5 to 15% brown finely porous shale
10993	10997	Shale, brown finely porous, 20% dolomite
10997	11015	Dolomite, 5 to 10% white to gray and brown finely porous shale, scattered fragments of clear quartzosed chert
11015	11017	Shale, white to gray finely porous, 20% dolomite
11017	11037	Dolomite, 5 to 25% brown and gray finely porous shale
11037	11038	Dolomite, 25% brown smooth chert
11038	11041	Shale, brown finely porous, 30% dolomite
11041	11062	Dolomite, 5% white and gray doloclastic chert and shale
11062	11077	Dolomite, 5 to 20% white, gray and brown finely doloclastic chert
11077	11080	Dolomite, 30% brown smooth and finely doloclastic chert
11080	11084	Dolomite, 5% brown finely doloclastic chert
11084	11087	Chert, finely quartzosed, 5% dolomite
11087	11103	Dolomite, 5 to 10% gray and brown finely quartzosed chert, minor amount of gray shale
11103	11107	Dolomite, 5% medium- to coarse-grained aggregate sandstone
11107	11110	Dolomite, 40% gray finely doloclastic chert
11110	11118	Dolomite, 5 to 10% medium to coarse, rounded frosted grained sand, few brown fine clustered oolites
11118	11121	Chert, gray finely doloclastic, few medium to coarse, rounded and frosted sand grains
11121	11127	Dolomite, 10% white and gray smooth chert, traces of gray shale
11127	11131	Dolomite, 5% white free oolites, traces of gray shale
11131	11132	Dolomite, 40% white and gray smooth and brown finely quartzosed chert
11132	11134	Dolomite, 5% white free and clustered oolites
11134	11146	Dolomite, 5% white and brown finely doloclastic chert, few fragments of white oolitic chert
11146	11153	Dolomite, 5% doloclastic and finely doloclastic chert, and fragments of silicified gastropods
11153	11154	Dolomite, 45% white and brown smooth chert, white and brown clustered oolites, and fragments of silicified gastropods
11154	11167	Dolomite, 40 to 60% white and gray finely doloclastic, rough and smooth chert
11167	11173	Dolomite, 20% white smooth and finely doloclastic chert
11173	11174	Dolomite, 30% medium rounded frosted sand grains
11174	11175	Chert, white and gray smooth
11175	11176	Dolomite, 20% white and gray smooth chert
11176	11188	Shale, white, gray, and brown finely porous, 15 to 25% dolomite
11188	11208	Dolomite, 5 to 20% white smooth and doloclastic chert
11208	11209	Chert, white oolitic
11209	11210	Dolomite, 5% white finely doloclastic chert

11210	11217	Chert, brown smooth and doloclastic, 30 to 50% dolomite
11217	11238	Dolomite, 5 to 25% white and gray finely doloclastic chert, minor amounts of gray shale
11238	11240	Dolomite, 35% white, dead doloclastic chert.
11240	11241	Chert, white, dead, doloclastic
11241	11249	Dolomite, 5% white, smooth and rough chert, minor amounts of pyrite, gray shale and brown, finely porous shale
11249	11260	Dolomite, 20 to 30% white, dead finely porous and doloclastic chert
11260	11267	Dolomite, 5 to 10% clear, finely quartzosed chert
11267	11271	Dolomite, 30% white smooth, doloclastic chert
11271	11272	Chert, white oolitic
11272	11278	Dolomite, 5% white oolitic chert, traces of pyrite and gray shale
11278	11285	Dolomite, 5% white finely doloclastic and finely quartzosed chert
11285	11304	Dolomite, 5% medium- to coarse-grained rounded and frosted sand, traces of gray shale
11304	11319	Dolomite, 5% gray shale and green doloclastic shale
<b>New Richmond Sandstone</b>		
11319	11328	Sandstone, fine- to medium-grained, rounded and frosted, 15 to 30% dolomite
<b>Oneota Dolomite</b>		
11328	11330	Chert, gray smooth and porous, 20% dolomite
11330	11343	Dolomite, 5% medium- to coarse-grained, rounded and frosted sand
11343	11345	Chert, white, dead, 10% dolomite
11345	11349	Dolomite, 10% white finely quartzosed chert
11349	11353	Dolomite, 20% green finely doloclastic chert, 15% medium-grained rounded and frosted sand
11353	11356	Chert, white and gray smooth
11356	11360	Dolomite, 5% green finely doloclastic chert
11360	11365	Dolomite, 20% finely quartzosed chert
11365	11370	Chert, brown, finely porous and quartzosed
11370	11381	Chert, gray and brown finely porous and quartzosed, 30 to 70% dolomite
11381	11386	Dolomite, 15% white, finely doloclastic chert
11386	11388	Dolomite, 35% white, finely quartzosed chert
11388	11391	Dolomite, 15% white, smooth and quartzosed chert
11391	11394	Chert, white finely doloclastic
11394	11398	Dolomite, 35% white, finely doloclastic chert
11398	11401	Dolomite, 35% very fine grained aggregate sand
11401	11405	Dolomite, 5% gray, quartzosed chert
11405	11409	Dolomite, 45% gray, quartzosed chert
11409	11413	Chert, white quartzosed
11413	11425	Dolomite, 30 to 35% brown, finely porous and quartzosed chert
11425	11431	Chert, brown, finely porous and quartzosed, 30 to 35% dolomite
11431	11455	Dolomite, 5 to 40% brown finely porous and quartzosed chert
11455	11458	Chert, brown finely porous and quartzosed
11458	11462	Dolomite, 40% white, doloclastic and quartzosed chert
11462	11468	Dolomite, 5% clear quartzosed chert and traces of pyrite

11468	11471	Chert, white, smooth
11471	11486	Dolomite, 5% white doloclastic and quartzosed chert
11486	11491	Dolomite, 40% brown, quartzosed chert
11491	11494	Dolomite, 20% brown and gray finely quartzosed chert, 20% pyrite
11494	11498	Dolomite, 5% very fine grained rounded and frosted sand
11498	11505	Chert, brown and gray finely porous and quartzosed, 5 to 25% dolomite
11505	11510	Dolomite, 5% gray shale
11510	11518	Chert, brown finely porous and quartzosed, 20 to 25% dolomite
11518	11546	Dolomite, 20 to 35% brown finely porous and quartzosed chert
11546	11560	Dolomite, 5 to 10% brown quartzosed chert
11560	11561	Chert, brown, smooth, 20% dolomite
11561	11564	Dolomite, 5% brown finely quartzosed chert, few sponge spicules
11564	11572	Dolomite, 15 to 20% brown quartzosed chert, minor amount of gray shale
11572	11586	Dolomite, 10 to 15% gray and brown shale and finely porous shale
11586	11604	Dolomite, 20 to 30% brown, quartzosed chert and finely porous shale
11604	11612	Dolomite, 10% brown, quartzosed chert
11612	11617	Dolomite, 35 to 40% very fine grained subangular sand, and brown finely quartzosed chert
11617	11619	Dolomite, 10 to 20% very fine to fine-grained rounded, frosted sand
11619	11623	Sandstone, very fine to fine-grained rounded, frosted, 40% dolomite
11623	11623	Chert, brown finely quartzosed, 25 to 40% dolomite
11625	11627	Dolomite, 10% quartzosed chert
11627	11631	Dolomite, 20% gray smooth chert, 20% fine- to coarse-grained rounded, frosted sand
11631	11635	Dolomite, 20% fine-grained rounded, frosted sand
11635	11636	Dolomite, 40% gray, porous shale
11636	11640	Sandstone, fine-grained aggregate
11640	11644	Sandstone, fine-grained rounded, frosted, 40% dolomite
11644	11650	Sandstone, fine- to medium-grained aggregate
11650	11655	Sandstone, fine- to medium-grained rounded, frosted, 40% dolomite
11655	11674	Sandstone, fine- to medium-grained rounded, frosted
11674	11677	Chert, brown, finely porous and quartzosed, 20% dolomite
11677	11684	Sandstone, fine- to medium-grained aggregate
<b>CAMBRIAN SYSTEM</b>		
<b>Trempealeau Formation</b>		
11684	11690	Shale, gray, 10% fine-grained aggregate, 30% dolomite
11690	11695	Dolomite, 20% brown finely quartzosed and doloclastic chert, 10% gray shale
11695	11700	Dolomite, 35% fine-grained aggregate sand, 10% gray shale
11700	11705	Sandstone, fine-grained aggregate, 5% gray shale, 40% dolomite
11705	11710	Dolomite, 30% brown, finely quartzosed chert, 20% fine-grained aggregate sand, 20% gray shale

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11710	11720	Dolomite, 30 to 40% fine-grained aggregate sand, 25% gray shale
11720	11725	Shale, gray, 10% fine-grained, aggregate sand, 35% dolomite
11725	11735	Sandstone, fine-grained, aggregate, 5 to 10% gray shale, 30 to 40% dolomite
11735	11750	Dolomite, 10% gray shale, traces of red shale and fine-grained rounded, frosted sand
11750	11760	Dolomite, 10% brown, quartzosed and finely porous chert, 5% gray shale, traces of red shale and fine-grained rounded, frosted sand
11760	11765	Dolomite, 10% fine-grained, rounded, frosted sand, traces of brown and gray shale and brown finely porous and quartzosed chert
11765	11775	Dolomite, 10% gray and brown shale, traces of fine-grained, rounded, frosted sand and gray finely porous and quartzosed chert
11775	11800	Dolomite, 30 to 40% gray, brown and red shale
11800	11825	Dolomite, 10% gray, brown, and red shale
11825	11840	Dolomite, 5 to 10% fine-grained, rounded, frosted sand, 5 to 10% gray and brown shale
11840	11850	Dolomite, 35 to 40% gray, brown, and red shale, traces of fine- to medium-grained, rounded, frosted sand
11850	11860	Dolomite, 15% gray, brown, and red shale, 5% very fine to fine-grained, rounded, frosted sand
11860	11910	Dolomite, 5 to 10% gray, brown, and red shale
11910	11920	Dolomite, 20% gray, brown, and red shale
11920	11923	No sample
11923	11927	Dolomite, 20% brown finely porous shale and brown finely quartzosed chert
11927	11936	Dolomite, 5 to 15% gray, finely porous shale
11936	11963	Dolomite, 5 to 15% gray shale and brown finely quartzosed chert
11963	11965	No sample
11965	11975	Dolomite, 30 to 40% gray, brown, and red shale
11975	11985	Dolomite, 20% gray, brown, and red shale, traces of brown, finely quartzosed chert
11985	12000	Dolomite, 15 to 20% brown, finely porous chert, minor amounts of gray and red shale
12000	12015	Dolomite, 10 to 15% gray and red shale, minor amount of brown, finely quartzosed chert
12015	12020	Dolomite, 10% gray shale, 10% brown, smooth chert, traces of very fine grained aggregate sand
12020	12025	Dolomite, 10% gray and red shale, 10% very fine grained aggregate sand
12025	12030	Dolomite, 10% gray and red shale, 10% brown, mottled chert, traces of very fine grained aggregate sand.
12030	12035	Dolomite, 20% gray and red shale, traces of brown, mottled chert
12035	12040	Dolomite, 10% gray and red shale, traces of brown, finely quartzosed chert
12040	12075	Dolomite, 5% gray, brown, and red shale
12075	12090	Dolomite, 5 to 10% gray, brown, and red shale, traces of brown mottled chert
12090	12105	Dolomite, 10 to 20% gray, brown, and red shale
12105	12115	Dolomite, 10 to 15% gray and red shale, traces of brown, mottled chert

12115	12130	Dolomite, 5% gray and red shale, traces of brown, dolocastic chert
12130	12155	Dolomite, 5% gray and red shale
12155	12165	Dolomite, 5 to 10% gray and black shale and brown finely porous shale, traces of quartzosed chert
12165	12210	Dolomite, 10 to 20% gray, brown, and red shale
12210	12245	Dolomite, 5% gray, brown, and red shale, traces of very fine grained subangular sand
12245	12265	Dolomite, 20 to 35% gray, brown, and red shale, traces of very fine grained subangular sand

**Franconia-Dresbach Formation**

12265	12275	Dolomite, 10% very fine to fine-grained, subangular and rounded, frosted sand, 5 to 10% gray shale
12275	12280	Dolomite, 25% very fine to fine-grained, subangular and rounded, frosted sand, 5% gray shale
12280	12290	Dolomite, 10% gray shale
12290	12300	Dolomite, 20 to 35% gray shale, traces of very fine grained subangular sand
12300	12305	Sandstone, fine-grained, rounded, frosted, aggregate, 20% gray shale, 30% dolomite
12305	12315	Dolomite, 5 to 15% fine- to coarse-grained, rounded, frosted sand, 15 to 25% gray and black shale
12315	12320	Dolomite, 10% fine-grained, rounded, frosted, aggregate sand, 10% gray and black shale
12320	12330	No sample
12330	12345	Dolomite, 30 to 35% gray shale, traces of fine-grained, aggregate sand
12345	12350	Dolomite, 30% gray shale, 15% fine-grained, aggregate sand
12350	12355	Dolomite, 20% fine-grained aggregate and coarse-grained, rounded, frosted sand, 10% gray shale
12355	12365	Dolomite, 10% fine-grained, subangular and rounded, frosted sand, 10% gray shale
12365	12395	Dolomite, 20 to 30% gray shale, 10% very fine to coarse-grained, rounded, frosted sand
12395	12400	Dolomite, 25% very fine to coarse-grained, rounded, frosted sand, 10% gray and brown shale
12400	12430	Dolomite, 20 to 35% very fine to coarse-grained, rounded, frosted sand, traces of gray shale and brown finely porous shale
12430	12440	Dolomite, 5 to 10% fine- to coarse-grained, rounded, frosted sand, 25 to 30% gray shale and brown, finely porous shale
12440	12460	Dolomite, 10 to 20% fine- to coarse-grained, rounded, frosted sand, 5 to 10% gray shale and brown, finely porous shale
12460	12485	Dolomite, 10 to 15% very fine to coarse-grained rounded, frosted sand, 5% gray shale

**Eau Claire Formation**

12485	12505	Dolomite, 5% gray shale and very fine to coarse grained, rounded, frosted sand
12505	12590	Dolomite, 10 to 25% gray, brown, and red shale, gray and brown finely porous shale, and traces of very fine grained, rounded frosted sand
12590	12635	Dolomite, 5% gray shale, gypsum, and very fine grained, rounded, frosted sand
12635	12650	Dolomite, 20 to 40% gray and red shale, traces of very fine grained rounded, frosted sand

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12650	12690	Dolomite, 10% gray and red shale and traces of gypsum
12690	12695	Dolomite, 15% very fine grained, rounded, frosted sand, and traces of gray and brown shale
12695	12720	Dolomite, 10 to 25% gray shale, brown finely porous shale and traces of fine- to medium-grained, rounded, frosted sand
12720	12745	Dolomite, 15 to 25% gray, brown and red shale and traces of very fine grained, rounded, frosted sand
12745	12770	Dolomite, 5% very fine grained, rounded, frosted sand, 5% gray, brown and red shale, and traces of gypsum
12770	12810	Dolomite, 10 to 25% very fine to coarse-grained, rounded, frosted sand, and traces of gray, brown and red shale
12810	12835	Dolomite, 10 to 25% gray and red shale, 5% very fine to coarse-grained, rounded frosted sand
12835	12840	Dolomite, 5% gray, brown and red shale, and traces of very fine grained, rounded, frosted sand
12840	12875	Dolomite, 10 to 20% very fine grained, subangular and rounded frosted sand, traces of gray shale
12875	12890	Dolomite, 5 to 10% very fine grained, subangular and rounded, frosted sand, 5% gray shale
12890	12910	Dolomite, 15 to 20% gray, brown, and red shale, 5% very fine grained, subangular sand
12910	12940	Dolomite, 5 to 20% gray shale, 5 to 20% very fine grained, rounded, frosted sand
12940	12945	Dolomite, 20% very fine to coarse-grained, aggregate sand, 5% black shale
12945	12955	Dolomite, 35% to 45% brown finely porous shale
12955	12960	Dolomite, 30% brown finely porous shale, 10% very fine grained, aggregate sand
12960	12970	Dolomite, 35% very fine to coarse-grained, aggregate sand, traces of brown and gray shale
12970	12975	Sandstone, very fine to coarse-grained, aggregate, traces of gray shale, 30% dolomite
12975	12980	Shale, brown, finely porous, traces of very fine to coarse-grained, aggregate sand, 35% dolomite
12980	12985	Dolomite, 30% brown finely porous shale, 5% very fine to coarse-grained, aggregate sand

## Mount Simon Sandstone

12985	12990	Dolomite, 30% very fine to coarse-grained, rounded, frosted, aggregate sand, 5% gray and black shale
12990	13004	Sandstone, fine- to coarse-grained, rounded, frosted, aggregate, trace of black shale, 30 to 40% dolomite
13004	13013	Sandstone, very fine to coarse-grained, rounded, frosted aggregate
13013	13019	Sandstone, arkosic
13019	13020	Chert, sandy and finely doloclastic
13020	13024	Sandstone, arkosic
13024	13026	Sandstone, very fine to coarse-grained, rounded, frosted, 35% gray finely porous shale, 25% dolomite
13026	13034	Sandstone, very fine to coarse-grained, rounded, frosted, 10 to 40% dolomite
13034	13038	Dolomite, 5% very fine grained, subangular sand
13038	13044	Dolomite, 20 to 40% brown, sandy, finely porous shale

13044	13049	Dolomite, 30% fine- to coarse-grained, rounded, frosted sand
13049	13050	Sandstone, fine- to coarse-grained, rounded, frosted sand, 10% dolomite
13050	13054	Dolomite, 10% very fine grained, rounded, frosted sand
13054	13056	Sandstone, fine- to coarse-grained, rounded, frosted, 50% dolomite
13056	13061	Sandstone, very fine to fine-grained, aggregate, 10 to 15% dolomite
13061	13063	Shale, gray, 5% dolomite
13063	13073	Sandstone, very fine to medium-grained, aggregate
13073	13076	Sandstone, arkosic
13076	13084	Sandstone, fine- to coarse-grained, rounded, frosted, 20 to 40% dolomite
13084	13104	Sandstone, medium- to coarse-grained, subangular, aggregate
13104	13112	Sandstone, fine- to medium-grained, subangular, 10 to 15% dolomite
13112	13123	Sandstone, fine- to medium-grained, aggregate
13123	13132	Sandstone, very fine grained, aggregate, traces of black shale
13132	13135	Shale, gray, 15% finely quartzose sand, 20% dolomite
13135	13143	Sandstone, very fine grained, aggregate, 10% dolomite
13143	13147	Shale, brown, fine porous and quartzosed
13147	13151	Dolomite, 25% very fine grained, rounded, frosted sand
13151	13154	Sandstone, very fine grained, aggregate, 20% dolomite
13154	13170	Sandstone, very fine grained, aggregate
13170	13175	Shale, gray and red, 20% very fine grained, aggregate sand, 40% dolomite
13175	13190	Sandstone, very fine grained, aggregate, traces of gray shale, 20 to 35% dolomite
13190	13200	Sandstone, fine- to medium-grained, rounded, frosted, traces to gray shale, 40% dolomite
13200	13260	Sandstone, very fine grained, aggregate, 20% to 30% dolomite
13260	13272	Sandstone, arkosic, fine-grained, aggregate, 20 to 25% dolomite

## PRE-CAMBRIAN

13272	13310	Gneiss, micaceous
13310	13327	Granite, gneiss
13327	13331	Depth correction
	13331	Total depth

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# ORDOVICIAN ROCKS OF THE SANDHILL WELL IN WEST VIRGINIA

By Leonard D. Harris<sup>2</sup>

## ABSTRACT

The Hope Natural Gas Company Sandhill well No. 9634 was completed in Pre-Cambrian rocks in February 1955. Ordovician rocks in this well occur in the interval between 7,811 and 11,737 feet and are subdivided from the top downward into the Juniata Formation, the Martinsburg Shale, the Trenton Limestone, a Middle Ordovician limestone sequence, and the Beekmantown Dolomite.

The Juanita Formation, which in the Sandhill well consists of 614 feet of grayish-red and greenish-gray shale and some interbedded siltstone, overlies a thickness of 1,103 feet of greenish-gray and medium-gray to dark-gray shale assigned to the Martinsburg Shale. The Trenton Limestone, a medium-gray coquinoid limestone with a bentonite zone in its lower part, is 202 feet thick and overlies a Middle Ordovician limestone sequence 976 feet thick, which includes bentonite in its upper part. An unconformity at the base of the Middle Ordovician sequence is interpreted as the same major unconformity as that at the base of similar Middle Ordovician rocks in much of central, eastern, and southern United States.

Nearly all the Lower Ordovician rocks, to which the general term Beekmantown Dolomite has been applied, are dolomite containing some argillaceous and arenaceous material. Chert is abundant in the middle part, and the basal 104 feet is dolomitic sandstone. Evidence in the cores suggests that at least the upper 927 feet of this 1031-foot sequence was subjected to a long period of solution.

Rocks in the Sandhill well are correlated with rocks in southern West Virginia and southwest Virginia on the basis of gross lithologic similarity, the bentonite zone in the Middle Ordovician, and the unconformity at the base of the Middle Ordovician limestone sequence. The Juniata, Martinsburg, and Trenton Formations can be correlated on a lithologic basis with some assurance, but all Middle Ordovician rocks below the Trenton can be compared only on gross lithology and no formations are differentiated. Rocks termed Beekmantown

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<sup>2</sup>U. S. Geological Survey, Washington, D. C. The author wishes to express his gratitude to R. E. Bayles, R. R. Flowers, W. H. Henry, R. L. Miller, T. Arkle, Jr., and P. H. Price, for their assistance and encouragement during the early phase of the report. Special thanks is due E. J. Lyons and K. J. Englund for their critical review of the report

Dolomite in the Sandhill well are tentatively correlated with strata of the Mascot, Kingsport, Longview, and Chepultepec Formations in southwest Virginia.

### INTRODUCTION

In February of 1955 the Hope Natural Gas Company completed their Sandhill well No. 9634 on the Power Oil Company tract, Walker District, Wood County, West Virginia. This well, which set a new deep test record for northeast United States by reaching a total depth of 13,331 feet, was drilled through a section of rocks ranging in age from Pennsylvanian at the surface to Pre-Cambrian at the bottom of the well. This paper is limited to a discussion of the stratigraphy of the rocks assigned to the Ordovician System in the well.

In addition to its record depth, the Sandhill well is significant in that approximately 2,200 feet of the 3,926 feet of rock assigned to the Ordovician was cored. Most of the coring was confined to the Lower and Middle Ordovician rocks, but a small part of the Upper Ordovician was also cored. This coring made feasible a more detailed study of the lithology and associated features of the Ordovician rocks than had been possible heretofore.

A descriptive log of the entire Sandhill well has been published by the West Virginia Geological and Economic Survey as Report of Investigations No. 14 (Bayles and others, 1956). R. R. Flowers and the author described the part of the well that was cored, and R. E. Bayles, W. H. Henry, C. R. Fettke, and R. R. Flowers described the part of the well from which cuttings were taken. Report of Investigations No. 14 has been used in this paper for the descriptions of the drilled parts of the Sandhill well.

### LITHOLOGY AND ASSOCIATED FEATURES

The Ordovician rocks in the Sandhill well occur in the interval from 7,811 to 11,737 feet. Lithology is used as a basis for separating this 3,926 feet of Ordovician rocks into several subdivisions. These subdivisions, from youngest to oldest, include the Juniata Formation, Martinsburg Shale, Trenton Limestone, Middle Ordovician limestone sequence, and the Beekmantown Dolomite. The Juniata and the upper part of the Martinsburg are of Late Ordovician age; the lower part of the Martinsburg, the Trenton, and the Middle Ordovician limestone sequence are of Middle Ordovician age; and the Beekmantown Dolomite is of Early Ordovician age.

As is the custom in describing the lithologic sequence in a well, the description proceeds from youngest to oldest. The depth interval included by each subdivision is in parentheses

after the subdivision heading, e. g., Juniata Formation (7,811 to 8,425 feet).

#### **Juniata Formation (7,811 to 8,425 feet)**

The Juniata Formation, 614 feet thick, is composed principally of grayish-red shale and siltstone; a few greenish-gray beds occur throughout the formation and are especially abundant near the base. This increase in abundance of greenish-gray beds in the lower part of the Juniata suggests a gradation from the greenish-gray beds of the upper part of the Martinsburg into the alternating red and green beds of the Juniata. Bayles and others (1956, p. 16) place the contact between the Juniata and Martinsburg at the base of the red Juniata-type rock. A reworked zone at the top of the Juniata apparently marks a disconformity between the Juniata and the overlying Tuscarora Sandstone of Silurian age.

#### **Martinsburg Shale (8,425 to 9,528 feet)**

The Martinsburg Shale, which is composed mainly of shale and siltstone with some interbedded argillaceous limestone, can be subdivided into three units. (Fig. 2). An upper unit, unit 3, is interbedded greenish-gray, calcareous siltstone and shale about 425 feet thick; unit 2 is 265 feet thick and includes mostly medium-gray calcareous shale; and unit 1, 413 feet thick, is a slightly calcareous, medium dark gray to dark-gray shale with some interbedded limestone. A bentonite bed occurs 183 feet above the base of unit 1 (Bayles and others, 1956, p. 17). Both the upper and lower contacts of the Martinsburg Shale are gradational.

#### **Trenton Limestone (9,528 to 9,730 feet)**

The Trenton Limestone is composed predominantly of light-gray coquinoid limestone and interbeds of medium dark gray, argillaceous, silt-size limestone and dark-gray shale. A zone containing three bentonite beds was found close to the base of the formation (Bayles and others, 1956, p. 19). The upper and lower contacts are gradational and both contacts were placed where coquinoid limestone predominates.

#### **Middle Ordovician limestone sequence (9,730 to 10,706 feet)**

Rocks assigned to the Middle Ordovician limestone sequence are quite similar in color and texture. They are mainly medium dark gray to dark gray, and the grain size is mostly in the clay to silt range. The principal differences in the rocks are the wide range in the amount of argillaceous material and, in the lower part of the sequence, the occurrence of dolomite. These differences have been used to subdivide this 976-foot sequence into six units (Fig. 2).

The uppermost unit, unit 6, is composed of medium dark gray, clay- to silt-size, argillaceous limestone with some interbedded, calcareous, medium dark gray shale. This unit is 143 feet thick. A single bentonite bed occurs about 8 feet below the top (Bayles and others, 1956, p. 19).

Unit 5 is 167 feet thick and consists of clay- to silt-size, medium light gray to dark-gray limestone and contains very little or no argillaceous material. Olive-black chert nodules occur about 15 feet below the top of the unit.

Unit 4 is 428 feet thick and is the thickest unit in the sequence. It is composed primarily of clay- to silt-size, argillaceous, dark-gray limestone which contains many interbeds and partings of dark-gray, calcareous shale. There are a few minor zones of coarse-grained material, but none of these zones are thick enough to warrant a separate description. Chert, although not abundant, occurs near the top and base of the unit as isolated nodules.

The next unit, unit 3 is a 55-foot transitional zone between the limestone facies of unit 4 and the dolomite facies of unit 2. The upper half of unit 3 is mainly clay- to silt-size, dark-gray limestone and some interbedded dark-gray dolomite. In contrast the lower half of the unit is mostly dark-gray dolomite and some limestone. Partings of grayish-black, pyritic, carbonaceous shale occur throughout the entire unit.

Unit 2 is composed of 165 feet of dolomite that is dark-gray in the upper one-third and medium gray in the lower two-thirds. The entire unit is argillaceous and contains numerous grayish-black, pyritic, carbonaceous shale partings. Silt-size quartz particles occur throughout the unit and disseminated grains of fine- to medium-grained quartz sand are abundant near the base.

The basal unit, unit 1, consists of 18 feet of dolomitic sandstone, in which the sand size decreases upward from medium-grained with a few disseminated granules at the base to fine- to medium-grained at the top.

An unconformity between unit 1 of the Middle Ordovician limestone sequence and the underlying Beekmantown Dolomite is demonstrated by the irregular nature of the contact, plus the fact that numerous solution features (vugs and solution joints) extends from the top to near the base of the Beekmantown (Plates 1, 2, and 3). Clastic material similar to that in unit 1 has completely filled all solution joints and vugs in the upper 122 feet of the Beekmantown (Fig. 1). A definite connection between the clastics of unit 1 and the clastic fill in the solution joints of the Beekmantown is shown at the contact where the sandstone of unit 1 is continuous with the sand-filled joints of the Beekmantown. This evidence suggests a long period of solution prior to the deposition of

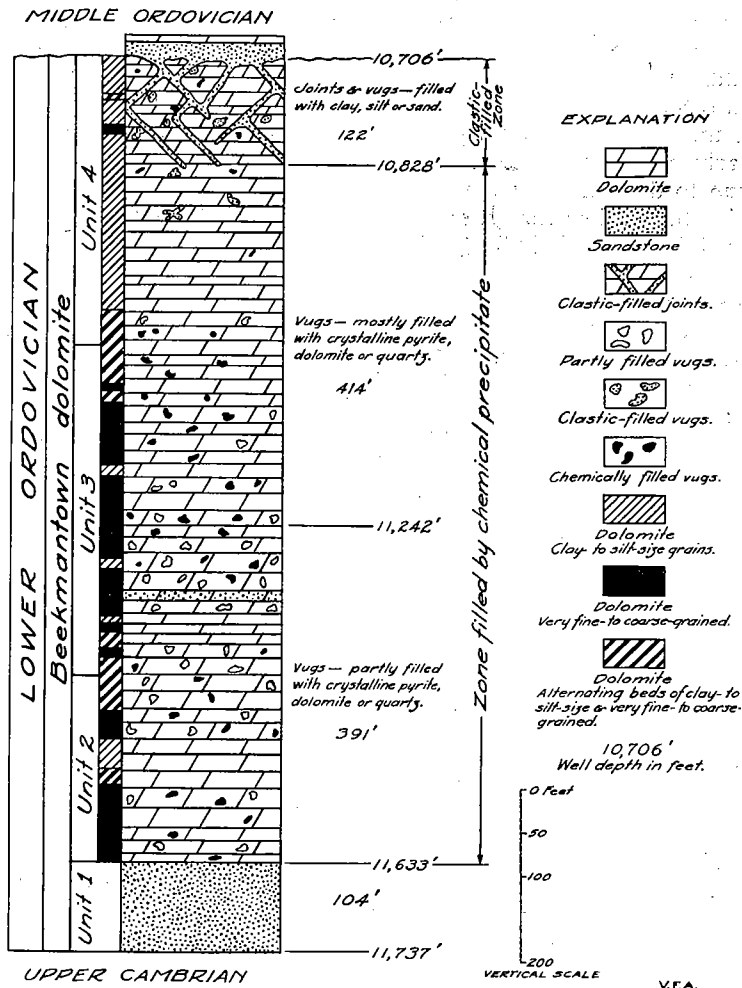


FIG. 1- Stratigraphic section of the Lower Ordovician rocks in the Sand Hill well, showing the zone of solution and state of filling of vugs and joints.

the Middle Ordovician limestone sequence. The unconformity at the base of the Middle Ordovician in the Sandhill well may be the same as the major unconformity at the base of a similar sequence in much of central, eastern, and southern United States.

It has been the general practice in regional subsurface studies in the northern Appalachian basin area to mark the base of the Middle Ordovician at the change from limestone

to dolomite. If this practice had been followed in the Sandhill well, about 210 feet of dolomite in the basal part of the Middle Ordovician would have been included in the Lower Ordovician. Fortunately that part of the section containing the unconformity in the Sandhill well was cored. This core clearly shows that there is not a definite change from limestone to dolomite between the Middle and Lower Ordovician rocks, but rather that they are separated by an unconformity. The dolomite of Middle Ordovician age differs from the dolomite of Lower Ordovician age in the following ways: (1) the gray color of most of the Middle Ordovician dolomite is much lighter, (2) the argillaceous content of the Middle Ordovician dolomite is considerably higher, and (3) there is a distinctive pyritic, carbonaceous, grayish-black shale that occurs as partings throughout the basal dolomite and dolomitic limestone beds of Middle Ordovician age but is not in the Lower Ordovician beds below the unconformity.

#### **Beekmantown Dolomite (10,706 to 11,737 feet)**

Most of the rocks comprising the 1,031 feet assigned to the Lower Ordovician in the Sandhill well are dolomite. Correlation features of these dolomites are subtle, and consequently regional correlation with specific formations is difficult. For this reason the more general term Beekmantown Dolomite is used, but the sequence is subdivided into four lithologic units.

Unit 4, the uppermost unit, is 331 feet thick and is composed principally of silt-size, medium dark gray dolomite which, in the lower 200 feet, contains some olive-black chert nodules and thin beds of chert or disseminated grains of silt and fine sand. The upper 122 feet contains many solution joints and vugs that have been completely filled with clastic material similar to the sediments above the unconformity at the top of the unit (Fig. 1).

Included in unit 3 is 381 feet of medium light gray to medium-gray dolomite which ranges from silt size to coarse grained; the coarse-grained dolomite is more prominent near the middle of the unit. The entire unit contains silt and fine-grained sand as disseminated grains and in thin beds, as well as some greenish-gray shale partings. Only the lower two-thirds of the unit contains abundant chert, which is usually light gray, mottled, bluish, purplish, or pink. Solution features, such as vugs and a few joints, are conspicuous throughout unit 3. These vugs and joints in the upper half of the unit are completely filled with crystalline pyrite, dolomite, or quartz, but in the lower half they are only partly filled.

In the next unit, unit 2, the dolomite ranges in crystallinity from silt-size to fine-grained and contains many thin beds and disseminated grains of silt and fine-grained sand, and some grayish-black shale partings; light-gray to olive-gray chert, although not abundant, occurs throughout the unit. This unit is 215 feet thick. Abundant open vugs are present in the upper part of the unit, but they are less abundant in the lower part of the unit (Fig. 1).

Unit 1, the basal unit, is a dolomitic, fine- to medium-grained, subangular to rounded, very light gray sandstone, 104 feet thick.

#### SOLUTION ZONE IN THE LOWER ORDOVICIAN ROCKS

Most of the upper 927 feet of the 1,031 feet of rocks assigned to the Beekmantown Dolomite shows solution joints and vugs. The abundance of solution features is evidently dependent upon grain size of the dolomite. This relationship is demonstrated in Figure 1, which illustrates diagrammatically the grain size of the dolomite and the position and abundance of solution features in the Beekmantown Dolomite. In the upper part of the formation, where the grain size is predominantly in the clay- to silt-size range, solution phenomena are confined mostly to joints. The joints, of course, would provide the easiest course for water percolation. In the middle and lower parts of the Beekmantown, however, where the coarser grained material is predominant, the solution features are more widespread and their abundance increases. This difference in degree of solution is probably due to the greater permeability of the coarse-grained dolomite.

The Beekmantown Dolomite can be subdivided into two major zones based on the type of material filling the solution features. The upper zone, 122 feet thick, is herein referred to as the clastic-filled zone, because all solution joints and vugs are filled with clastic material similar to the sediments above the unconformity at the top of the Beekmantown Dolomite (Plates 1 and 2). The lower zone, 805 feet thick, is called the chemical-precipitate zone, because most joints and vugs are filled or partly filled with crystalline pyrite, dolomite, or quartz. This chemical-precipitate zone is further subdivided into two parts based on the completeness of filling. In the upper 414 feet nearly all joints and vugs are filled with crystalline pyrite, dolomite, or quartz, but in the lower 291 feet most of the vugs are open or only partly filled with crystalline material (Plate 3). Solution features seem to decrease gradually in abundance in the lower part of the partly filled zone, which is possibly due to interbedding of clay- to silt-size

dolomite or simply because intense solution did not extend into this part of the section.

PLATE 1.—The unconformity at the top of the Beekmantown Dolomite and clastic-filled solution features directly below the unconformity.



FIGURE A.—Core of 10,706 feet showing the unconformity at the top of the Beekmantown Dolomite and same solution features in the Beekmantown filled with Middle Ordovician clastics.

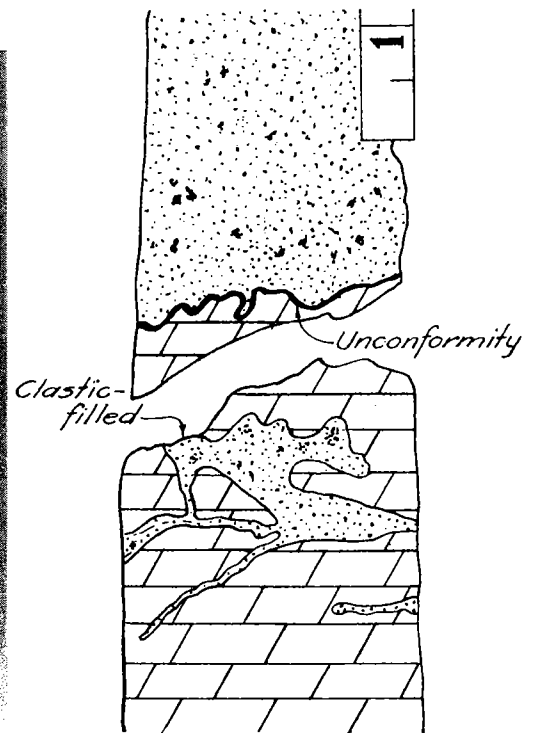


FIGURE B.—Generalized diagram of Figure A, indicating the irregular nature of the unconformity and the general shape of the solution features filled with Middle Ordovician clastics.

It is evident that solution in the upper part of the Beekmantown must have been intense enough to form an interconnected system of solution joints; otherwise, Middle Ordovician clastics could not have filled all solution cavities to a depth of 122 feet below the unconformity. This interconnected system of openings probably extends below the main clastic-filled zone and possibly even throughout most of lower zones of the Beekmantown, as shown by isolated joints filled with clastic material 60 feet below the main 122-foot clastic-filled zone. Furthermore, there appears to be a gradation in the

PLATE 2.—Solution features in the Beekmantown Dolomite filled with Middle Ordovician clastics.

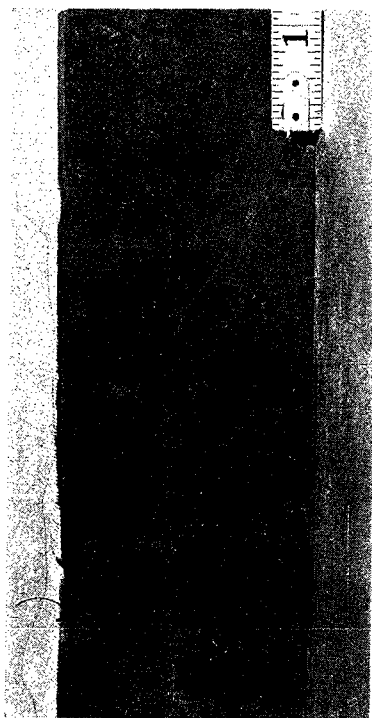


FIGURE A.—Core of Beekmantown Dolomite taken at 10,767 feet, about 60 feet below the unconformity at the top of the Beekmantown. A solution joint cuts diagonally across the core from top center to lower left.

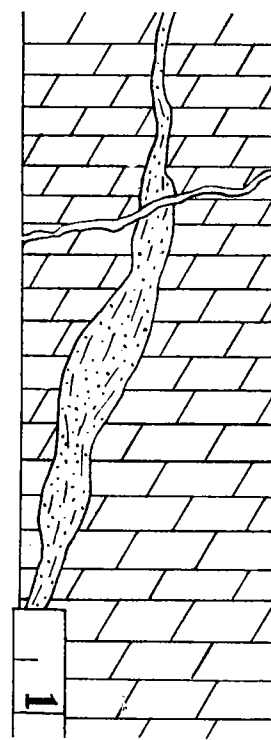


FIGURE B.—Line drawing of Figure A, showing the direction of the solution joint through the Beekmantown Dolomite and the nature of the clastic fill material (mainly clay), and disseminated grains of silt and sand.

type or amount of material that fills the solution features. Thus, the vugs or joints are mostly clastic filled in the upper part, are chemically filled in the central part, and are only partly chemically filled in the lower part.

An interconnected system of openings in the Lower Ordovician could be of economic significance. One of the important features of this zone is the fact that nearly all openings are sealed with either clastic or chemically precipitated material for about 500 feet below the unconformity at the base of the Middle Ordovician. This filled section should act as a cap to seal gas or liquids that occur below this filled

PLATE 3.—Solution features in the Beekmantown Dolomite that are partly filled with chemically precipitated, crystalline material.

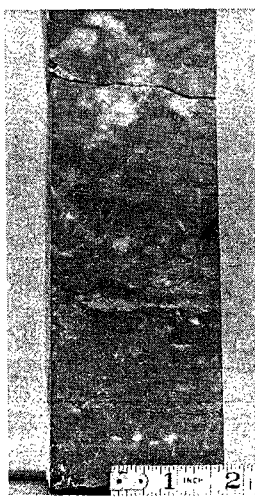


FIGURE A.—Core at 11,142 feet in which the vugs (white areas) are filled with crystalline pyrite and dolomite.

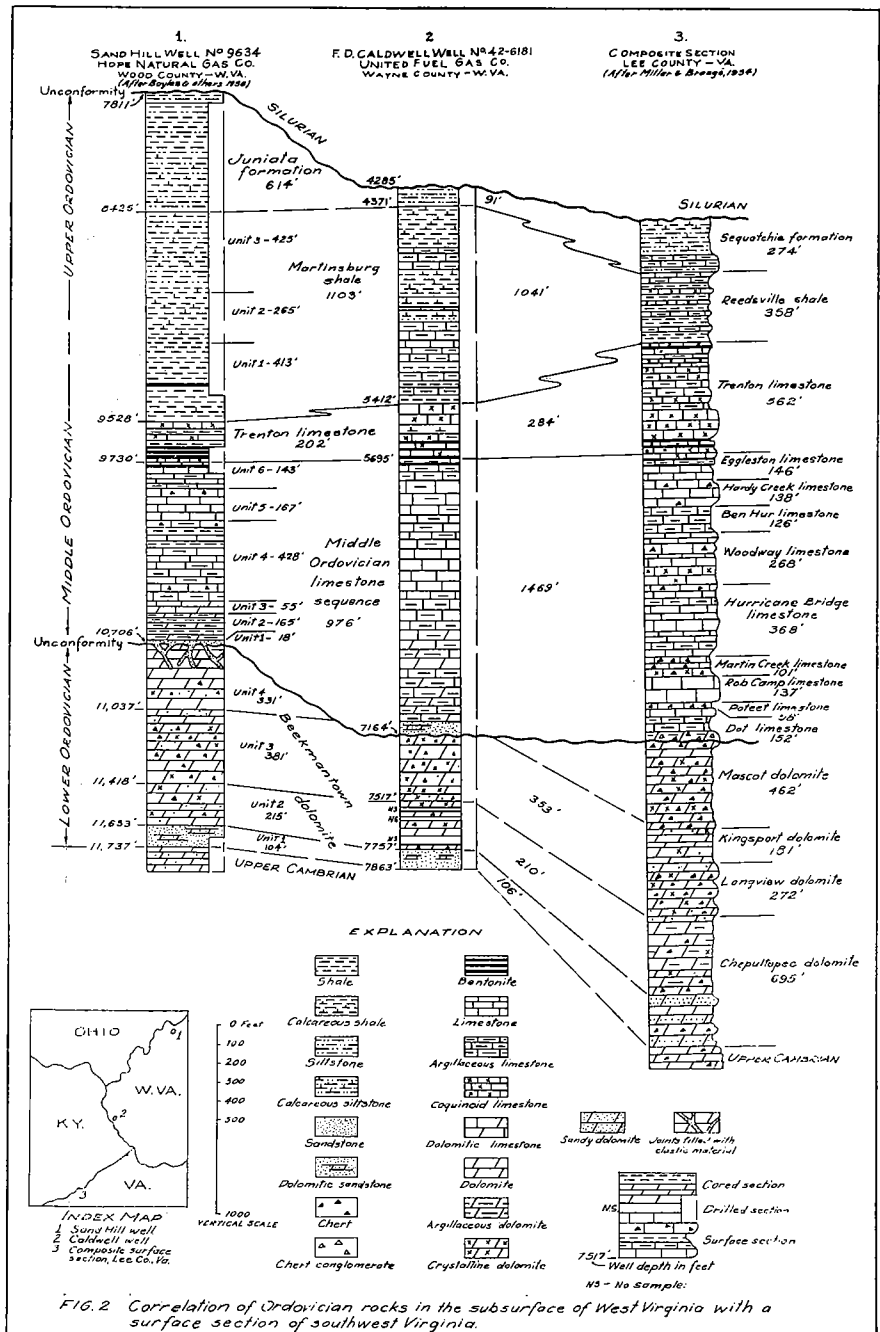


FIGURE B.—Core at 11,246 feet in which vugs are open. Many vugs are elongate and parallel suggesting solution along a pre-existing joint system.

zone. That such a seal exists is suggested by three gas shows in the interval from 11,203 to 11,304 feet, where open vugs first appear in abundance, and by the fact that salt water bled from all cores from 11,224 to 11,636 feet (Bayles and others, 1956, p. 22-23). The relationship of the gas and salt water suggests that gas was trapped on top of a 400-foot column of salt water beneath the sealed zone but, because the Lower Ordovician rocks penetrated by the Sandhill well are nearly flat, the economic potential of this zone was decreased.

#### CORRELATION OF THE ROCKS IN THE SANDHILL WELL WITH ROCKS IN SOUTHERN WEST VIRGINIA AND SOUTHWEST VIRGINIA

Correlation of the rocks in the subsurface of West Virginia with rocks exposed on the surface in southwest Virginia is based on lithologic similarities, the bentonite zone in the Middle Ordovician, and the unconformity at the base of the Middle Ordovician limestone sequence. Figure 2 diagrammatically illustrates how these diagnostic features were used to correlate the rocks in the Sandhill well (Bayles and others, 1956) with rocks in the F. D. Caldwell well in Wayne County, West Virginia, and a generalized surface section in Lee



County, Virginia (Miller and Brosge, 1954). A description of the F. D. Caldwell well has been published by Freeman (1953, p. 337-340), but her description of the well is not used in this report because the stratigraphic nomenclature used by her is not the same as the nomenclature used in this report. Consequently, the cuttings from the Caldwell well were re-described and plotted as section No. 2 of Figure 2. The actual lithologic descriptions and formational boundaries as used by Freeman and the present author closely parallel each other.

The red shale and siltstone beds typical of the Juniata are generally thought to be non-marine, but the equivalent shale, siltstone, and argillaceous limestone of the Sequatchie Formation to the south, are marine. In general this red zone thins to the south, but it is much thicker in the Sandhill well (614 feet) and the southwest Virginia section (274 feet) than it is in the Caldwell well (91 feet). This thinning of the red zone in the Caldwell well, as shown in Figure 2, may be due either to erosion prior to the deposition of the Silurian rocks, or it may be the result of regional facies interfingering as outlined by Freeman (1953, p. 34). Freeman has shown that directly west of the Caldwell well the red facies, usually associated with the Juniata or Sequatchie, is gradually supplanted by a green facies. This suggests that the Caldwell well is located in a transitional zone between the two facies and that possibly some of the medium-gray to greenish-gray shale assigned to the Martinsburg Shale in the Caldwell well is equivalent to the basal beds of the Juniata in the Sandhill well.

The Martinsburg Shale can be recognized as the shale and siltstone facies that overlies an expanded Trenton Limestone in the section to the south of the Sandhill well. The thinning of the Martinsburg to the south from 1,103 feet to 358 feet, and the corresponding thickening of the Trenton, is apparently due to the interfingering of the Martinsburg and Trenton facies. This interfingering is suggested by (1) the occurrence of argillaceous limestone and sporadic thin interbeds of coquinoid limestone typical of the Trenton in the basal part of the Martinsburg in the Caldwell well and (2) the presence of a single bentonite bed in the lower part of the Martinsburg of the Sandhill well and in the upper part of the Trenton in the Lee County, Virginia, section (Fig. 2).

Even though the Trenton Limestone thickens from 202 feet in the Sandhill well to 562 feet in Lee County, Virginia, it still retains a coquinoid character. A hand specimen from the outcrop in southwest Virginia can not be easily distinguished from the coquinoid limestone in the Sandhill well.

All three sections illustrated (Fig. 2) have a series of four bentonites spanning a zone that includes the basal beds

of the Trenton Limestone and the uppermost beds of the Middle Ordovician limestone sequence. This persistence of a zone of bentonite in rocks of the same character, accompanied by a change from medium-gray, coquinoid limestone to a clay- to silt-size, olive-gray limestone, suggests that this zone can be used with some degree of assurance as a correlation tool.

The Middle Ordovician limestone sequence in all three sections is bracketed by a bentonite zone at the top and an unconformity at the base (Fig. 2). This limestone sequence thickens from 976 feet in the Sandhill well to more than 1,400 feet in both sections to the south, but almost all of the thickening takes place in the area between the Sandhill and Caldwell wells. Although individual formations in southwest Virginia can not be definitely identified in the Caldwell or Sandhill wells, the lithologies, which are typical of the Middle Ordovician rocks, are remarkably similar. Lithologically, most of the limestone in the three sections is in the clay- to silt-size range; a few coarse zones are prominent only in the Lee County, Virginia, section. The limestone in the Sandhill core is mainly medium dark gray to olive gray, but to the south, even though olive gray is the predominant color, light olive gray, less argillaceous limestone is conspicuous. The occurrence of the lighter colored, less argillaceous limestone in the Virginia section suggests deposition in an environment which was more remote from the influence of a land mass; consequently, less argillaceous material was contributed.

The basal strata of the Middle Ordovician are similar in the Lee County section and in the Sandhill and Caldwell wells. Each section includes a clastic zone overlain by argillaceous dolomite that grades upward into limestone. The clastic zone in the Lee County, Virginia, section is composed primarily of chert fragments, whereas in the other two sections the basal clastic zone is sandstone. The basal chert conglomerate in the Virginia section is known to be reworked residuum derived from the weathering of the Mascot Dolomite. It is possible that the sands at the base of the Middle Ordovician sequence in the Sandhill well and in the Caldwell well are also residuum derived from weathering of the upper part of the Beekmantown Dolomite. A wide range in thickness of the dolomite section that overlies the clastic zone in Virginia is not unusual; in a short distance laterally this dolomite section ranges from a few feet to 150 feet in thickness. This variation in thickness is due to the uneven erosional surface upon which the basal sediments were deposited. If the erosion surface of West Virginia is comparable to that observed on the outcrop in southwest Virginia, the basal dolomite unit can be expected to have a wide range in thickness.

The Beekmantown Dolomite in the Sandhill well is subdivided into four lithologic units; all but the uppermost (unit 4) of these units can be identified in the Caldwell well. The absence of unit 4 in the Caldwell well is due to erosion associated with the unconformity at the top of the Beekmantown. The lithologic similarities used to correlate the several units of the Lower Ordovician in both the Caldwell and Sandhill wells can be summarized as follows; unit 3 in both wells is characterized by its coarse crystallinity, light-gray to medium-gray color, the abundance of light-gray chert, disseminated grains of sand, and greenish-gray shale partings; the dolomite of unit 2 in both wells is olive gray to medium dark gray, contains some olive-gray chert and disseminated sand grains; the sandstone underlying unit 2 is 104 feet thick in the Sandhill well and 106 feet thick in the Caldwell well.

Similarities exist between the Lower Ordovician rocks in both wells and the Lower Ordovician rocks in the Lee County, Virginia, section, but correlation of specific units is tentative. The identification of specific units tends to be masked by slight facies changes, and by an increase in the thickness of Lower Ordovician rocks from 1,031 feet in the Sandhill well to 1,610 feet in the Virginia section.

The rocks in unit 4 of the Sandhill well resemble in some respects the Mascot Dolomite of the Lee County, Virginia, section. Both intervals include interbedded medium-gray to medium dark-gray dolomite, but chert occurs in only the lower part of unit 4 in the Sandhill well whereas chert is abundant throughout the Mascot. In Virginia, the Kingsport Dolomite is mostly a clay- to silt-size, light-gray, essentially non-cherty dolomite, and the underlying Longview Dolomite is mostly a crystalline, light-gray dolomite containing abundant chert. These two formations combined are similar to unit 3 of the Sandhill well, which is interbedded silt- to coarse-grained, light-gray, essentially non-cherty dolomite in the upper part and crystalline, light-gray, cherty dolomite in the lower part. Units 1 and 2 of the Sandhill well resemble the Chepultepec Dolomite of Lee County in color, grain size, and in the abundance of sands.

### CONCLUSIONS

In correlating the Ordovician rocks in the Sandhill well with rocks in the Caldwell well and with the section in Lee County, Virginia, it is apparent that the two most useful criteria are lithologic similarities and the sequence of sedimentation. Rocks in the Upper Ordovician are predominantly clastic, the Middle Ordovician are mostly limestone, and the Lower Ordovician are mainly dolomite (Fig. 2). This remarkable similarity in rock type and sequence of sedimen-

tation persists even though the Upper Ordovician rocks thin toward the south and the Lower and Middle Ordovician rocks thicken toward the south.

Another useful aid in correlation is a zone of bentonite that straddles the contact between the Trenton Limestone and the Middle Ordovician limestone sequence. This bentonite zone can be easily recognized for two reasons: (1) the unusual appearance of the bentonite, which is a light-gray to greenish-gray, translucent clay containing mica flakes, and (2) the bentonite always occurs in the transition zone where there is a change from the medium-gray, crystalline limestone typical of the Trenton Limestone to the olive-gray, clay-size limestone typical of the Middle Ordovician limestone sequence.

All three sections illustrated in the correlation diagram (Fig. 2) contain an unconformity at the top of the Lower Ordovician. The position of this unconformity is important because it marks the base of the Middle Ordovician rocks, and because it is associated with a sequence of lithologies that are sufficiently diagnostic to identify this horizon.

In the Sandhill well the zone that includes the unconformity at the top of the Lower Ordovician, as well as most of the Lower Ordovician rocks, was cored. The coring made possible an unequalled opportunity to study the unconformity, the deposits associated with the unconformity, and the effects of solution on the Lower Ordovician carbonates. The relationship of the solution features to grain size of dolomite indicates that solution was less widespread in beds containing clay- to silt-sized particles and was more widespread in beds containing very fine to coarse particles. An interconnected system of solution features throughout the Beekmantown Dolomite is suggested by the abundance of solution features filled with Middle Ordovician sediments in the upper part of the Beekmantown, together with the presence of solution features in the middle and lower parts of the Beekmantown that are filled or partly filled with chemically precipitated crystalline material. Nearly all of the solution openings in the upper part of the Beekmantown are sealed, and this sealed zone evidently acted as a cap that trapped small amounts of gas and abundant salt water in the unfilled solution cavities in the lower part of the formation. If the Lower Ordovician rocks penetrated in the Sandhill well had some structural closure instead of being nearly flat-lying, the economic possibilities of the open vug zone would have been increased.

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# PETROGRAPHIC, CHEMICAL, AND FAUNAL STUDIES, CAMBRO-ORDOVICIAN CARBONATES IN THE SANDHILL WELL, WOOD COUNTY, WEST VIRGINIA

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R. E. Mershon<sup>4</sup> and K. J. Miller<sup>5</sup>

## INTRODUCTION

The studies herein discussed are a part of a unified effort by several geologists to gather as much information as possible on the Power Oil Co. No. 9634 (Sandhill) well, Wood County, West Virginia. The importance of the well, not a producer, lay in the fact that it penetrated the Paleozoic section of this area and was located in an area removed from other wells contacting the deeper Paleozoic rocks. The well then served as an important key to a knowledge of the deeper rocks and to future exploration in this general region. The intermediate geographic position of this well between the eastern outcrop of the Valley and Ridge Province and the western outcrop of the Mississippi Valley makes it potentially valuable in demonstrating the lateral relationship of the lower Paleozoic units. The availability of core from the deeper portion of the well made possible a detailed study of the petrography, chemistry, and fauna of the Trenton and sub-Trenton carbonates. Thus better correlation and closer formational contact were hoped for through application of several lines of approach.

Financial support for laboratory work was offered by the Pennsylvania Topographic and Geologic Survey, acting through a special grant by the Pennsylvania Department of Internal Affairs. Acknowledgments are also due Hope Natural Gas Company, who supplied the sliced core for study and transportation to Pittsburgh. The Peoples Natural Gas Company generously supplied storage facilities.

The work was carried out under the general supervision of the senior author. The actual work was performed by the junior authors as partial fulfillments of requirements towards the Master's degree at the University of Pittsburgh. The

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<sup>4</sup>The Texas Co., Ardmore, Oklahoma.

<sup>5</sup>U. S. Air Force, West Springfield, Mass.

following these titles will identify the workers with their particular field of concentration: I. I. Aarons, "A Petrographic Study of Canadian and St. Croixan Rocks of a Deep Test Well in Wood County, West Virginia;" William M. McCollough, "A Chemical Analysis of the Core from a Deep Test Well, Wood County, West Virginia;" Robert E. Mershon, "A Sedimentary Analysis of the Core from a Deep Test Well, Walker District, Wood County, West Virginia;" and Kenneth J. Miller, "Paleontological Study of an Appalachian Deep Test Well, Wood County, West Virginia."

The present article represents a condensation of these four theses which are too voluminous to include herein in their entirety. The senior author has added interpretations and is to be held responsible for many of the conclusions drawn.

The well from which the core was taken is known as the Power Oil Company No. 9634. It is located approximately 14 miles east of Parkersburg in Wood County, Walker District, West Virginia (Fig. 1). The well is located near the axis of the Burning Springs Anticline.

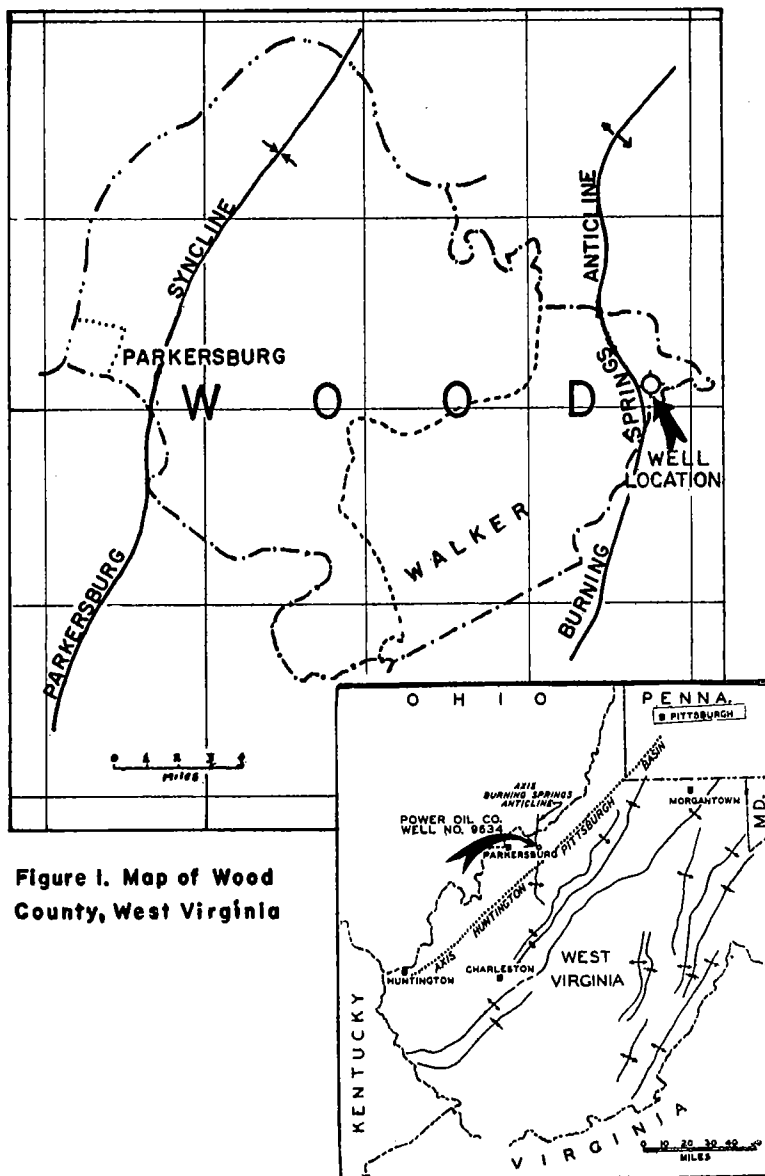
### PETROGRAPHIC AND RADIOACTIVE LOG COMPARISONS, MIDDLE ORDOVICIAN

#### Purpose of Study:

A detailed petrographic study of thin sections was thought important to a better description of the rock types, the fabric of the carbonate, the correlation of the rock and fabric types to deflections on the radioactive logs, the correlation of rock types to classified formational units on the outcrop, and finally to establish closer formational contacts by comparing pronounced vertical changes in lithology to significant deflections in the electric and radioactive logs.

#### Laboratory Procedures:

Standard thin sections were prepared at about five-foot intervals throughout the approximate 1000 feet of limestone core. The samples generally represent the dominant lithology of the interval. However, the five-foot interval was shortened occasionally to include a thinner unit clearly different megascopically. For the lower Ordovician (Beekmantown) dolomites, approximately another 1000 feet, samples were taken from units where the change in lithology was clearly visible and where a variation in composition was indicated by a pronounced deflection on the radioactive and electric logs. Thus the sample interval averaged about 15 to 20 feet in the dolomites. Thin sections were prepared from the top of the Trenton Limestone at approximately 9529 feet depth, to the



**Figure 1. Map of Wood County, West Virginia**

sandy dolomites of the upper Cambrian, at about depth 11,630 feet.

In the microscopic study of the thin sections, the fabric, grain size, bedding characteristics, color, and mineral composition were observed. Photomicrographs of each thin section

were attached at the correct depth of the neutron log, allowing a direct comparison with the log. The neutron log was chosen to represent the lithology because it showed less variation for closely similar carbonate rock types than did the resistance type log. Thus a given thickness of limestone or dolomite having a fairly uniform composition and/or fabric would register as a fair "plateau" on the neutron log but as a curve with one or more peaks of considerable amplitude on the resistivity log. The plateaus represent average rock type which are more nearly compatible with formational units. However, the greater sensitivity of the resistivity logs allowed refinement in selecting the lithologic boundaries. The neutron log had the further advantage of permitting a distinction between a shale break and a porous section by a quick comparison with the gamma ray log. Also bentonitic zones were readily observed from the radioactive logs.

#### **General Log Response to the Carbonate Section:**

In general there was a close relationship between density of the limestone and the amount of deflection on the neutron log. The shaly limestones of the Trenton show the lowest values with the exception of the predominant Cincinnati shales above. The values increase as the silty partings decrease and the limestones become purer. Trenton bioclastic zones show a negative deflection on the neutron curve, presumably due to their higher porosity. The higher calcium lutites of the Black River Limestones form a positive "plateau." The high-calcium lutites of the Chazy recorded some of the highest values, although they were not consistently high. The Beekmantown Dolomites indicated medium to high plateaus with a number of small negative deflections due apparently to shaly zones. In general a comparison of the electrical and radioactive logs with the lithology of the carbonates indicates the deflection due more to clay and silt content than to fabric. The amount of unfilled vugs also are a factor. However, these are distributed somewhat at random through the carbonate and are of doubtful importance in analyzing the lithology for formational characteristics.

#### **Correlation with Eastern Outcrop:**

The middle and lower Ordovician carbonate units in the well compare remarkably to those of the eastern outcrop, especially the central Pennsylvania section (Fig. 2). The following descriptions were taken from the photomicrographs of thin sections and radioactive logs which unfortunately can not be feasibly reproduced in this paper.

The top of the Trenton Limestone begins at depth 9529 feet. The overlying dark, carbonaceous shales are readily dis-


STANDARD SECTION			FORMATION	MEMBER		
O R D O V I C I A N	CINCINNATIAN		REEDSVILLE	Maysville Eden		
	M O H A W K I A N	T R E N T O N	GLOUCESTER	ANTES		
			COLLINGWOOD			
			Hillier COBOURG Hallowell	COBURN		
			Denmark SHERMAN FALL Shoreham	SALONA		
			KIRKFIELD	NEALMONT		Rodman Centre H. Oak Hall
		ROCKLAND	Valentine Valley View			
		B L A C K R I V E R	CHAUMONT	BENNER		Stover
			LOWVILLE			Snyder
	PAMELIA		HATTER	Hostler Grazier Eyer ?		
	-----		?	-----		
	CHAZY		VALCOUR	LOYSBURG	Clover	
			CROWN PT.	?		
			DAYPOINT			
	C A N A D .	B E E K .		BELLEFONTE	"Tea Creek" "Coffee Run"	
			AXEMANN			
			NITTANY			
			STONEHENGE			

FIGURE 2—Section in Central Pennsylvania used for comparison in this study.

tinguished lithologically and reflect in the log as a pronounced drop in the neutron curve and rise in the gamma ray curve. The contact would correspond closely to the Antes Shale-Coburn Limestone of central Pennsylvania (Kay, 1944). Eastward in Pennsylvania the dark shales of the Antes disappear leaving the Trenton Limestones subjacent to buff and

olive shales of the Martinsburg Formation, a relationship found over wide areas in the Valley and Ridge Province of West Virginia, Virginia, and Tennessee. Thus the contact in this well corresponds closely to those of the western belts of Pennsylvania or to those other areas of the outcrop where the basal "Martinsburg" Shale consists of dark carbonaceous shales of the Antes type. The middle Trenton in this well consists of alternating thin dark-gray fossiliferous, often bioclastic limestones, and thin shales similar to the Coburn and Salona Limestones of central Pennsylvania. The neutron and gamma ray logs indicate a fairly even plateau, with minor deflections at the shale horizons, to depth 9739'. Here a major high and low on the gamma and neutron logs respectively are interpreted as one of the several metabentonite beds in the Salona. The lithology corresponds very closely to the Salona dark, carbonaceous limestone, bioclastic zones, and thin shale partings. It would compare favorably in lithology, stratigraphic position, and fauna (to be discussed later) with the Oranda Limestone in northern Virginia and southeastern Pennsylvania. The Salona facies is indicated on the neutron log by a slightly higher plateau than the Coburn facies, representing a slightly lower clay-silt composition.

The contact with the subjacent Nealmont facies at depth 9806' represents a change to brownish to medium-gray thicker-bedded calcilutite and calcisiltite, containing algal (furoid) tubes and occasional mud pellets. This unit resembles closely the Centre Hall member of the Nealmont Limestone which in the Nittany Valley area of central Pennsylvania contrasts with the less clayey and silty Oak Hall member, here reflected in the rapid positive deflection of the neutron curve at depth 9860' at the beginning of rather pure calcilutites. The negative deflections on the neutron curve and corresponding positive deflection on the gamma ray log at 9865' and 9873' are considered to be thin metabentonite horizons, with the sizable deflection at 9900' a better-developed metabentonite. The Oak Hall horizon in this well illustrates very nicely a gradational picture recently recognized by Rones (1955) in Nittany Valley of Pennsylvania, where through numerous chemical analyses and detailed stratigraphy, it was demonstrated that the gray medium-textured Oak Hall Limestone grades into the impure Valley View Limestone at the base, and the exceptionally pure calcilutites of the Valentine at the top. The interval from 9860' to 9900' resembles the Valentine lithologically, and has its high-calcium composition. The metabentonite at 9900' likely represents the metabentonite that occurs at the base of the Valentine (Kay, 1944). It is questioned that the Valley View facies is present beneath the Valentine in the well for the following reasons: the Benner equivalent occurs

directly below 9906'; there are no metabentonites discernable that could represent B, C, D, and E, known from the Valley View outcrop; and there are no impure beds separating the Valentine lithology and the Benner which could represent the Valley View. The Nealmont is thought to be of lower Trenton age and equivalent to the Rockland and Hull (Kirkfield) of the standard New York section. Kay (1944) has recognized 200 feet of Nealmont in Pendleton County, West Virginia, where a distinct metabentonite 30 feet above the base was correlated with the bentonite low in the Oak Hall in Highland County, Virginia. Other suggested possible correlations based on bentonites would be with the Eggleston Formation of Virginia and the Tyrone Limestone of Kentucky and Tennessee.

The interval from 9906' to 10,073' (Fig. 4) shows remarkable lithologic comparison to the Benner Formation of central Pennsylvania, including the important aspects of the Stover and Snyder Members. The brownish-gray calcilutite from 9906' to approximately 9993' resembles the Stover Member. Specimens of the characteristic *Camarocladia* (fucoids) are readily observed in thin sections. The significant deflection at 9932' in both the gamma ray and neutron logs is believed to represent a metabentonite zone which has the position of metabentonite F in the upper half of the Stover on the outcrop. The Snyder Member, 9993' to 10,073', is characterized both in the well and on the outcrop by interbedded gray fine-grained limestones, calcilutites and thin beds of bioclastics, calcarenites and dolosiltites. The silty dolomite beds, readily recognized in thin section and in stained samples are typical of the Snyder Member, as are the bioclastic and calcarenitic beds. The high neutron curve "plateau" reflects the rather pure composition of the Snyder. The Benner Limestone is considered equal in part to the Witten Limestone of southwest Virginia (Prouty, 1946). The Benner corresponds in large part with the Black River Group as generally compared to the New York standard section. It carries the widespread "Lowville" facies.

The negative deflection of the neutron curve at 10,073' reflects the contact with the highly impure, silty, upper Hatter Limestone (Hostler Member), a contact readily placed on the outcrop. The thin sections show thin, cross-laminated silty limestone and some extremely fossiliferous beds. The much purer Grazier Member is readily observed below beginning at 10,150' and indicating a well-developed "plateau" on the neutron curve to depth 10,207', the base of the Hatter Formation. Fucoids, found abundantly in the Grazier outcrop, are also observed in the thin sections from the core. A thin calcarenite near the base of this unit presumably represents the



tively pure calcilitite of the subjacent Loysburg Limestone (10,207' to 10,425'). In central Pennsylvania Kay (1944) has divided the Loysburg into the Clover Limestone member at the top and the informal "tiger-stripe member" below. Although both lithologic types show in the well, the Clover comprises most of the interval and consists of gray calcilitites alternating with thin calcisiltites, and fine-grained limestones. The "tiger-stripe" beds, so named for the alternating half-inch (more or less) beds of dolomite and calcilitites with a banded appearance occurs near the base of the Loysburg. Essentially the same lithology may be found lower, in the "transition beds," and the "tiger-stripe" in the Loysburg merely represents the highest occurrence of this lithology. The Loysburg also contains occasional thicker beds (0.5 to 2 feet) of dolomite which complicates the drawing of a close boundary with the Beekmantown Limestones and Dolomite. A "transitional zone" between definite elements of both is recognized in thicknesses from zero to 400 feet over wide areas in parts of Pennsylvania, Maryland, West Virginia, and Virginia. Often it becomes necessary to set the basal Loysburg (Chazy) contact faunally (see faunal discussion). Interpretation from the neutron log indicates the base to be at about 10,425' where the curve shows a median intensity which slowly declines to approximately 10,510'.

Although the Loysburg Limestone and its correlatives are generally considered of Chazy age and are so regarded herein for correlative purposes, there is some reason to believe its age may be post-Valcour in the New York standard; probably this should await more detailed faunal studies. The Loysburg correlates with the upper part of the "Stones River" of Stose (1909) in south-central Pennsylvania.

The alternating dolomites and limestones occurring between about 10,425' and 10,510' are "transitional beds" between definite Loysburg above and the well-developed Beekmantown Dolomites below. The thickness of this zone varies on the eastern outcrop from 0-400 feet, inferring varying relief along an unconformity on the top of the Beekmantown, likely at 10,510' in the well. Conglomerates within the "transitional beds" are thought to represent reworked Beekmantown Dolomites. Thus it would appear the "transition beds" are of post-Beekmantown, presumably Chazy, age.

Below 10,510' the neutron curve assumes a fairly constant "plateau" to about depth 10,714'. The lithology of the upper Bellefonte is one of the most readily recognized units in the well, being a grayish-brown aphanitic dolomite as in the upper Bellefonte of central Pennsylvania. The uniqueness of the lithology lies in the fact that it is one of the very few occurrences in the Appalachians of any appreciable thickness of

extremely dense (aphanitic) dolomite. Ronés (1955) assigned the manuscript name "Tea Creek" to this upper member of the Bellefonte Dolomite, occurring from the top of the formation down to the "Bellefonte Sandstone" of Butts (1936). The latter represents the thickest of the sandstone beds occurring in the highly sandy Bellefonte. In the type Bellefonte, the "Bellefonte Sandstone" separates the aphanitic "Tea Creek" above from the megascopically crystalline "Coffee Run" Member (Ronés, 1955) below. The well-developed sandstone zone with interbedded dolomites at 10,699 to 10,714 feet in the well is interpreted as the "Bellefonte Sandstone" zone. This zone might well be taken for the St. Peter Sandstone in that it represents the first well-developed sandstone below the Middle Ordovician limestones. However, in the well, 190 feet of Beekmantown (Prairie du Chien) Dolomite—plus 80 additional feet if the "transitional beds" were placed in the Beekmantown—separate the sandstone from the lowest beds that can be called Chazy. For the sandstone to represent true St. Peter, it would mean a definite Beekmantown (Prairie du Chien) age for that sandstone and would likewise infer that the Pennsylvania and West Virginia Beekmantown contains younger beds (equivalent to the upper Bellefonte) that would be wanting in the Prairie du Chien of the upper Mississippi Valley. The writers favor the belief that the true St. Peter is not represented in the well by this sandstone and that the sandstone represents a stratigraphically lower zone.

The lower Bellefonte ("Coffee Run") facies extends from 10,714' to approximately 11,030'. The rock consists of fine- to coarse-grained gray to brownish-gray dolomite with numerous clay-silt partings locally. The latter account for negative deflections on the neutron curve which otherwise maintains a fairly constant plateau level.

Below approximately 11,030' the lithology has the essential characteristics of the Nittany Dolomite of central Pennsylvania. The contact is not sharp in the well, nor in the field in many places.

The Axemann Limestone separates the Nittany Dolomite and Bellefonte Limestone in central Pennsylvania. Field studies in that area indicate that the Axemann disappears laterally either by thinning or through gradation into dolomite, a problem at present not resolved. The alternating dark- and light-gray dolomite in a somewhat cyclical manner is observed in the well and is an important and persistent Nittany characteristic in the field. Also the Nittany is characteristically vuggy. All thin sections indicated vugs, mostly filled with secondary mineral dolomite. Some vugs are unfilled. The dolomite is mostly medium grained and contains appreciable

silt and sand which appear somewhat more abundant in proportion to clay than is found in the eastern outcrop. This might imply a coarsening of the clastic portion of the Nittany Dolomite in a general westward direction and a general westward source of the detrital grains. If this is true it conforms with more conclusive evidence for the source direction of upper Cambrian sandstones to be discussed later. The neutron curve does not indicate a distinctive pattern for the Nittany but in general the plateau is a little higher than for the Bellefonte Dolomite and the positive and negative deflections show different patterns in the two formations. Attention should be called to an unusually high deflection in the neutron curve between 11,322' and 11,335'. This zone has many unfilled vugs and a high concentration of silica, and magnesium carbonate in excess of calcium carbonate. It would appear to be a highly leached zone, though there is no evidence that would point to disconformity here. Considerable chert occurs throughout the Nittany, in nodules, beds, and cavity fillings. Much of the chert is doloclastic. Also siliceous oolites are fairly common, especially in the lower part.

The Stonehenge equivalent is represented in the well from about 11,500' to 11,637' representing a thinning of several hundred feet from the central Pennsylvania outcrop. Also the Stonehenge is preponderantly limestone but has become entirely dolomite in this well. The outstanding and most persistent lithic characteristic of the Stonehenge on its outcrop—the intraformational breccia, is found throughout the Stonehenge in the well. The breccia, usually limestone in a limestone matrix on the outcrop, has been dolomitized along with the matrix in the well, giving the same composition as the Larke Dolomite of central Pennsylvania which is correlated with the Stonehenge (Prouty, 1954). Chert has replaced the breccia in places. The Stonehenge contains considerable gray to white chert throughout its thickness and is not readily distinguished from the Nittany Chert. Together the two cherty zones likely represent equivalents of those in the Oneota Dolomite of the Mississippi Valley. The dolomite of the Stonehenge differs in no outstanding details from the Nittany, but is generally darker and does not show the tendency towards cyclic repetition of nearly white and medium-gray beds so widely characteristic of the Nittany. The Stonehenge in the well has the same stratigraphic position and the essential lithologic characteristics of the Chepultepec Dolomite of Virginia and Tennessee.

The base of the Stonehenge marks the Cambrian-Ordovician contact, at depth 11,637'. The contact is obvious from the neutron log which deflects off the scale in a positive direction. The contact is readily picked lithologically on the

basis of the well-developed sandstones and sandy dolomites of the uppermost Cambrian.

### CHEMICAL ANALYSES OF THE ORDOVICIAN CARBONATES

#### Purpose of Study:

It was considered that chemical studies of the lower Ordovician carbonates might help resolve the problem of "transitional beds" and also help place contacts in the Beekmantown Formations. It was hoped that a comparison of the analyses to the neutron curve could help interpret the meaning of the deflections in terms of the rock composition.

#### Laboratory Technique:

Complete analyses were not necessary for the purpose, so they were confined to calcium, magnesium, and silica. The  $R_2O_3$  group was not determined directly but was calculated. The calcium and magnesium determinations were by the versonate method with modifications after Cheng et al. (1951). Silica analyses were determined by a colorimetric method using a standard silica curve and Fisher electrophotometer. Analytical procedures were checked for accuracy against National Bureau of Standards samples. A summary of results are shown below. Data are average of triplicate runs.

	Argillaceous Limestone		Dolomite	
	NBS No. 1A		NBS No. 88	
	Found	Standard	Found	Standard
SiO <sub>2</sub> -----	14.20	14.10	0.33	0.31
CaO -----	41.19	41.30	30.18	30.49
MgO -----	2.21	2.19	21.32	21.48

#### Analyses Results and Interpretation:

The complete chemical analyses (nearly 150 each for  $CaCO_3$ ,  $MgCO_3$ ,  $SiO_2$ , and  $R_2O_3$ ) are not included but can be obtained from the original thesis if desired. Table 1, however, shows analyses considered important to contact relations. The silica values include silicon from all constituents in the rock as clay, quartz, and chert. The relative amount of each was estimated by examining the filter residue from the carbonate analysis. The residue, consisting of the insoluble fraction, clearly showed the quartz grains, chert fragments, and clay or shale portions. Estimates were empirical but readily show the relative amounts of the constituents comprising the insoluble fraction. This fraction was reported quantitatively as per cent. silica and per cent.  $R_2O_3$ .

The sandstones encountered were found to have dolomitic cement and were often ferruginous. The ferruginous char-

acteristic was not always obvious, as might be expected, but the high value found for the  $R_2O_3$  group suggests the presence of iron compounds.

The presence of pyrite, gypsum, and anhydrite in the sample undoubtedly influenced the values found. The pyrite was of particular concern, being present in almost every unit described, and consequently present in many of the samples. All calcium in the sample was reported as calcium carbonate. The calcium in gypsum and anhydrite was included and subsequently increased the value found. Gypsum and anhydrite were not found from 10,620' to the depth studied, with the greatest concentration in the unit being from 10,510' to 10,560'. Also in the same interval the magnesium carbonate increased appreciably, as is commonly the case, indicating the compatibility of saline conditions and dolomitization.

The "transition zone" mentioned above shows very readily in the chemical analyses from 10,425' to 10,510' (Table 1). The zone consists of alternating dolomite and limestones, with increasing dolomite towards the base. Within the 10,495'-10,500' interval the rock assumes a higher magnesium content and could represent the top of the Beekmantown. However the silica content shows a quick increase at 10,510' which continues high through the upper Bellefonte (Beekmantown). The contact that would occur between the "transitional beds" and the Beekmantown (Prairie du Chien) would be in the interval 10,495 - 10,510'. A gas show recorded between 10,490' and 10,496' may be connected with the contact (unconformity). The chemical analyses of the "transitional beds" are much closer to those of the Loysburg (Chazy) above than to the Beekmantown inferring a Chazy, or at least post-Beekmantown age for them. Because of the variation in thickness (0-400 feet) of the "transition beds" in short distances on the eastern outcrop, an unconformity is inferred at the base of the "transition beds" in the well. This agrees closely with an unconformity picked at 10,497' by the West Virginia Geological Survey (1956).

The Beekmantown Formations are not readily distinguished chemically but certain generalizations may be made. The Upper Bellefonte ("Tea Creek") is much higher in silica than the upper part of the lower Bellefonte ("Coffee Run") facies. A sharp contrast is noted at the contact near 10,715' agreeing closely with the thin section and log study (10,714'). However the lower Bellefonte becomes quite high in silica in the lower portion.

The Bellefonte and Nittany Dolomites show contrasting ratios of calcium-magnesium carbonate at the contact, approximately 11,030'. In the Bellefonte the two are nearly in

equal proportion, whereas the Nittany shows a consistently higher calcium carbonate content.

The Nittany-Stonehenge contact at about 11,500' shows no appreciable calcium-magnesium carbonate change at the contact but the silica content is consistently higher by a few percentage points in the Stonehenge than in the Nittany. The top of the Cambrian, chemically, (11,635') may be readily observed from the sandstones and sandy dolomites. It is of interest to observe that at least the upper 40 feet of Cambrian dolomite show an excess of magnesium carbonate over calcium carbonate, possibly reflecting preferential leaching of the calcium carbonate near the contact.

TABLE I  
CHEMICAL ANALYSES AT SELECTED DEPTHS

Sample	%	%	%	%
Interval	CaCO <sub>3</sub>	MgCO <sub>3</sub>	SiO <sub>2</sub>	R <sub>2</sub> O <sub>3</sub>
10,405-410	91.39	1.93	1.08	4.56
10,410-415	92.08	1.80	1.10	5.02
10,415-420	90.85	1.91	2.80	4.44
10,420-425	85.88	1.91	8.90	3.31
10,425-430	84.28	5.85	4.32	5.55
10,430-435	79.11	6.26	9.90	4.73
10,435-440	71.58	13.92	10.35	4.15
10,440-445	83.70	11.38	5.32	4.92
10,445-450	78.70	9.73	9.06	2.51
10,450-455	86.64	9.53	2.92	0.91
10,455-460	77.63	17.14	4.62	0.61
10,460-465	85.17	7.88	4.57	2.38
10,465-470	77.84	6.46	9.04	6.66
10,470-475	69.23	12.57	12.05	6.15
10,475-480	82.28	13.89	2.78	0.05
10,480-485	77.38	19.10	2.10	1.42
10,485-490	86.51	10.92	0.82	1.75
10,490-495	85.64	8.16	0.98	5.32
10,495-500	70.00	23.59	1.85	4.56
10,500-505	63.00	28.02	1.70	6.28
10,505-510	65.00	28.31	1.03	5.66
10,510-515	66.95	21.00	11.05	1.00
10,515-520	59.78	22.93	11.55	5.73
10,520-525	67.80	22.55	8.50	1.15
10,525-530	55.20	37.52	7.84	
10,530-535	53.39	36.94	7.33	2.34
11,595-600	40.23	35.63	19.83	4.31
11,600-605	38.17	36.39	14.11	11.33
11,630-635	39.63	40.18	15.22	4.97
11,635-640	19.21	22.13	41.36	17.30
11,669-674	18.63	24.08	48.21	9.08
11,674-676	45.88	44.55	7.21	2.36
11,676-681	20.62	24.52	39.21	15.00

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## FAUNAL STUDY OF THE ORDOVICIAN CARBONATES

### Introduction:

Of the 2568 feet of core taken from the Sandhill well, that portion from the lower Martinsburg (Antes) Shale downward was cut longitudinally into four slices for the detailed studies in different laboratories. An outer slice of the core was used for the faunal studies to provide maximum surface area for the initial detection of the fossil zones. Though every inch of the core was examined on the surface, it was obviously impractical and unnecessary to split the core along each lamina in search of the fossils. Wherever cross-sections of fossils were observed, however, the core was broken open with a rock trimmer for further observation. The macro-fossils were the principal objective in the study although some micro-fossils (mainly ostracodes) were studied. The results of the identifications (Table II) are listed according to depths from the top of well. Included in the original but not shown in the Table is the lithology for each identified fossil occurrence (for environmental purposes) and publication sources for identifications. Many of the identifications were of little value in resolving formational contacts because of extensive vertical ranges, but added information for general age assignments. Many frustrating hours were spent in search of identifiable fossils from the dolomites of the Beekmantown and Cambrian. As is often the case during dolomitization, the fossils are largely obliterated. Included cherts, which often preserve silicified forms, yielded a few, largely fragmented, specimens.

### Faunal Comparisons and Correlations:

The black carbonaceous limy shale above the Trenton Limestone in the well was referred to above as the Antes Shale equivalent. It is feasible on a faunal basis to subdivide the Antes in terms of the New York standard equivalents. From the top of the sliced core at 9,416' to 9,421' depth the occurrence of *Climacograptus typicalis*, *Diplograptus amplexicaulis*, *Triarthrus eatoni*, *Rafinesquina alternata*, and *Lingula riciniformis* infer a general Antes age with the *Climacograptus typicalis* indicating a Gloucester (upper Antes) age. The latter form is missing below 9,421 feet, with *Triarthrus eatoni* occurring to a depth of 9,529 feet. The first appearance of *Isotelus gigas*, a more typical middle Trenton form, together with the downward disappearance of *Triarthrus eatoni* would infer the faunal base of the Antes to be at approximately 9,529 feet, and the interval 9,421' to 9,529' to represent the Collingwood of the Trenton standard.

The presence of *Hormotoma trentonensis* at 9,625 feet would indicate the presence of the Coburn Limestone and the Cobourg equivalent in Ontario. *Rafinesquina deltoidea*, which is a characteristic brachiopod of the upper part of the Hallowell Member of the Cobourg of Ontario, is found at 9,608 feet and would infer the upper boundary of the lower Coburn to be no lower than this depth in the well. Above approximately 9,608' to the base of the Antes would then equal essentially the Hillier Member of the Cobourg. The faunal base of the Coburn equivalents can not be readily ascertained in the well due to the uncored interval from 9,665' to 9,790' (Fig. 4). The contact was placed at 9,739 feet in the neutron-log thin-section study.

	Gp. or Ser.	Standard This report	Petrographic-R.A. Log Study	Paleontological Study	Chemical Study	Lithologic Study - Dolomites
ORDOVICIAN	TRENTON	ANTES	-- 9529	— - 9529		
		COBURN	9529 - 9739	9529 - ?		
		SALONA	9739 - 9806	? - 9806		
		NEALMONT	9806 - 9906	9806 - 9895		
	BLACK RIVER	BENNER	9906 - 10073	9895 - 10064		
		HATTER	10073 - 10207	10064 - 10218		
	CHAZY	LOYSBURG	10207 - 10425	10218 - 10423		
		Transition Zone	10425 - 10510	10423 - 10537	10425 - 10510	
	CANADIAN	BELLEFONTE	10510 - 11030	10537 - —	10510 - —	10541 - 11038
		AXEMANN-NITTANY	11030 - 11500			11038 - 11500
STONEHENGE		11500 - 11637		— 11635	11500 - 11637	
CAMBRIAN	ST. CROIX	(Gatesburg)			11635 - —	11637 - 12280
		TREMPEALEAU				11637 - 11740
		FRANCONIA				11740 - —
		DRESBACH				— - 12465
		EAU CLAIR				12465 - 12990
MT SIMON				12990 - 13272		

FIGURE 4—Summary of depths of formations in the "Sandhill" well for the different methods of study.

The Salona Limestone, identified through lithologic criteria, offered very little in the way of identifiable fossils. Though quite fossiliferous, most forms have become fragmented apparently, as indicated by the highly slickensided core, through appreciable crumpling of the thin-bedded shales and limestones. A few brachiopods were identified as to genus only.

The upper Nealmont is conspicuously less fossiliferous than the lower Salona. A fucoidal zone highly characteristic of the Centre Hall (middle member) on the outcrop, occurs in the upper part between 9,806 and 9,870 feet. The Rodman

(upper member) can not be demonstrated paleontologically, nor lithologically for that matter. Typical Nealmont forms found between 9,837' and 9,895' are **Phragmolites sp.**, **Lepeditia sp.** and **Bathyrurus spiniger**. The last is a typical Rockland form and therefore indicates a low Nealmont (Oak Hill) age.

The top of the Black River is marked faunally by the occurrence of numerous **Camarocladia gracilis** appearing directly below the last occurrence of **Bathyrurus spiniger** at 9,895'. The **Camarocladia** zone is an invaluable marker for the upper Benner (Stover Member) in the central Pennsylvania outcrop and marks a horizon traceable into the Witten Limestone in southwest Virginia. **Tetradium cellulosum** (Hall) occurs in the **Camarocladia** zone and is a common associate over similar areas. The lower Benner (Snyder Member) though identified readily from the thin-section study, shows little faunally other than **Tetradium cellulosum** that is characteristic. The persistent **Camarocladia** zone ends at about 9,930' indicating a minimum faunal depth for the Stover-Snyder contact, which is well above the contact at 9,993' indicated from the thin-section studies and neutron log. The presence of **Tetradium cellulosum** indicates the continuation of Benner Limestone below 9,993 feet.

The Benner-Hatter contact in the well could not be drawn sharply from the fauna observed, nor could all the members of the Hatter be separated on this basis alone. However, the common occurrence of the bryozoan **Escharopora**, and the algae **Girvanella** and **Solenopora** and brachiopod **Valcourea deflecta** within the Hatter (10,064' to 12,205') as indicated by thin-section and neutron-log studies, indicates comparison to the Hatter and Shippensburg of central and southeast Pennsylvania and Benbolt-Wardell of southwest Virginia (Fig. 3). The Grazier Member is identified in the well between 10,150' and 10,207', by the prolific occurrence of fucoids which identify this member on the outcrop.

The Loysburg (provisionally Chazy age) may be identified faunally by the abrupt occurrence below 10,218' of **Lepeditia fabulites**, **Tetradium syringoporoides** and **Lophospira**. Similar zones are found in the upper "Stones River" of south-central Pennsylvania, the New Market Limestone of northern Virginia and Maryland, and the Perry Limestone of southwest Virginia which are considered partial correlatives. To conform with the usual Chazy assignment of the Loysburg, the Black River-Chazy contact would then be placed between the Loysburg and Hatter at depth 10,218' on a faunal basis, as compared to 10,207' by thin-section petrography radioactive-log method.

The lowest **Tetradium syringoporoides** was observed at

10,406 feet. This form has not been observed within the "transitional beds," between the Loysburg proper and the massive Beekmantown Dolomites. The lowest definite post-Beekmantown fossil observed, *Multicostella platys* was at 10,423' which is taken to be the faunal base of the Loysburg and the approximate contact with the subjacent "transitional beds." This agrees closely with the contact indicated by other methods (10,425'). *Leperditia fabulites* occurs below to at least depth 10,469' which would fall within the "transition beds." The middle Ordovician age of this ostracode indicates the "transitional beds" to be of Chazy rather than Beekmantown age, an assignment supported by the chemical studies

TABLE II  
FAUNAL IDENTIFICATIONS FROM THE MIDDLE ORDOVICIAN

Depth of Core	Identification	Class or common name
9,416	<i>Diplograptus amplexicaulis</i> (Hall)	graptolite
	<i>Climacograptus</i> cf. <i>C. typicalis</i> (Hall)	graptolite
9,417.5	<i>Lingula nicklesi</i> Bassler	brachiopod
9,418	<i>Homotelus simplex</i> (Raymond & Narraway)	trilobite
9,419	<i>Zygospira</i> sp.	brachiopod
	<i>Rafinesquina</i> sp.	brachiopod
9,419.7	<i>Climacograptus typicalis</i> (Hall)	graptolite
9,419.8	<i>Orthoceras</i> aff. <i>junceum</i> (Hall)	cephalopod
	<i>Climacograptus typicalis</i> Hall	graptolite
9,420.6	<i>Sinuites cancellatus</i> (Hall)	gastropod
9,421	<i>Climacograptus typicalis</i> (Hall)	graptolite
	<i>Cryptolithus</i> sp.	trilobite
9,422.5	<i>Diplograptus</i> sp.	graptolite
9,423	<i>Dalmanella fertilis</i> (Bassler)	brachiopod
9,424	<i>Cryptolithus tessellatus</i> Green	trilobite
	<i>Rhytimya</i> sp.	pelecypod
9,426	<i>Diplograptus amplexicaulis</i> (Hall)	graptolite
9,426.7	<i>Rafinesquina</i> sp.	brachiopod
	<i>Zygospira exigua</i> (Hall)	brachiopod
9,426.8	<i>Diplograptus amplexicaulis</i> (Hall)	graptolite
9,428.5	<i>Diplograptus amplexicaulis</i> (Hall)	graptolite
9,430.5	<i>Nuculites</i> sp.	pelecypod
	<i>Illaenus americanus</i> (Billings)	trilobite
9,432.5	<i>Calymene granulosa</i> (Foerste)	trilobite
	<i>Homotelus simplex</i> . (Raymond & Narraway)	trilobite
9,437	<i>Pterygomtopus</i> sp.	trilobite
	<i>Homotelus simplex</i> (Raymond & Narraway)	trilobite
9,441.2	<i>Ctenodonta gibberula</i> Slater	pelecypod
9,442.2	<i>Calymene granulosa</i> (Foerste)	trilobite
9,444	<i>Diplograptus amplexicaulis</i> (Hall)	graptolite
9,445	<i>Homotelus simplex</i> (Raymond & Narraway)	trilobite
9,445.6	<i>Lingula ricinformis</i> (Hall)	brachiopod
9,449	<i>Isotelus</i> sp.	trilobite
9,461	<i>Cryptolithus tessellatus</i> Green	trilobite
9,468.7	<i>Lingula ricinformis</i> Hall	brachiopod
9,474.5	<i>Homotelus simplex</i> (Raymond & Narraway)	trilobite
	<i>Triarthrus eatoni</i> (Hall)	trilobite
9,480.2	<i>Triarthrus eatoni</i> (Hall)	trilobite
9,483.5	<i>Triarthrus eatoni</i> (Hall)	trilobite
9,488	<i>Homotelus simplex</i> (Raymond & Narraway)	trilobite

9,503	<i>Triarthrus eatoni</i> (Hall)	trilobite
9,515.4	<i>Diplograptus</i> sp.	graptolite
9,516	<i>Orthoceras</i> sp.	cephalopod
9,523.8	<i>Lingula rincinformis</i> (Hall)	brachiopod
9,524.9	<i>Diplograptus</i> sp.	graptolite
9,527	<i>Triarthrus eatoni</i> (Hall)	trilobite
9,529.4	<i>Isotelus gigas</i> (DeKay)	trilobite
9,530.7	<i>Merocrinus</i> sp.	crinoid
9,532.5	<i>Sowerbyella</i> cf. <i>S. rugosa</i> (Meek)	brachiopod
9,535.7	<i>Dalmanella</i> cf. <i>D. testudinaria</i> (Bolman)	brachiopod
9,538	<i>Catazyga</i> cf. <i>C. erratica</i> (Hall)	brachiopod
9,540	<i>Rafinesquina squamula</i> (James)?	brachiopod
9,543.1	<i>Dalmanella multisecta</i> (Meek)?	brachiopod
9,564.6	<i>Rhinidictya</i> cf. <i>nicholsoni</i> Ulrich	bryozoa
9,574.3	<i>Lepidocoleus jamesi</i> (Hall & Whitfield)	crustacea
9,577.5	<i>Lepidocoleus jamesi</i> (Hall & Whitfield)	crustacea
	<i>Dalmanella</i> cf. <i>D. multisecta</i> (Meek)	brachiopod
9,581.5	<i>Modiolopsis modiolaris</i> (Conrad)	pelecypod
9,585.9	<i>Ctenobolbina ciliata</i> (Emmons)	ostracode
9,587.7	<i>Pholidops</i> cf. <i>cininnatiensis</i> Hall	brachiopod
9,589.1	<i>Cryptolithus tessellatus</i>	trilobite
	<i>Ctenobolbina ciliata</i> (Emmons)	ostracode
9,593.6	<i>Ctenobolbina ciliata</i> (Emmons)	ostracode
9,596.7	<i>Isotelus</i> cf. <i>I. gigas</i> DeKay	trilobite
9,606	<i>Isotelus gigas</i> DeKay	trilobite
9,608.3	<i>Rafinesquina</i> cf. <i>R. deltoidea</i> (Conrad)	brachiopod
9,625.4	<i>Hormotoma trentonensis</i> (Ulrich & Scofield)	gastropod
9,650.6	<i>Rafinesquina</i> cf. <i>R. deltoidea</i> (Conrad)	brachiopod
9,845	<i>Phragmolites compressus</i> (Conrad)?	cephalopod
9,879	<i>Bathyrurus</i> cf. <i>B. spiniger</i> (Hall)	trilobite
9,895.7	<i>Camarocladia</i> cf. <i>gracilis</i> Bassler	fucoid
	<i>Tetradium cellulolum</i> (Hall)	coral
9,897	<i>Rhinidictya</i> sp.	bryozoa
	<i>Camarocladia</i> cf. <i>C. gracilis</i> Bassler	fucoid
9,927.7	<i>Camarocladia</i> cf. <i>C. gracilis</i> Bassler	fucoid
9,947.5	<i>Rhinidictya nicholsoni</i> Ulrich	bryozoa
9,956.4	<i>Cryptophragmus</i> ?	coral
	Fucoids	algae
10,003	<i>Solinopora</i> sp.	algae
10,047	<i>Rafinesquina</i> cf. <i>R. hermitagensis</i> Bassler	brachiopod
10,096.3	<i>Girvanella</i> ?	algae
10,101.8	<i>Rhinidictya nicholsoni</i> Ulrich	bryozoa
	<i>Escharopora</i> sp.	bryozoa
10,102.8	<i>Escharopora</i> sp.	bryozoa
10,142.4	<i>Pianodema</i> cf. <i>subaequata</i> (Conrad)	brachiopod
10,144	<i>Pianodema subaequata</i> (Conrad)	brachiopod
10,168	<i>Valcourea deflecta</i> ?	brachiopod
10,182	<i>Pianodema subaequata</i> (Conrad)	brachiopod
10,218.5	<i>Leperditia fabulites</i> (Conrad)	ostracode
10,254	<i>Rafinesquina</i> sp.	brachiopod
	<i>Tetradium syringoporoides</i> Ulrich	coral
10,363.6	<i>Tetradium syringoporoides</i> Ulrich	coral
10,364	<i>Tetradium syringoporoides</i> Ulrich	coral
	<i>Zygospira recurvirostris</i> ? (Hall)	brachiopod
	<i>Pianodema subaequata</i> (Conrad)	brachiopod
	<i>Rhinidictya nicholsoni</i> Ulrich	bryozoa
10,379	<i>Strophomena</i> cf. <i>S. incurvata</i> (Shepard)	brachiopod
10,379.1	<i>Diabolocrinus asperatus</i> (Miller & Gurley)	crinoid
10,406.8	<i>Tetradium</i> sp. cf. <i>T. syringoporoides</i> Ulrich	coral
10,422.5	<i>Multicostella</i> aff. <i>M. platys</i> (Billings)	brachiopod

10,469.3	Leperditia fabulites (Conrad)	ostracode
11,353.8	Unidentifiable	gastropod
	Unidentifiable	brachiopod
	Unidentifiable	trilobite

### LITHOLOGIC STUDIES OF THE DOLOMITE SECTION

#### Introduction:

Certain characteristics of the dolomite can better be studied from the core than through the microscopic examination of the cuttings alone. Thus thin sections were prepared at intervals indicated by apparent megascopic changes from the top of the Beekmantown to the base of the dolomite section, including a number of sandstone beds of the Cambrian. A number of thin sections were made of cuttings in uncored intervals. Some of the data collected but not included in this report are visual estimates of the percentage of porosity types (viz., vacuole, intergranular, disseminated open, bedding-plane, cavernous, and joint or fracture); and description of quartz grains as to roundness and sphericity. For these data and for numerous photomicrographs the reader is referred to the original thesis by Aarons.

#### Summary:

Based on lithology alone the top of the Beekmantown was placed at 10,541' considerably lower than with the additional aid of the chemical analyses and radioactive log. The base of the Bellefonte was placed beneath the abundant black, nodular chert at 11,038', agreeing very closely with the log studies (Fig. 4).

The Nittany is mostly light-gray dolomite with occasional alternating bluish-gray dolomite. The chert is mostly white to gray, and often doloclastic and containing siliceous oolites. The numerous vugs are often open or may be filled with mineral dolomite or quartz. The above characteristics are highly comparable to those of the Nittany outcrop. The base of the formation was chosen below the common oolitic cherts and above the intraformational breccia (Stonehenge-Larke), at depth 11,500'.

The Stonehenge consists of blue-gray dolomite, with silty dolomite near the top and sandy dolomite near the base. The intraformational breccia is the most outstanding characteristic of the formation not only in the well but wherever it is observed on the eastern outcrop. Considerable gray cherts in bands, lenses, and nodules throughout. The lower contact was drawn beneath these cherts which also marks the beginning of well-developed sandstone beds (upper Cambrian) at depth 11,637'.

The post-Dresbach upper Cambrian in the well is com-

pared closely with the Copper Ridge of Tennessee and Virginia and the Gatesburg of central Pennsylvania, the occurrence of sandstone in the uppermost part being more typical of the former. However elements of the Mississippi Valley sequence can be recognized and the upper Cambrian of the well can in general be more closely identified with and expressed in the nomenclature of that area. The Trempealeau ("Copper Ridge") consists of grayish-white quartzose and dolomitic sandstone with some interbedded blue-gray sandy dolomite. This lithology fits rather closely the descriptions of the Trempealeau by Cohee (1948). The Trempealeau-Franconia contact was placed at 11,740 feet at the base of the highly sandy beds.

The Franconia consists of dark blue-gray to light blue-gray dolomite except for the lower 60 feet which contains interbedded mottled blue-gray silty and sandy dolomite. Oolites, some up to .75 mm. in diameter, occur in both the upper and lower part. An intraformational conglomerate zone occurs a little above the middle. The contact with the Dresbach is not sharp but is placed at 12,280' where a change from predominantly dolomite to predominantly sandstone occurs.

The Dresbach consists of interbedded dolomitic sandstone and sandy dolomite with a little blue-gray, occasionally mottled and oolitic dolomite. The sandstone is nearly white, frosted, very fine to coarse-grained, and subangular to subrounded. At the base the sandstone is quartzose and coarser than higher in the formation. Small amounts of glauconite were observed. The contact with the Eau Claire was drawn at 12,465' where a change from predominantly sandstone (Dresbach) to predominantly dolomite occurs.

The upper sandy dolomite of the Eau Claire is bluish brownish-gray mottled, argillaceous, sometimes oolitic. The dolomite throughout has much the same bluish-gray mottled appearance and also carries occasional oolites. Glauconite is found occasionally in the lower half of the formation where silty and sandy mottled dolomite predominates. Though the Eau Claire is sandy throughout, especially in the upper and lower part, no massive sandstones were observed. The contact with the Mt. Simon was drawn at depth 12,990' where well-developed dolomitic sandstones occur.

The Mt. Simon equivalent in the well is a poorly sorted dolomitic sandstone of silt to fine-pebble size with a fine to medium mean. The quartz grains are angular to subrounded. Considerable feldspar and clay occurs throughout, with occasional oolitic zones represented. A variety of color exists, mainly light and dark brownish and bluish gray; the lower 12 feet is pink to brownish-pink, perhaps indicating a "granite

wash" from the subjacent crystallines. Occurring near the middle of the formation are 34 feet of clean light-gray to white quartzose sandstone.

A number of thin beds of sandy dolomite are interbedded with sandstone, especially in the upper half of the formation, the dolomite having the same range of colors as the sandstone. The contact of the Mt. Simon with the Pre-Cambrian crystallines was drawn at depth 13,272'.

### CONCLUSIONS BASED ON THE VARIOUS STUDIES

#### Comparative Results of the Different Methods:

No one method was considered entirely satisfactory in drawing the contacts for all the formational units. The radioactive log thin-section petrography work is considered most accurate for the middle Ordovician down to the top of the Chazy. The chemical analyses were considered most accurate in resolving the contact between the Loysburg and the "transition beds," and the "transition beds"—Beekmantown contact. There were alternate choices for these two contacts shown on the radioactive log, one set of which agreed with the contacts based on chemical analyses. The paleontology contributed mainly in establishing the presence of the units in terms of the standard section rather than in placing contacts. Faunal contacts within Trenton units, however, essentially agreed with the radioactive log studies; contacts within the Black River and Chazy compared fairly well. Obviously the accuracy of the faunal contacts would depend on the extent of recovery of identifiable fossils and the index value of those forms. In some instances only minimum depths for the faunal contacts were possible. The depth of the Beekmantown top is considered more accurate in the chemical and radioactive log petrographic study (10,510') than from the lithologic study alone (10,541'). Chemical analyses were of little help in defining the contacts of the formations comprising the Canadian dolomites, except in terms of the broad generalities mentioned under this heading. Paleontology was not helpful within the dolomite section due to the apparent obliteration of fossils accompanying dolomitization. No better way was found of identifying the Upper Cambrian units than by petrography and lithology.

As each method proved most helpful in certain defined parts of the core, it is obvious that an integrated program, if feasible, would be preferable to any one method. The following represents a summary of the formation tops and the method or methods believed most reliable in each case:

Coburn -----	9,529'	Radioactive log-petrography, & paleontology
Salona -----	9,739'	" " "
Nealmon -----	9,806'	" " " " "
Benner -----	9,906'	" " "
Hatter -----	10,073'	" " "
Loysburg -----	10,207'	" " "
"Transition-beds" -----	10,425'	Chemical analyses
Bellefonte -----	10,510'	" "
Nittany -----	11,038'	Lithology
Stonehenge -----	11,500'	"
Trempealeau -----	11,637'	"
Franconia-Dresbach -----	11,740'	"
Eau Claire -----	12,465'	"
Mt. Simon -----	12,990'	"
Pre-Cambrian -----	13,272'	"

#### General Sedimentary Framework:

The middle and lower Ordovician rocks of the well bear a remarkable resemblance to those of the central Pennsylvania outcrop. Closer comparison appeared possible here than with the geographically closer southeast West Virginia and southwest Virginia sections, although considerable resemblance exists to these sections. Since southeast West Virginia more nearly represents the same structural belts as central Pennsylvania, it appears reasonable to assume that the isoliths cross the structural belts at a low angle, with a little more easterly azimuth. The Trenton Limestones show the same order of thickness, 1000 feet, more or less, in the central Pennsylvania outcrop as the Sandhill well (Fig. 6). The Black River is also the same order of thickness, approximately 300 feet, but would be slightly thinner in the well than the maximum on the outcrop in central Pennsylvania. The Chazy thickness comparison in the two areas would depend on the local thickness of the "transitional beds" but the Loysburg part of the Chazy is thicker in the well (218 feet) than on the Pennsylvania outcrop (usually less than 100 feet). Northwest of the well (Figs. 6 and 7) the Chazy is overlapped by the Black River before reaching the Vance No. 1 Well, Delaware County, Ohio and Krause No. 1 Well, Ashland County, Ohio. The lower Ordovician (Canadian) dolomites in the Sandhill well, with a thickness of approximately 1,100 feet, reflects the general westward thinning of these rocks from roughly 3,600 feet in central Pennsylvania to 2,050 to 2,700 in the general West Virginia outcrop (Woodward, 1951), to its point of disappearance before attaining the Krause No. 1 and Vance No. 1 wells (Figs. 6 and 7). The entire Canadian section is dolomite in the well reflecting the tendency for limestone to pass westwardly into dolomite, a gradation noted in southwest Virginia and northeast Tennessee (Prouty, 1948). In general the Canadian dolomites in the well contain more quartz sand than is generally noted on the

eastern outcrop, a condition favoring a westward source for the clastics occurring within the Canadian dolomites. The presence of the Bellefonte Sandstone in the well infers a much more widespread sand than suggested by Krynine and Tuttle (1941) who attributed it to local vertical uplift of the Nittany Arch in central Pennsylvania.

The upper Cambrian dolomites tie in more closely with the Upper Mississippi Valley rocks. The Trempealeau equivalent in the well, however, represents a closer transitional relationship with the eastern outcrop than do the pre-Trempealeau upper Cambrian units. This is based on the close comparison of the uppermost Cambrian of the well with the Copper Ridge Dolomite of Tennessee and Virginia and the Mines (upper Gatesburg) of central Pennsylvania. The upper Cambrian thins westward from the well in part by convergence and in part by truncation along the pre-Black River unconformity in the area of the Findlay Arch (Figs. 6 and 7). Southeastwardly, the upper Cambrian diverges into the thicker Copper Ridge-Nolichucky (Gatesburg-Warrior sequence northeastwardly), with the Mt. Simon equivalents being overlapped. The quartz sand content of the upper Cambrian in the well is somewhat intermediate, quantitatively, between that of the more sandy upper Mississippi Valley and eastern outcrop sections. This tends to corroborate the findings in northeast Tennessee (Prouty, 1948 a & b) based on a sedimentary study of the upper Cambrian sandstones which pointed to a general westward source direction for these sands.

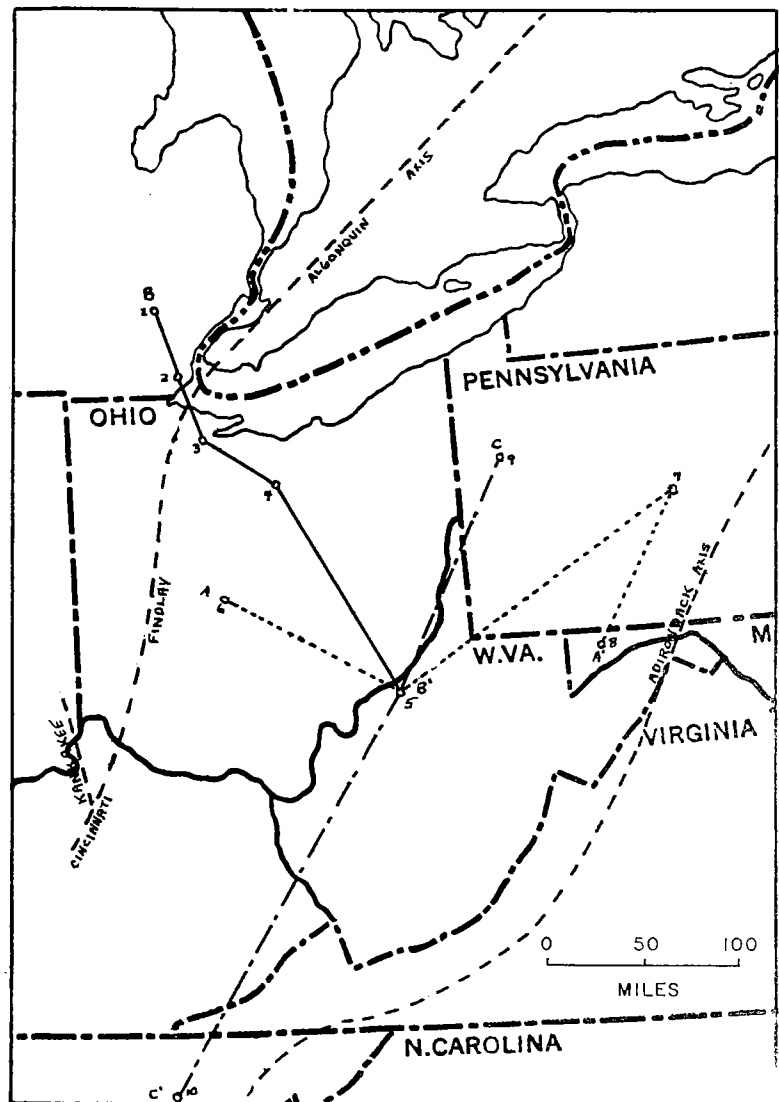


FIGURE 5—Map showing lines of cross-sections, A—A', B—B', and C—C'.

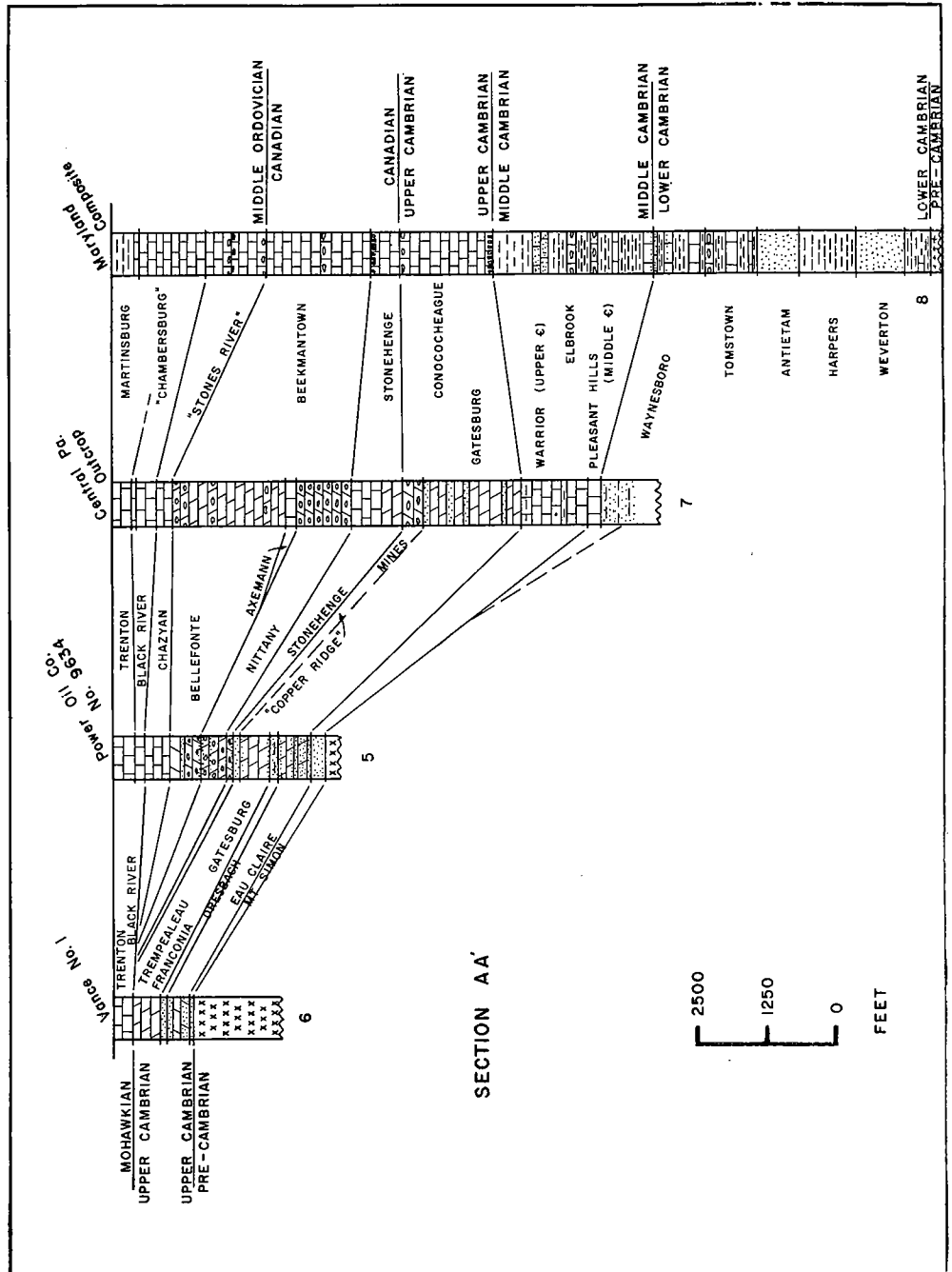


FIGURE 6—Cross-section along line A—A'.

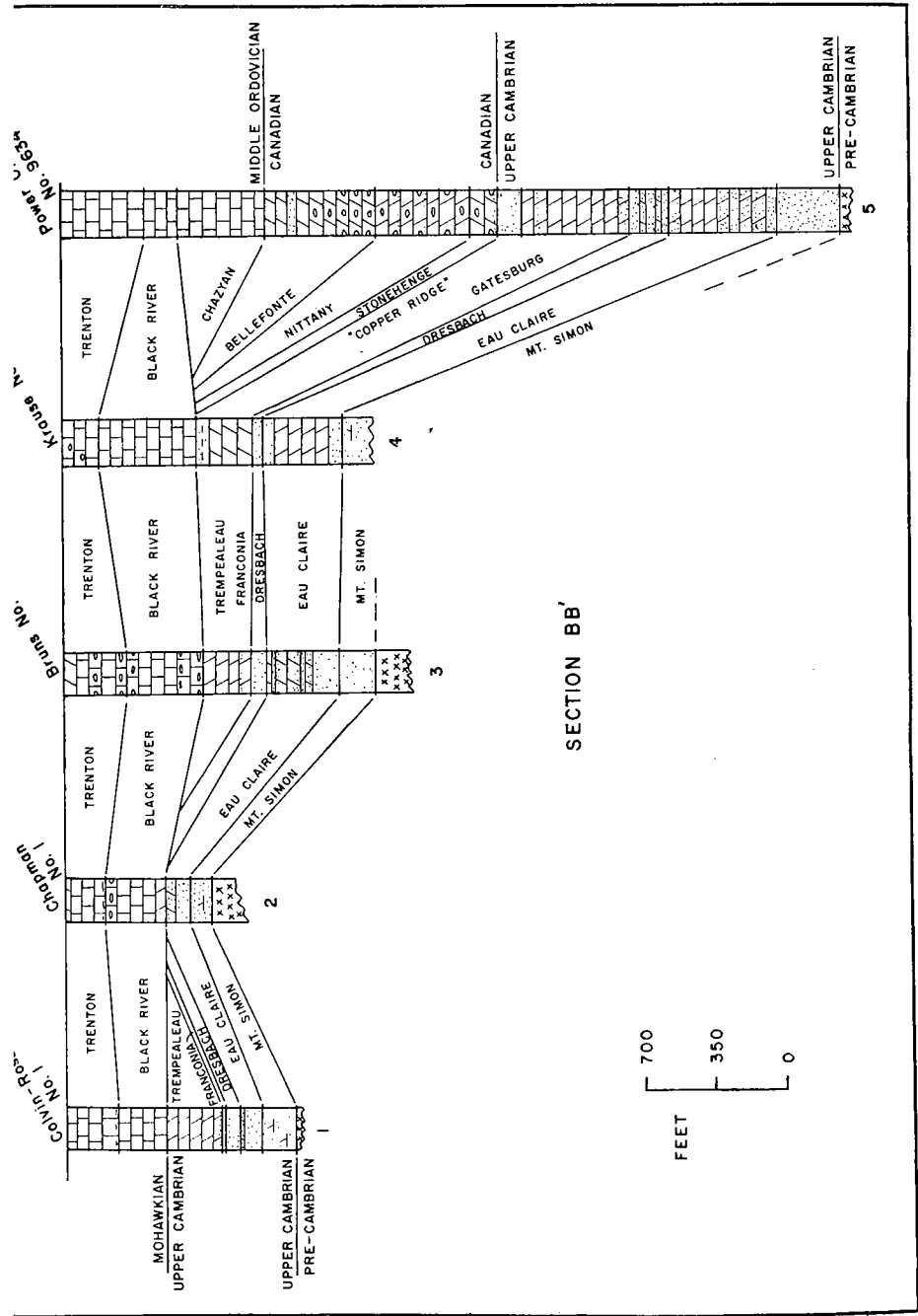


FIGURE 7—Cross-section along line B—B'.

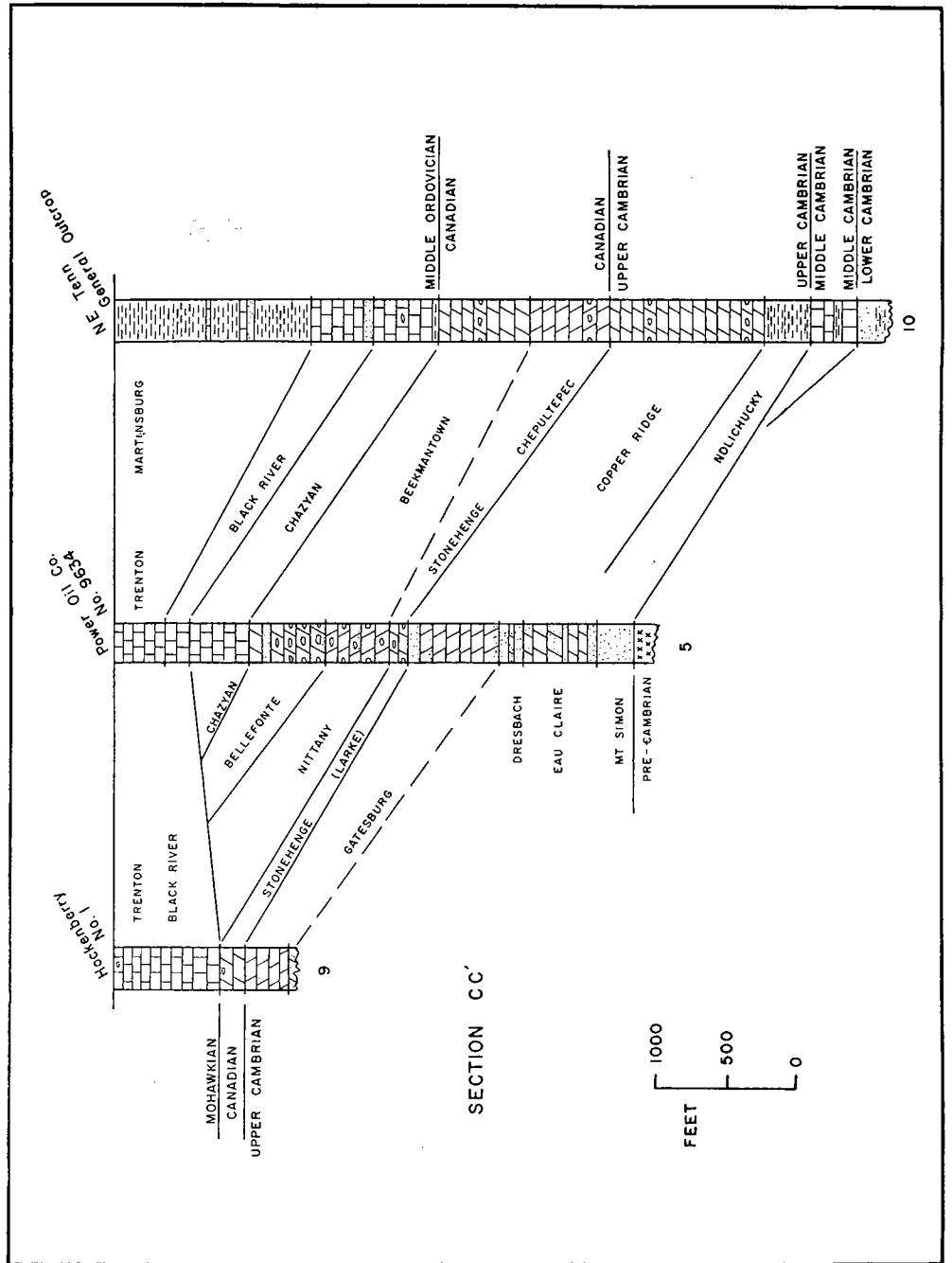


FIGURE 8—Cross-section along line C—C'.

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# PHYSICAL PROPERTIES OF A SERIES OF DOLOMITE CORES

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## ABSTRACT

Porosities, permeabilities, and mineral densities have been measured for a series of dolomite cores from West Virginia. Most of the porosity is due to vugs rather than intergranular pores and most of these vugs are interconnected. Porosities measured on small plugs have been shown by a statistical test to be unreliable for this sort of formation. Most of the samples studied have a mineral density which is essentially that of dolomite. Several have lower densities which may be due to inaccessible void space or to the presence of a less dense mineral.

All of the cores have permeability to gas, although there is an appreciable variation from one to the next. Most of this permeability is due to vugs and fractures. Horizontal permeability is appreciably greater than vertical.

## INTRODUCTION

In the course of drilling the Hope Natural Gas Company's No. 9634 well in West Virginia, many hundreds of feet of core were taken from a formation which had not been previously investigated thoroughly. Since there was a strong show of gas at one point, and since this formation underlies a large area, it was decided to obtain additional fundamental information on some of these samples, primarily for future reference. Twenty-five core samples which appeared to have appreciable porosity were selected from the much larger number available; it was not intended that these be a representative sample of the entire formation or even of any part. In general, it was desired to obtain as much fundamental information of a reservoir engineering nature as time would allow.

For heterogeneous cores of this sort, it is an axiom that the larger the core the more representative the laboratory measurement is of the reservoir property and so it was planned to take horizontal air permeabilities on radial cores with outer

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diameters the same as the samples received. By using a larger drill than would normally be used for the center holes in the radial cores, suitable plugs would be obtained for measuring vertical permeabilities. The latter could not be compared directly with the horizontal permeabilities because of the difference in size of the samples, but they could be compared with those of additional horizontal plugs.

Porosities on larger samples than those used in the usual core analyses were also desirable. From measurement of the weights and the physical dimensions of the cut cores and plugs together with an assumed mineral density, it is possible to calculate a total porosity. By weighing the plugs first dry and then saturated with a liquid, it is also possible to obtain an effective porosity, i.e., one for the accessible pore space. By an additional calculation, it is also possible to obtain the mineral density. The degree of agreement between assumed (handbook) mineral density and calculated mineral density gives an indication both of the homogeneity of the reservoir rock material and the extent to which the pores are interconnected. The latter is, of course, also reflected in the agreement between the two porosity values.

## APPARATUS AND PROCEDURE

### Core Preparation:

The cores were assigned numbers from one to twenty-five, according to increasing depth of origin. These numbers and the corresponding depths are given in Table 1 along with a verbal description of their appearance.

These were cut horizontally with a 10" (Dimet) diamond saw and then holes drilled through the center with a  $\frac{3}{4}$ " I. D. ( $\frac{7}{8}$ " O.D.) diamond drill. This operation produced conventional radial cores for horizontal permeabilities ( $4\frac{3}{8}$ " O.D.), as well as small  $\frac{3}{4}$ " plugs for vertical permeabilities. In general, the position of the horizontal cuts was chosen in order to give two full flat faces without chips off the edges. A second consideration was to obtain the largest possible core up to the maximum height of 4" imposed by the length of the diamond drill. In one case (No. 7) two radial cores were cut from the same large core to compare properties of adjacent samples. The outer surfaces of the large cores were in satisfactory condition as received and were used without further finishing.

In the case of sample No. 7, the top core was numbered 7-1 and the bottom 7-2. When two  $\frac{3}{4}$ " plugs were taken from one radial core, the more shallow had an "a" added to it (e.g. 7-1-a), the next a "b", etc.

Table I  
General Description of Samples

Sample Number	Depth (feet)	Appearance
1	11,202.6—11,203	H.F., V.G.E.H., C.L.V.
2	11,205.5—11,205.9	H.F., V.G.E.H., C.L.V.
3	11,242.2—11,242.7	H.F., V.G.E.H., C.L.V.
4	11,244 —11,244.5	H.F., V.G.E.H., C.L.V., also chalky yellow-white mineral
5	11,246.6—11,247.1	No H.F., V.F., C.L.V., many 1/16" vugs
6	11,277.4—11,277.7	Irregular fractures, C.L.V.
7	11,308.6—11,309.1	Irregular fractures, C.L.V., many 1/16" vugs, V.G.E.H.
8	11,325 —4" + 1"	One V.F., one H.F., no vugs, few spots white mineral
9	11,326.6—11,327.1	H.F., few vugs but V.G.E.H., no C.L.V. but rather vugs have white material in them
10	11,330.5—11,330.8	H.F., many medium and larger vugs, C.L.V.
11	11,331.4—11,331.8	H.F., large loosely filled vugs, C.L.V.
12	11,333.5—11,334	H.F., many 1/16" vugs and none larger than 1/8"
13	11,334.4—11,334.9	Some irregular fractures, small vugs, C.L.V.
14	11,336 —11,336.4	Some V.F., large and medium vugs, C.L.V.
15	11,336.4—11,336.8	No H.F., no V.F., no vugs
16	11,339 —11,339.6	V.F., medium to large vugs, C.L.V.
17	11,340.4—11,340.8	Medium vugs
18	11,349.2—11,349.6	One large and no small vugs, layer of dark mineral
19	11,461.4—11,462	Few medium vugs, C.L.V.
20	11,464.9—11,465.2	Few medium vugs, C.L.V.
21	11,478.5—11,479.1	H.F., irregular fractures, few medium vugs V.G.E.H.
22	11,480.1—11,480.8	H.F. filled with white mineral, few medium vugs, C.L.V.
23	11,484 —4" + 3"	V.F., many small to medium vugs
24	11,642	No vugs or fractures
25	13,092.2—13,092.6	No vugs, or fractures, sandstone

Note: H.F. = horizontal fractures  
 V.F. = vertical fractures  
 V.G.E.H. = vugs (have) greater extension horizontally  
 C.L.V. = crystalline lining to vugs

Nine horizontal 3/4" plugs were also cut from the excess material left after cutting the radial cores. These had an "H" added to their number as follows: 8-H-1.

**Porosity Measurements:**

After cutting, the cores were dried in an air oven at 110° C. for several hours, cooled in a desiccator, weighed on either an analytical balance (3/4" plugs) or an assay balance (radial cores) and measured with Vernier calipers. With an

assumed mineral density of 2.85 g/cc for dolomite, it is possible to calculate a porosity in a straightforward manner from the volume and weight, and these are designated  $f_{2.85}$  in Table 2.

Table 2  
Porosities and Mineral Densities

Radial Core No.	$f_{2.85}$ %	$f_w$ %	Plug No.	$f_{2.85}$ %	$f_w$ %	P (Mineral) g/cc
1-1	3.1		1-1-a	1.3		
			1-1-b	2.3		
2-1	4.8		2-1-a	0.5		
			2-1-b	1.5		
3-1	4.8	3.8	3-1-a	1.5		
			3-1-b	0.2	0.4	2.82
			3-H-1	0.8	0.7	2.83
4-1	2.3		4-1-a	1.4		
			4-1-b	1.2		
			4-1-c	0.9		
			4-H-1	0.6		
5-1	5.4		5-1-a	3.6		
			5-1-b	4.2		
			5-H-1	1.0		
6-1	3.5*		6-1-a	2.8		
7-1	4.8	4.4	7-1-a	2.8	2.8	2.83
			7-1-b	3.6	3.5	2.84
7-2	5.5	5.1	7-2-a	12.7	12.3	2.84
			7-2-b	2.6	2.6	2.84
8-1	8.6	3.5	8-1-a	6.3		
			8-1-b	7.1	1.6	2.70
			8-H-1	5.9	.7	2.68
9-1	9.0	3.1	9-1-a	6.5		
			9-1-b	7.0	1.4	2.68
10-1	13.9		10-1-a	7.2		
11-1	9.4	9.1	11-1-a	8.2	8.1	2.84
			11-1-b	9.1	9.1	2.84
			11-1-c	4.7	4.5	2.84
12-1	13.5	13.3	12-1-a	13.5	13.5	2.85
			12-1-b	5.0	4.9	2.83
			12-H-1	5.7		
			12-H-2	10.4		
13-1	7.9	6.8	13-1-a	3.0	2.8	2.84
			13-1-b	2.4	1.9	2.80
14-1	8.4*		14-1-a*			
15-1	6.8	5.0	15-1-a	4.3	2.0	2.74
			15-H-1	5.9		
16-1	7.3	7.3	16-1-a	4.1	3.9	2.85
			16-1-b	2.0	2.3	2.84
17-1	6.5		17-1-a	4.2		
18-1	4.3	4.3	18-1-a	0.3	0.2	2.86
			18-1-b	0.9	0.5	2.85
19-1	5.6	4.9	19-1-a	4.7	3.7	2.82
20-1	4.6		20-1-a	2.2*		
			20-1-b	--*		
21-1	3.2		21-1-a	1.6		
			21-1-b	2.9		
			21-H-1	1.7		

22-1	3.5	3.2	22-1-a	14.4	13.8	2.83
			22-1-b	2.8	2.8	2.85
23-1	2.3		23-1-a	1.2		
			23-1-b	2.0		
24-1	6.1		24-1-a	5.1		
	1.0**		24-1-b	5.5		
25-1	2.2**		25-1-a	1.8	1.8	2.65
			25-1-b	2.0	2.0	2.66

\* Chipped

\*\* Calculated with P=2.65 g/cc for quartz

For the  $\frac{3}{4}$ " plugs it was also possible to obtain porosities more directly and at the same time to determine the mineral density. After thorough evacuation the plugs were saturated with water and then weighed in a wide-mouthed pycnometer otherwise completely filled with water. With a knowledge of the external dimensions of the cores, it was then possible to calculate porosities and these are designated as  $f_w$ . A further calculation gave the mineral density and these are also presented in Table 2.

#### Permeability Measurements:

Air permeabilities were measured on the radial cores and the  $\frac{3}{4}$ " plugs at five different pressure differentials, and these are given in Table 3. For a few samples the rates were too high at the higher pressure differentials to measure with the equipment on hand and this is indicated by a dash in the table. For others the rates were too low to measure even at the highest pressure differential available (1 atmosphere) and this is indicated by a zero in the table. The minimum measurable permeability for the small plugs is about 0.5 md.

A Ruska air permeameter with downstream pressure atmospheric was used in all cases but a modified core holder was used for the radial cores. It merely consisted of two end plates with rubber gaskets and three tie rods; this was connected downstream from the rotameters of the permeameter. This instrument was calibrated against a soap film-burette ratemeter and a wet test meter.

## RESULTS AND DISCUSSION

#### Porosity and Mineral Density:

An inspection of Table 2 shows a number of interesting points. There is no apparent relation between the porosity of a large core and the small plugs cut from it. With only two exceptions the small plugs from a particular sample had a smaller porosity than the large radial cores from the same sample. In a way this is due to an experimental bias, that is, during the cutting of the small cores there is a tendency for them to break at the vugular or porous places. Since part

of the porous region is removed when a new cut is made, one would expect smaller porosity and permeability values for these smaller cores. Statistically, one would expect that there would be a few plugs which would have a higher porosity value than their parent core and this is also the case here.

The porosity values for the large cores are probably reliable ones for use in estimating reservoir volumes. The two adjacent cores from Sample 7 show reasonable agreement; there were more surface vugs in Core 7-2 than Core 7-1 and a visual inspection would have indicated a greater difference in porosity than that measured. There is a much wider range of values for adjacent small plugs as well as between the small plugs and their respective large core. These variations of porosity values of plugs from a particular parent sample do serve to emphasize the extreme heterogeneity of this formation when considered in terms of volumes the size of the plugs. The differences between porosities of adjacent and near-by large cores also indicate heterogeneity even on this larger scale. The average of the porosities of all the large cores (excluding 25-1) is 6.2% with the two extremes being 2.3% and 13.9%, and the average porosity of the plugs is 3.9% with the two extremes being 0.2% and 14.4%. These are mentioned merely to give an idea of orders of magnitude and should not be considered as typical of the entire formation.

An inspection of Table 2 also shows that there is a general increase in porosity from the top of the formation down to samples 10 to 12 (11,330 feet) followed again by a decrease in porosity down to the bottom of the formation. Sample 25 is obviously a sandstone and is not a member of the main set of cores.

For the small plugs the check between porosities calculated with an assumed mineral density of 2.85 g/cc and those measured by saturation with water is generally good. In many cases the latter is the smaller, indicating a small amount of pore space inaccessible to water or else the presence of a larger amount of a less dense mineral. In the two plugs from Sample 19 there is a greater difference than was expected.

The agreement between many of the calculated mineral densities and the handbook value was also quite good. This indicates primarily that the formation is relatively uniform as far as mineral density goes but it is also a result of the pore space being generally accessible to liquids. The average value for all the cores tested (excluding Sample 25 and those noted below) is 2.84 g/cc, which is the same as that of the handbook within experimental error. The values measured for Sample 25 also agree quite well with that in the handbook for quartz (2.65 g/cc).

After the main body of experimental work had been com-

pleted, a visual check was made between the appearance of the cores and their calculated porosities. For Samples 8, 9, and 15 the latter seemed to be higher than expected, and so  $f_w$  and mineral densities were determined for plugs from these samples. The latter were appreciably lower than the average for the other samples, and the  $f_w$ 's for these particular samples were also appreciably lower than the calculated ones. A subsequent report by Shearrow<sup>2</sup> identified this formation from which samples 8 and 9 were obtained as the New Richmond Sandstone, a sandstone with from 15 to 30% dolomite. Our density values are in line with expected values for such a sandstone. Although Sample 15 came from a depth described as dolomite with 5% sandstone, it is likely that our particular sample contained appreciably more sandstone and thus had the reported density. Values of  $f_w$  were calculated for the large cores using the mineral densities determined for the corresponding plugs on the assumption of no inaccessible pore space. These are also included in column 3 of Table 2. The values of  $f_w$  for the radial cores from these samples should be considered more reliable than the  $f_{2.85}$  values, particularly for Samples 8, 9, 15, and 25. However, the elevation from which Sample 24 is taken was also described as sandstone with 40% dolomite and so the true porosity was probably about 3%.

It is often interesting to carry out a statistical analysis on a large number of measurements such as we have here for porosity, and we have done the following. It is assumed that we have here two samples of cores both taken from the same source or population. One is the set of radial cores and the other is the set of plugs cut from the center of the radial cores plus those cut just adjacent to the radial cores for horizontal permeability measurements. It would be interesting to know if the mean of the porosity values of the plugs, which are the size of sample usually used for measuring this quantity, differs significantly (in the statistical sense) from the mean of the porosity values of the radial cores, which we consider to be representative of the formation in this property. 'Student's *t*-test' may be used in a situation such as this.<sup>3</sup> We have carried out the calculation omitting Sample 14 because the plug was lost and 25 for reasons mentioned above, and have considered the two halves of Sample 7 to be two separate samples. The  $f_{2.85}$ 's of the plugs from each original core sample were averaged and we used the discrepancies between these and the  $f_{2.85}$  for the corresponding radial core in this test. We obtain a '*t*' of 4.11 with twenty-three degrees of freedom. There is less than one chance in a thousand that a difference in means as observed here would occur by chance and thus this difference is highly significant. This indicates that porosity values obtained for small plugs are not a reliable

measure of reservoir porosities if the latter may be considered to be measured adequately by large radial cores.

#### **Permeabilities.**

The permeabilities at the five pressure differentials are given in Table 3 for all of the large radial cores and all of the small plugs. A similar generalization to that made for porosities can also be made here, namely, that the larger the sample the greater the permeability and the closer it probably is to the formation permeability. However, there is another effect superimposed here, namely, that the horizontal permeability is generally greater than the vertical. This can be seen by a comparison of the values for the small vertical and horizontal samples, but it is a relatively minor effect compared to size. Of the horizontal plugs, 55.6% have measurable permeability, whereas only 8.2% of the vertical ones do. As is apparent, all of the large cores have measurable permeability.

Considering for the moment only the large cores, it can be seen that although many have appreciable permeability, quite a number have very low permeability. If a rough comparison can be made, the spread in permeabilities is much greater than is the spread in porosities and there is no general relation between these two measurements. In general, there is certainly enough permeability to allow the movement of considerable gas but the wide variation in values, together with the lower permeabilities, may indicate appreciable permeability stratification.

For all of the cores and plugs there is variation of permeability with pressure differential. Some of this is in a direction that can be explained by the Klinkenberg Effect, that is, a decrease in apparent permeability with an increase in mean pressure and in this case pressure differential. Unfortunately, the mean pressure could not be varied over a very large range with the instrument used. If the standard plot of permeability versus the reciprocal of mean pressure is made, the slope changes erratically from one sample to the next, which would be indicative of different types of fluid-carrying channels in the various cores. In retrospect, it is felt that at least some of the measurements were made in the turbulent region rather than in the viscous region of fluid flow. If this were the case, then the true permeabilities as defined by D'Arcy's Law would be greater than those given in Table 3.

#### **General Observations:**

In the course of carrying out this work, several general observations were made, and it is worth recording them. First of all, it was noticed while cutting the cores that there was an appreciable variation in the ease of cutting. In general, those

Table 3  
Air Permealibities at Different Pressure Differentials  
(Millidarcies)

Sample No.	$\Delta P$ At <sub>m</sub>					Average
	1.00	0.80	0.60	0.40	0.20	
1-1	36.1	33.2	31.0	28.6	28.3	31.4
1-1-a	0					
1-1-b	0					
2-1-a	0			—	267	315
2-1-b	0					
3-1	53.0	46.7	47.5	49.8	55.8	50.6
3-1-a	0					
3-1-b	0					
3-H-1	1.7					1.7
4-1					—	363
4-1-a	1.1					363
4-1-b	0					1.1
4-1-c	0					
4-H-1	1.2					1.2
5-1	6.0	6.4	7.1	7.8	7.8	7.0
5-1-a	0					
5-1-b	0					
5-H-1	0					
6-1	48.2	49.9	49.4	50.8	54.4	50.6
6-1-a	0					
7-1	1.1	1.1	1.1	1.5	1.7	1.3
7-1-a	0					
7-1-b	5.0	4.7	5.6	4.4	4.0	4.7
7-2	6.1	6.6	7.5	9.2	9.6	7.8
7-2-a	0					
7-2-b	0					
8-1	32.7	26.3	24.5	25.0	26.9	27.1
8-1-a	0					
8-1-b	0					
8-H-b	0					
9-1	1.5	1.5	1.2	1.4	1.8	1.5
9-1-a	0					
9-1-b	0					
1-1	36.1	33.2	31.0	28.6	38.3	31.4
10-1	0					>10,000
10-1-a	0					>10,000
11-1			116	121	134	128
11-1-a	0					
11-1-b	0					
11-1-c	0					
12-1	77.4	77.6	77.5	77.8	79.3	77.9
12-1-a	1.1					1.1
12-1-b	0					
12-H-1	2.1	1.9				2.0
12-H-2	5.3	5.2	4.6	4.4		4.9
13-1	5.1	4.5	4.0	3.2	4.0	4.2
13-1-a	0					
13-1-b	0					
13-H-1	0					
14-1	49.7	48.2	49.3	48.5	48.0	48.7
14-1-a	0					
15-1	0.5	0.5	0.5	0.5	0.5	0.5

Sample No.	1.00	0.80	0.60	0.40	0.20	0.10	Average
15-1-a	0						
15-H-1	0						
16-1	22.7	21.7	20.9	19.7	20.2		21.0
16-1-a	0						
16-1-b	0						
17-1	9.9	8.9	9.2	8.5	7.2		8.7
17-1-a	0						
18-1	34.3	34.8	35.3	36.1	37.4		37.6
18-1-a	0						
18-1-b	0						
19-1	0.3	0.3	0.3	0.3	0.3		0.3
19-1-a	0						
19-1-b	0						
20-1	36.2	35.9	36.2	36.1	39.9		36.9
20-1-a	1.5						
20-1-b	0						
21-1	8.0	7.2	7.5	7.0	5.9		7.1
21-1-a	0						
21-1-b	0						
21-H-1	15.0	13.8	13.2	16.9	24.7		16.7
22-1	42.1	38.3	36.1	34.2	34.3		37.6
22-1-a	0						
22-1-b	0						
23-1				123	125		124
23-1-a	0						
23-1-b	0						
24-1	0.7	0.7	0.6	0.8	0.8		0.7
24-1-a	0						
24-1-b	0						
25-1	0.3	0.3	0.3	0.2			0.3
25-1-a	0						
25-1-b	0						

with the greater porosity were easier to cut but, since it was not possible to assign a number to the ease of cutting, it was not possible to make a more quantitative correlation.

After the permeabilities were run on a number of the radial cores, and while air was still coming through them, water was poured on to the surface of the core. From an observation of the distribution of the bubbles, it was apparent that all of the gas was coming from both vugs and fractures, and that none was coming from an intergranular permeability. It is realized that the water would fill any intergranular pores immediately, thereby minimizing their contribution to the permeability, but it was also noted that the air rate decreased only slightly when the water was poured on. Therefore, it was felt that this was a valid test.

Toward the end of the experimental work, an attempt was made to duplicate some of the permeabilities made several months earlier. In all cases the earlier measurements were higher for some unknown reason. Several possible sources of error were checked without success, and so the earlier measurements are the ones presented. This anomaly does not

invalidate the general conclusions obtained, although it may indicate an error in the absolute values of permeabilities.

### CONCLUSIONS

1. Practically all of the void space found in this series of samples is that represented by vugs; only a very small amount is due to intergranular pores and to fractures.

2. The porosity values obtained for the large cores are probably representative of the formation itself, whereas those obtained for small plugs are not. The average value of the former for this series of samples is 6.2%, and the two extremes are 2.3% and 13.9%.

3. Most of the void space is accessible for most of the samples, although a few of the samples may have inaccessible void space.

4. Most of the samples tested had a mineral density which is essentially that of dolomite, but a few had lower measured densities. Some of the latter were predominantly sandstone and some were mixtures of the two minerals.

5. It has been shown statistically that small plugs can not be used to measure porosity of a formation such as this.

6. All of the large cores measured have permeability to gas, although there is an appreciable variation from one sample to the next. By far the major contribution to this permeability is made by vugs and fractures, with a negligible contribution being made by an intergranular space.

7. The permeabilities measured for the large cores are probably representative of the formation, whereas those measured for the small plugs are not.

8. There is an appreciable stratification of permeability, that is, a very jagged permeability-depth profile. Horizontal permeability is notably greater than vertical.

9. There is an observed variation of permeability with pressure differential. Some of this was probably due to Klinkenberg Effect, but many of the measurements may have been made in the turbulent flow region. If the latter is the case, the permeabilities reported are lower than the true ones.

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PHYSICAL PROPERTIES OF  
LIMESTONE AND DOLOMITE CORES FROM  
THE SANDHILL WELL,  
WOOD COUNTY, WEST VIRGINIA

By Eugene C. Robertson

*Publication Authorized by Director,  
U. S. Geological Survey*

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# PHYSICAL PROPERTIES OF LIMESTONE AND DOLOMITE CORES FROM THE SANDHILL WELL, WOOD COUNTY, WEST VIRGINIA

By Eugene C. Robertson

## ABSTRACT

(To be published by the West Virginia Geological Survey in a Symposium volume of papers concerned with the cores from a well drilled by the Hope Natural Gas Company, West Virginia.)

The density, porosity, thermal conductivity, magnetic susceptibility, elastic moduli, and dielectric constant were measured on 132 cores from the Sandhill well. Of these cores, 41 are from 925 feet of Black River and Trenton Limestone, and 52 are from an underlying 1,110 feet of Beekmantown Dolomite. These are contiguous sequences of Middle and Early Ordovician Age.

Chemical analyses were made of most of the limestone and dolomite cores; the mean sum of  $\text{CaCO}_3 + \text{MgCO}_3$  is 91% for the limestone sequences and is 83% for the dolomite sequence. In addition, qualitative mineralogical compositions were determined on all cores with an X-ray diffractometer. The chemical and mineralogical compositions of the limestone and of the dolomite sequences are very uniform to the limits of analytical accuracy, about 5%.

The mean densities of the limestone and dolomite sequences are 2.696 gm/cc and 2.814 gm/cc, respectively. The variation within each sequence is very low, less than the observational accuracy of 0.4%. The mean porosity is about 0.4% for both the limestone and dolomite sequences, with a standard deviation of about 0.3% for both. The mean thermal conductivities for the limestone and dolomite sequences are 6.77 mcal/cm sec deg C and 11.39 mcal/cm sec deg C respectively; the local and long range variations for both sequences are about 5%. The mean magnetic susceptibility is  $3.0 \times 10^{-6}$  cgsu/cc for the limestone sequence and  $2.2 \times 10^{-6}$  cgsu/cc for the dolomite sequence; these indicate that any magnetite content must be  $< 10$ ppm. The mean dielectric constant ratio relative to air is 9.4 for the limestone and 8.6 for the dolomite; the measurements were made on dry samples at 1,000 cycles/sec.

Good measurements of the elastic moduli were made on only 4 limestone and on 5 dolomite samples; mean values for limestone and dolomite respectively are as follows:

Young's modulus,  $7.75 \times 10^5$  bars and  $8.02 \times 10^5$  bars; rigidity modulus,  $2.98 \times 10^5$  bars and  $3.28 \times 10^5$  bars; Poisson's ratio, 0.30 and 0.22; longitudinal internal friction 0.021 and 0.033; and shear internal friction 0.007 and 0.014. All other determinations of the moduli were much less reliable than these because of imperfections of bonding of grains in the rocks.

The chemical and mineralogical compositions and all the physical properties show that the limestone and dolomite sequences are each remarkably uniform. This uniformity and the abrupt change from one rock to the other shows an extraordinarily close geologic control. Although disguised by the errors of measurement, the data indicate that the local variation and the long range variation in compositions and properties in each sequence are about equal. If the thermal conductivities of the rocks are measured, temperature logs from wells can be used to identify geologic formations in a region of uniform heat flow; thus practical use of the temperature logs can be made in prospecting.

### INTRODUCTION

The availability of over 2,000 feet of nearly continuous 4-3/8-inch diameter core from the Sandhill well made it possible to make a thorough study of the physical properties of the Black River and Trenton Limestones and the Beekmantown Dolomite, of Middle and Early Ordovician age, respectively. Good sampling of these rocks was obtained by taking 93 specimens, 6 to 10 inches long, at 20-foot spacings, (omitting 8 specimens) through the interval of 9,596 to 11,631 feet depth.

This interval may be divided lithologically at about 10,521 feet into an upper 925 feet of limestone (41 cores) and a lower 1,110 feet of dolomite (52 cores), hereafter referred to as the limestone and dolomite sequences. The properties of an additional 14 specimens above and 16 specimens below this sequence also were measured, but emphasis is placed herein on the results obtained on the limestone and dolomite sequences.

The same samples were used in measuring thermal conductivity, density, porosity, and dielectric constant. These samples are hereafter called "conductivity disks"; they are flat cylinders of 1-1/2-inch diameter and 1/4-inch thickness. The flat surfaces were carefully ground to be parallel within  $\pm 0.0005$  inch, and the diameter was held to  $\pm 0.005$  inch. Duplicate disks were prepared from each core to study local variation of the properties. Sizes used in other tests are described in the proper sections.

The following physical properties were measured: density, porosity, thermal conductivity, magnetic susceptibility, elastic moduli, and dielectric constant. As an aid to

interpretation of these data, chemical and mineralogical analyses were made on each of the cores. The most thorough study was made of the densities and thermal conductivities because measurements of these properties differ distinctly between limestone and dolomite, whereas measurements of the other properties do not. Application of the data can be made to geology; in particular, the difference in thermal conductivities is of practical use in prospecting for oil and gas.

The Hope Natural Gas Company through Robert E. Bayles generously provided this valuable suite of fresh rock samples, impossible to obtain from outcrops. The assistance of S. A. H. Goldstein, L. Werber, and A. L. Baldwin in making physical property measurements is gratefully acknowledged. It is a pleasure to acknowledge the aid of Francis Birch in improving our techniques and precision of measurement; many helpful suggestions for the presentation of the data were given by Birch and by Harry Hughes, Richard A. Robie, Louis Peselnick, and George Keller. W. M. McCullough and C. E. Prouty kindly made available 61 chemical analyses.

#### CHEMICAL AND MINERALOGICAL COMPOSITIONS

For comparison purposes, the usefulness of any measurement of a physical property of a rock sample is greatly enhanced by knowing the rock's chemical and mineralogical compositions, and so considerable effort was made to obtain them. The results of these analyses are listed according to depth in Table 1. A plot of the chemically-analyzed calcium and magnesium carbonates is given in Figure 1 for the contiguous limestone and dolomite sequences.

Table 1.—Chemical and mineralogical compositions of core samples from the Sandhill well.

Depth	Chemical Analyses <sup>1</sup>			X-Ray Mineralogical Analyses <sup>2</sup>					Misc.
	CaCO <sub>3</sub>	MgCO <sub>3</sub>	R <sub>2</sub> O <sub>3</sub> Insol	Calcite	Dolomite	Quartz	Feldspar	Clay	
3,455				M (15)	tr. (1)	M <sup>3</sup>			Mica (S)
3,455						M	S	S	Chlorite (S)
7,687				tr.	S	M		S	Mica (tr.)
7,708									Chlorite (S)
7,726									Unknown (S)
7,763				S (1)	S (2)	M			Unknown (S)
7,777				S (1)	M (50)	M	S	S	Mica (S)
7,803				S (1)	M (20)	M	S	S	Mica (S)
7,833				tr. (1.5)	tr. (1)	M	S	S	Mica (S)
7,857				tr. (1)	tr. (1.5)	M	tr.	S	Mica (S)
9,416				M (16)	tr. (1)	M	tr.	S	Mica (S)
9,536				M (7)	S (1)	M	tr.	S	Mica (S)
9,557				M (3)	S (1)	M	S	S	Mica (S)
9,577				M (10)	tr. (1)	M	S	S	Mica (S)
9,596				M		S	tr.	tr.	Unknown (S)

<sup>1</sup>Chemical analyses for specimens from depths 10,371 feet to 11,684 feet inclusive are from McCullough and Prouty in their companion paper in this volume. The chemical analyses from 9,791 feet to 10,350 feet inclusive were made by R. Gantner, Fuels Branch, U. S. Geological Survey. All chemical analyses are in weight per cent. Ratios of calcite to dolomite in parentheses after percentages were calculated by stoichiometric proportions.

<sup>2</sup>The mineralogical analyses were made on an X-ray diffractometer by Paul D. Blackmon, Geochemistry and Petrology Branch, U. S. Geological Survey.

<sup>3</sup>Symbols: M = major constituent, S = subordinate constituent, tr. = trace constituent. Ratios of calcite to dolomite by weight are given in parentheses after the symbols when determined.

Depth	Chemical Analyses <sup>1</sup>			X-Ray Mineralogical Analyses <sup>2</sup>						
	CaCO <sub>3</sub>	MgCO <sub>3</sub>	R <sub>2</sub> O <sub>3</sub>	Insol	Calcite	Dolomite	Quartz	Feldspar	Clay	Misc.
9,616					M (100)	tr. (1)	S			
9,636					M	tr. (1)	S	tr.	S	Mica (S)
9,656					M (12)	tr. (1)	S	tr.	S	Mica (S)
9,664					M (5)	S (1)	M			
9,791	85 (6)	6 (1)			M (10)	S (1)	tr.		S	
9,809	74 (4)	7 (1)			M (7)	S (1)	S			
9,829					M	S	S		S	
9,849	77 (11)	3 (1)			M (9)	S (1)	S			
9,870	88 (16)	2 (1)			M (2)	M (1)	S	S		
9,890	88 (6)	7 (1)			M (2)	M (1)	S	S		
9,910	92 (17)	2 (1)			M (3)	M (1)	S	S		
9,929	82 (6)	6 (1)			M (12)	tr. (1)	tr.			
9,950	82 (4)	9 (1)			M (6)	S (1)	S		S	
9,971	93 (13)	3 (1)			M (32)	S (1)	S			
9,990	92 (11)	4 (1)			M (8)	S (1)	S			
10,010	85 (5)	8 (1)			M (10)	S (1)	S			
10,030	89 (8)	5 (1)			M (10)	S (1)	S			
10,051	93 (17)	2 (1)			M (2)	M (1)	tr.			
10,071	75 (6)	6 (1)			M (5)	S (1)	S		S	
10,089	92 (13)	3 (1)			M (16)	tr. (1)	S		tr.	
10,110	82 (10)	4 (1)			M (8)	S (1)	S	tr.	tr.	
10,131	94	tr.			M (15)	S (1)	S			
10,150	91 (13)	3 (1)			M (50)	S (1)	S		tr.	
10,172	90 (12)	4 (1)			M (20)	S (1)	S			
10,190	95 (18)	2 (1)			M (2)	M (1)	S			
10,211	92 (7)	6 (1)			M (6)	S (1)	tr.			
10,231	92 (9)	4 (1)			M (2.5)	S (1)	S	tr.	tr.	
10,250	88 (16)	2 (1)			M (15)	S (1)	S			
10,270	90 (13)	3 (1)			M (1.5)	M (1)	S	tr.	tr.	
10,290	86 (6)	6 (1)					S	tr.	tr.	

Depth	Chemical Analyses <sup>1</sup>			X-Ray Mineralogical Analyses <sup>2</sup>						
	CaCO <sub>3</sub>	MgCO <sub>3</sub>	R <sub>2</sub> O <sub>3</sub>	Insol	Calcite	Dolomite	Quartz	Feldspar	Clay	Misc.
10,310	93 (17)	2 (1)			M (10)	S (1)	S		tr.	
10,330	83 (5)	7 (1)			M (10)	S (1)	S			
10,350	88 (11)	4 (1)			M (20)	S (1)	S			
10,371	77 (5)	6 (1)	9	10	M (3)	M (1)	S			
10,391	91 (8)	5 (1)	2	2	M (4)	M (1)	S		tr.	
10,411	92 (23)	2 (1)	5	1	M (7)	S (1)	S		tr.	
10,430	79 (5)	6 (1)	5	10	M (5)	S (1)	S		tr.	
10,450	87 (4)	10 (1)	1	3	M (13)	S (1)	S			
10,471	69 (2)	13 (1)	6	12	M (12)	S (1)	S		tr.	
10,511	67 (1)	21 (1)	1	6	M (3)	M (1)	S			
10,531	51 (1)	36 (10)	2	7	M (3)	M (1)	S			
10,551	51 (1)	37 (12)	6	7	M (3)	M (1)	S			
10,570	43	41	7	10	tr. (1)	M (100)	S		tr.	Anhydrite (S)
10,590	47	43	3	7	tr. (1)	M (100)	S		tr.	
10,610	48	41	8	11	tr. (1)	M (100)	S		tr.	
10,631	47 (1)	37 (27)	11	11	S (1)	M (10)	S		S	
10,651	41 (1)	34 (100)	3	22			S		S	
10,670	34	34	11	21			S		tr.	
10,692	12	22	14	52			M		S	
10,710	42	41	8	8			tr.		tr.	
10,730	53	45		1			S		tr.	
10,750	53	47					tr.		tr.	
10,771	55	46					tr.		tr.	
10,791	50	48	1	1			tr.		tr.	
10,831	43	36	8	15			tr.		tr.	
10,851	39	38	5	19			tr.		tr.	
10,871	41	40	7	12			S		tr.	
10,891	42	41	3	14			S		tr.	
10,911	38	38	9	16	S (1)	M (10)	S		S	
10,931	42	41	6	12	tr. (1)	M (100)	S		tr.	

Depth	Chemical Analyses <sup>1</sup>			X-Ray Mineralogical Analyses <sup>2</sup>						
	CaCO <sub>3</sub>	MgCO <sub>3</sub>	R <sub>2</sub> O <sub>3</sub>	Insol	Calcite	Dolomite	Quartz	Feldspar	Clay	Misc.
10,951	41	39	7	14	tr. (1)	M (50)	S	tr.		
10,971	43	42	3	12	S (1)	M (50)	S	S		
10,991	47	43	2	8		M	tr.	tr.		
11,011	44	38	7	11		M	S			
11,031	48	42	3	8		M	S	tr.		
11,050	49	41	9	9		M	S	tr.		
11,070	46	38	8	8		M	tr.	tr.		
11,090	44	43	6	8	tr. (1)	M (150)	tr.			
11,101	47	41	6	5		M	tr.			
11,130	45	40	4	11		M	tr.			
11,150	47	40	4	17		M	tr.			
11,170	43	40	3	14		M	M			
11,190	44	42	5	10		M	S	tr.		
11,211	50 (1)	39 (31)	3	8		M	tr.	tr.		
11,230	47	45	6	8		M	tr.	tr.		
11,251	42	39	6	13		M	tr.	tr.		
11,267	41	40	5	14		M	tr.	tr.		
11,291	40	43	4	12		M	tr.	tr.		
11,330	43	39	4	14		M	M	tr.		
11,349	44	42	6	9		M	S			
11,371	40	45	7	8		M	tr.	tr.		
11,391	43	37	7	10		M	tr.	tr.		
11,410	42	39	7	12		M	M	tr.		
11,431	43	42	4	11		M	S	tr.		
11,450	39	38	10	14		M	S	tr.		
11,470	42	41	6	12	S (1)	M (1)	M	tr.		
11,491	42	41	6	12		M	tr.	tr.		
11,510	40	42	9	10		M	tr.	tr.		
11,531	40	42	6	13		M	tr.	tr.		
11,551	40	42	6	13		M	tr.	tr.		

Depth	Chemical Analyses <sup>1</sup>			X-Ray Mineralogical Analyses <sup>2</sup>						
	CaCO <sub>3</sub>	MgCO <sub>3</sub>	R <sub>2</sub> O <sub>3</sub>	Insol	Calcite	Dolomite	Quartz	Feldspar	Clay	Misc.
11,571	38	38	6	18		M	tr.	tr.		
11,591	46	39	4	20		M	tr.	tr.		
11,611	38	36	11	14	tr. (1)	M (150)	tr.	tr.		
11,631	40	40	5	15	tr. (1)	M (150)	tr.	tr.		
11,650	19	22	17	41		M	M	tr.		
11,671	19	24	9	48		M	tr.	tr.		
11,684	21	25	15	39		M	M	tr.		
11,924						M	tr.	tr.		
11,945						M	tr.	tr.		
13,005					tr. (1)	M (150)	tr.	S		
13,026					tr. (1)	M (50)	M	S		
13,045						M	tr.	tr.		
13,066						M	M	S		S
13,086						M	M	S		S
13,106						M	M	S		S
13,126					tr. (1)	M (10)	S	M		S
13,146						M	tr.	S		tr.
13,165						M	M	M		S
13,314					tr. (1)		M	M		S
13,318					tr. (1)	tr. (1)	M	M		S

Hornblende (M)

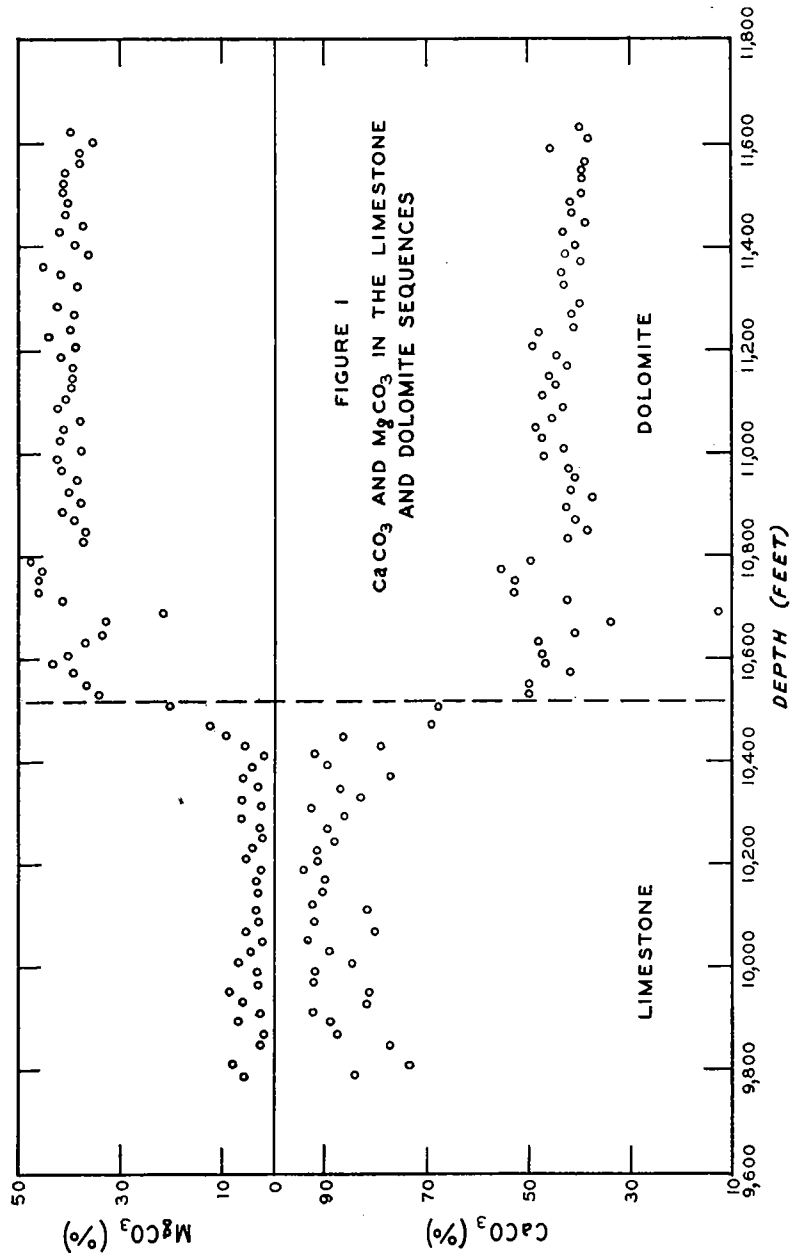


Figure 1.— $\text{CaCO}_3$  and  $\text{MgCO}_3$  in the limestone and dolomite sequences.

In their contribution to this symposium, McCullough and Prouty describe the method they used for analysis and state its accuracy. The samples analyzed by McCullough were splits of each 5-foot interval of the original core. The calcium and magnesium analyses made by Gantnier were done by the versenate method (see, Shapiro and Brannock, 1957); this is only an approximate method, but the accuracy is  $\pm 3\%$  for each element for samples low in argillaceous minerals. The samples analyzed by Gantnier are small portions of the core specimens used for the physical property measurements.

The variability of the rock compositions in the 5-foot intervals was tested by having 9 duplicate samples of limestone and dolomite analyzed by Gantnier; however, the duplication consisted only in that each sample came from somewhere within the interval represented by one of McCullough's analyses. The range of differences between the two analyses for  $\text{CaCO}_3$  is from +5.1 to -10.2%, and the range for  $\text{MgCO}_3$  (in the dolomite samples) is from +9.6 to -5.7%. Without regard to sign, the mean value (M) and the standard deviation (SD) of the differences in  $\text{CaCO}_3$  are  $M = 5.7\%$ ,  $SD = 3.1\%$ . The values for the differences in  $\text{MgCO}_3$  (for dolomite samples) are  $M = 4.5\%$ ,  $SD = 2.4\%$ . Based on the 9 analyses, the variation of  $\text{CaCO}_3$  and of  $\text{MgCO}_3$  in the rocks within 5-foot intervals is fairly small, and the absolute accuracy of measurement can be taken as  $\pm 5\%$ .

The mineralogical composition of a rock is more important than its chemical composition in interpreting measurements of its physical properties; although the state of aggregation of the mineral grains can affect the physical properties more than either their mineralogical or chemical compositions. In determining the content of calcite and dolomite in these rocks, approximate measurements were made on bulk samples with an X-ray diffractometer: the heights of peaks on a pattern of the rock sample were compared with those of mechanical mixtures of pure minerals (Tennant and Berger, 1957). The following peaks of  $2\theta$  were used: calcite  $29.4^\circ$  and  $47.6^\circ$ ; dolomite,  $31.0^\circ$  and  $41.2^\circ$ . The amount of the other minerals present were estimated roughly from their major peaks in a similar way.

The uncertainty of the observed calcite-dolomite ratios from the X-ray measurements is shown by comparison with the computed ratios from the chemical analyses (Table 1). Even allowing for a variation of 5% in the determinations of  $\text{CaCO}_3$  and  $\text{MgCO}_3$ , and allowing for solid solution of  $\text{MgCO}_3$  up to 4% (Goldsmith, et al., 1955) in calcite, the agreement is just fair, mainly due to inaccuracies in the X-ray technique.

An indication of the purity of the limestone and dolomite sequences as carbonate rocks is the approach of the sum of the chemically-analyzed  $\text{CaCO}_3$  and  $\text{MgCO}_3$  to 100%. For 35 samples of the limestone sequence, the mean and standard deviation of the sum of the carbonates are  $M = 91\%$ ,  $SD = 5\%$ ; for 54 samples of the dolomite sequence, the mean and standard deviation are  $M = 83\%$ ,  $SD = 9\%$ . Quartz is the principle impurity in these carbonate rocks (Table 1). Unusual impurities in a 6-inch breccia layer at 10,631 feet depth are celestite and anhydrite, 16% and 4%, respectively, based on density and X-ray diffraction measurements.

In general, taking analytical accuracy into account, the limestone and the dolomite sequences are moderately pure carbonates and perhaps even more significant geologically the sequences are uniform in chemical and mineralogical composition.

### DENSITY

In rocks as well consolidated as these are, the density reflects the major mineralogy perceptibly: the presence of 10% of an impurity with a density contrast of 0.2 gm/cc can be detected fairly easily. However, the effect on the density of very much smaller amounts of impurities is not observable unless refined techniques are used; the density of the grains alone must be obtained, eliminating the effect of porosity completely.

Linear dimensions of the conductivity disks (1- $\frac{1}{2}$ -inch diameter by  $\frac{1}{4}$ -inch thick) were measured with a micrometer to 0.0001 inch, and their weights were measured on a chemical balance to 0.001 gram. The following accuracies of measurement apply: weight  $\pm 0.01\%$ , diameter  $\pm 0.1\%$ , and thickness  $\pm 0.2\%$ . The overall accuracy is 0.4%, which agrees with the figure given by Mason (p. 32, 1944) for this method of measurement.

Dry and water-saturated densities were measured on duplicate disks prepared from each core. The dry weight was measured after drying them under a vacuum of about 0.1 mm Hg at 80°C; the saturated weight was measured after saturating the disk under water subjected to a similar vacuum. The periods for drying and for saturating were about 4 hours each.

The average value of the saturated density of each pair is listed in Table 2; only the saturated densities are tabulated

Table 2.—Physical properties of core samples from the Sandhill well.

Depth (feet)	Density (gm/cc)	Porosity (%)	Thermal Cond. $10^{-3}$ cal (cm sec deg C)	Di- electric Constant (Ratio relative to air)	Magnetic Suscep- tibility cc	Young's Modulus ( $10^8$ bars)	Rigidity Modulus ( $10^8$ bars)	Poisson's Ratio (cm) (cm)	Longi- tudinal Internal Friction	Shear Internal Friction
3,455	2,591	.70	15.0	5.0	1					
7,668	2,661	1.45	9.8	6.8	20					
7,687	2,587	.95	13.6	4.6	1					
7,708	2,563	.85	14.2	5.3	<1					
7,726	2,608	1.25	14.6	4.5	<1					0.121
7,763	2,597	1.00	13.2	4.9	1					
7,777	2,553	.50	12.0	5.1	2					
7,803	2,702	1.05	10.1	6.6	9					
7,833	2,682	1.20	8.4	9.3						
9,416	2,720	.60	6.4	11.8						
9,536										
9,557										
9,577	2,646	2.65	3.6	7.9	8					
9,596	2,667	.85	5.8	8.8	4					
9,616	2,698	.55	7.4	8.4	1					
9,636	2,688	.40	6.7	8.5	<1					.020
9,656	2,703	.25	7.3	8.7	1					
9,664	2,681	.45	7.1	8.4	2					
9,791	2,704	.30	6.9	9.4	<1					
9,879	2,702	1.35	5.5	8.1	2					
9,829	2,705	.70	6.6	11.0	2					
9,849	2,681	.85	6.0	6.0	5					
9,870	2,697	.90	6.4	9.4	2					
9,890	2,701	.30	6.9	8.5	<1					.042
9,910	2,681	.15	7.0	13.0	1					
9,929	2,693	.30	6.9	8.6	2					
9,950	2,692	.15	6.8	11.7	2					
9,971	2,683	.10	6.4	12.1	2					
						3.05	1.70	-0.12	0.057	0.121
						5.70	2.45	.16	.065	.020
						4.40	2.20	.01	.033	.042
						5.80	2.20	.32	.026	.036

PROPERTIES, LIMESTONE & DOLOMITE CORES

Depth	Density	Porosity	Thermal Cond.	Di-electric Constant	Magnetic Susceptibility	Young's Modulus	Rigidity Modulus	Poisson's Ratio	Longitudinal Internal Friction	Shear Internal Friction
9,990	2.690	.15	6.8	9.0	1	5.90	2.50	.16	.018	.009
10,010	2.718	.30	7.1	8.5	3					
10,030	2.697	.35	7.1	8.8	3					
10,051	2.695	.05	7.2		2					
10,071	2.702	.55	6.5	12.4						
10,089	2.694	.25	6.4	7.8		7.90	3.05	.30	.013	.007
10,110	2.708	.15	7.2	9.4						
10,131	2.699	.15	7.1	9.0						
10,150	2.692	.05	7.1	9.7		7.75	3.00	.30	.020	.008
10,172	2.699	.50	7.6	8.5						
10,190	2.693	.55	7.6	8.3		7.40	2.95	.26	.011	.004
10,211	2.676	.45	6.7	8.7						
10,231	2.708	.30	7.1	9.4						
10,250	2.690	.50	6.6	8.8						
10,270	2.703	.35	6.9	10.6	2	5.90	2.55	.17	.029	.025
10,290	2.704	.50	6.3	11.3	6	3.70	2.20	.15	.072	.081
10,310	2.690	.15	6.6	10.5	8	5.95	2.60	.14	.041	.031
10,330	2.707	.50	6.6	8.8	6					
10,350	2.703	.30	6.9	11.9	6	4.96	2.35	.04	.065	.013
10,371	2.666	.90	6.0	7.2	8					
10,391	2.709	.25	6.2	8.9	13	6.00	2.75	.10	.015	.027
10,411	2.692	.35	6.9	8.5	79					
10,430	2.706	.10	7.4	9.4	30					
10,450	2.701	.20	6.9	15.1						
10,471	2.665	.10	6.3	17.3	28	7.95	2.95	.35	.041	.007
10,511	2.710	.05	6.9	10.7	9					
10,531	2.801	1.05	8.3	8.3	10	7.25	2.95	.23	.05	.01
10,551	2.831	.30	10.7	7.4	2					
10,570	2.833	1.00	8.8	8.0	5	7.23	2.95	.22	.0319	.0144
10,590	2.929	.55	9.5	7.8	<1					
10,610	2.774	.27	11.4	7.2	1					
10,631	3.004	.35	8.0	10.6	4	7.50	3.05	.22	.042	.024
10,651	2.800	.45	11.0	17.7	4					

Depth	Density	Porosity	Thermal Cond.	Di-electric Constant	Magnetic Susceptibility	Young's Modulus	Rigidity Modulus	Poisson's Ratio	Longitudinal Internal Friction	Shear Internal Friction
10,670	2.790		9.3	32.0	5					
10,692	2.665	.70	13.2	8.1						
10,710	2.839	.14	11.1	9.1	6					
10,730										
10,750	2.749	.50	10.8	8.5						
10,771	2.771	.20	12.0	8.2						
10,791	2.813	.45	12.2	7.7						
10,831										
10,851	2.783	.15	9.7	11.5	1	9.50	3.75	.26	.019	.008
10,871	2.832	.20	11.7	9.6	3	8.65	3.64	.19	.023	.014
10,891	2.817	.10	11.5	8.1	1					
10,911	2.797	.45	10.4	12.9	2	8.55	2.95	.44	.04	.04
10,931	2.836	.35	12.6	7.8	2					
10,951	2.804	.45	10.6	8.6	4					
10,971	2.811	.25	11.3		4	7.50	3.45	.11	.026	.023
10,991	2.813	.35	11.1		2	6.90	3.05	.13	.024	.027
11,011	2.841	.20	11.8	7.7						
11,031	2.815	.40	11.4	5.9		6.15	2.80	0.1	.023	.057
11,050	2.835	.25	11.7	7.4	<1					
11,070	2.827	.25	12.2	7.1	2	5.95	2.75	.09	.038	.025
11,090	2.824	.45	13.2	10.5	1					
11,101	2.825	.40	13.2	10.0	1	7.45	3.25	.14	.032	.029
11,130	2.819	.20	13.7	8.6	1	4.25	2.30	-.09	.068	.043
11,150	2.818	.35	12.6	8.4	1					
11,170	2.756	.15	11.2	7.4	<1	8.55	3.70	.16	.031	.015
11,190	2.797	.30	11.6	7.7	1	3.05	2.10	-.27	.022	.038
11,211	2.790	.60	12.1	9.3	1					
11,230	2.814	.40	11.6	10.0	2					
11,251	2.819	.45	12.1	8.9	1	3.55	2.20	-.21	.114	.038
11,267	2.819	.30	11.5	8.1	1	4.45	2.35	-.06	.065	.031
11,291	2.817	.45	11.9	9.6	1					
11,330	2.676	.55	9.7	11.1	<1					
11,349	2.805	.65	11.6	7.5	1					

Depth	Density	Porosity	Thermal Cond.	Dielectric Constant	Magnetic Susceptibility	Young's Modulus	Rigidity Modulus	Poisson's Ratio	Longitudinal Internal Friction	Shear Internal Friction
11,371	2.825	.35	11.6	8.5	3					
11,391	2.792	1.05	11.2	7.6	<1	6.60	2.90	.13	.078	.044
11,410	2.815	.45	12.2	8.0		6.85	2.90	.18	.036	.041
11,431	2.816	.45	11.8	9.7	2					
11,450	2.813	.20	11.3	7.7		6.45	2.90	.12	.03	.02
11,470	2.835	.45	11.2	7.4						
11,491	2.803	.40	12.2	9.2						
11,510	2.799	.35	10.1	8.2	2					
11,531	2.825	.25	11.9	8.1						
11,551	2.819	.45	13.1	8.4						
11,571	2.824	.30	12.2	8.4	2					
11,591	2.821	.30	12.4	9.1						
11,611	2.806	.30	11.0	10.1						
11,631	2.813	.40	11.8	8.0						
11,650	2.651	.45	14.7	4.6		2.95	1.85	-.20	.112	.041
11,671	2.729	.45	14.0	6.8		3.30	2.00	-.16	.095	.055
11,684	2.630	.50	15.2	4.5		4.35	2.45	-.11	.025	.031
11,924	2.824	.75	12.4	5.6		7.20	3.05	.19	.074	.067
11,945	2.819	.30	13.4	8.6	1					
13,005	2.819	.25	9.2	7.8	4					
13,026	2.678	.65	10.0	6.2	6					
13,045	2.832	.20	10.4	7.6	8	7.10	2.95	.19	.024	.010
13,066	2.663	.60	13.7	5.7	2					
13,086	2.660	.70	12.6	5.2	6					
13,106	2.515	2.50	13.5	4.5	<1					
13,126	2.683	.60	7.0	7.0	8					
13,146	2.799	.35	8.0	8.6	10	5.25	2.50	.05	.028	.010
13,165	2.675	.85	7.4	6.9						
13,314	2.910	.35	5.0	43.5	57					
13,318	2.650	.20	7.9	9.3	8					



Table 3.—Means and standard deviations of the carbonate content and of various physical properties of the limestone and of dolomite sequences.

Statistical Parameter <sup>1</sup>	Carbonate Content <sup>2</sup>		Density (gm/cc)	Porosity (%)	Thermal	Thermal	Magnetic Susceptibility <sup>5</sup> (cc)	Dielectric Constant <sup>6</sup> Ratio relative to air
	CaCO <sub>3</sub> (%)	MgCO <sub>3</sub> (%)			Conductivity <sup>3</sup> (10 <sup>-3</sup> cal (cm sec deg C))	Conductivity <sup>4</sup> Difference (10 <sup>-3</sup> cal (cm sec deg C))		
Mean	87.0	4.5	2.696	0.38	6.77	0.30	3.0	9.4
SD	5.9	2.2	0.015	0.28	0.46	0.17	2.5	1.5
N	33	33	41	41	41	32	26	38
					Limestone: 9,596 ft. - 10,521 ft.			
Mean	43.1	40.0	2.814	0.41	11.39	1.20	2.2	8.6
SD	6.1	3.9	0.046 (0.020)	0.22	1.19	0.71	1.0	1.3
N	54	54	52 (48)	52	52	56	38	49
					Dolomite: 10,521 ft. - 11,631 ft.			

<sup>1</sup>SD = standard deviation. N = number of measurements.  
<sup>2</sup>The carbonate content is from the chemical analyses in Table 1; intermediate composition of samples at 10,471 feet and 10,511 feet were not included.  
<sup>3</sup>Thermal conductivities are for saturated samples.  
<sup>4</sup>Thermal conductivity difference is the increase in conductivity due to the water.  
<sup>5</sup>High values of magnetic susceptibility between 10,391 feet and 10,511 feet were not calculated in mean for limestone.  
<sup>6</sup>High values of the dielectric constant at 10,480 feet, to 10,471 feet, and 10,670 feet were not used. The dielectric constant ratio is relative to air, whose constant is 8.85 x 10<sup>-1</sup> farads/cm.

standard deviations of the densities are given in Table 3 and also on Figure 2. These may be compared with the densities of single crystal calcite of 2.710 gm/cc and of single crystal dolomite of 2.85 gm/cc.

The uniformity of the density of the 925-foot limestone sequence is indicated by the small standard deviation, 0.015 gm/cc, 0.5% of the mean. The variation of the 1,110-foot dolomite sequence around the mean value is enlarged because of 2 high samples with celestite impurity and 2 low samples with quartz impurity; leaving out these 4 densities, the standard deviation is reduced from 0.046 to 0.020 gm/cc, and the latter value is plotted on Figure 2. As the measurement uncertainty of 0.4% contributes to these variations, actually the rocks must be more uniform than even those low values indicate, and the long range variation within each sequence must be very small.

The local variation in density within a few inches in each rock core might be shown by the difference in density of the duplicate samples prepared. Taking account of signs, for 30 sample pairs in the limestone sequence, the mean difference is  $M = 0.001$  gm/cc, and  $SD = 0.014$  gm/cc, and for 44 sample pairs in the dolomite sequence, the mean difference is  $M = 0.008$  gm/cc, and  $SD = 0.014$  gm/cc. The scatter shown by the standard deviations is about equal to the accuracy of measurement, so the local variation is so small as to be undetectable. This conclusion is supported statistically by the t-test for significance.

### POROSITY

The porosity of these well-consolidated rocks is low, and so it has little effect on most of their physical properties.

The porosity is the ratio of the pore volume to the total volume of a sample. The porosities were determined by obtaining the difference between the dry and water-saturated weights of the conductivity disks and dividing by the volume of the sample; the porosity is expressed as a percentage. The accuracy is rather arbitrarily estimated to be no better than  $\pm 30\%$  of the porosity measurement, due to incomplete drying and incomplete saturation, especially in isolated and in surface pores.

The average porosities of the duplicate disks are listed in Table 2. Most of them are less than 1%, with a mean value of 0.4% for both the limestone and the dolomite sequences (Table 3). There is considerable variation as shown by the standard deviations, but it is randomly scattered, and a plot of the porosity against the depth indicates no regularity with rock type nor with depth.

The local variation in porosity might be shown by the

differences between the duplicate samples: taking account of signs,  $M = 0.10\%$ ,  $SD = 0.28\%$ , for 30 sample pairs in the limestone sequence, and  $M = 0.04\%$ ,  $SD = 0.20\%$ , for 44 sample pairs in the dolomite sequence. The random local variation shown by the standard deviations is equal to the long range variation, but neither can be distinguished clearly because of the errors of measurement. This apparent local variation is supported by the t-test for significance.

Of course, these porosities are the small-scale ones of dense samples and do not reveal the porosity of fractures, vugs, shaly partings, and other unconsolidated layers, which affect the bulk porosity of these rocks on a large scale. In general, the small-scale porosities of the limestone and dolomite sequences are quite low, and do not seem to be related to the mineralogy of the rocks.

#### THERMAL CONDUCTIVITY

In these massive rocks, the thermal conductivity depends principally on the composition of the rocks, although additional variables are the porosity, cohesion and size and shape of the grains, composition and degree of water saturation, and temperature and pressure conditions of measurement.

The method used for measurement of thermal conductivity is described by Birch (p. 600-602 and figure 14, 1950). In this technique, the disk of unknown rock is substituted for a standard. By measuring the temperature drops across two porcelain secondary standards and across the unknown, and knowing their thicknesses, the thermal conductivity can be calculated. Heat flows from a heater at the top to the a cooling coil at the bottom through a stack of disks, including an unknown, 2 standards, and 4 copper. Temperature is measured with thermistors in holes in the copper disks rather than with copper-constantan thermocouples in order to retain accuracy while using a simple Wheatstone bridge instead of using a precise but expensive potentiometer. The total drop in temperature is only  $6^{\circ}\text{C}$ ; this low gradient is used in order to cut down lateral radiation and convection losses. The duplicate conductivity disks ( $1\frac{1}{2}$ " dia. by  $\frac{1}{4}$ " thick) were measured.

Calibrations of the conductivity of the porcelain secondary standards have been made with a divided bar apparatus and by checking against well-calibrated disks of single crystal quartz and of glass. The calibration error of the quartz and the glass is  $\pm 3\%$ ; a systematic error for all samples.

The accuracy of dimension is about  $\pm 0.5\%$ , and the accuracy of the temperature measurements is  $\pm 1\%$ ; these and other sources of random error may be checked by repeat-

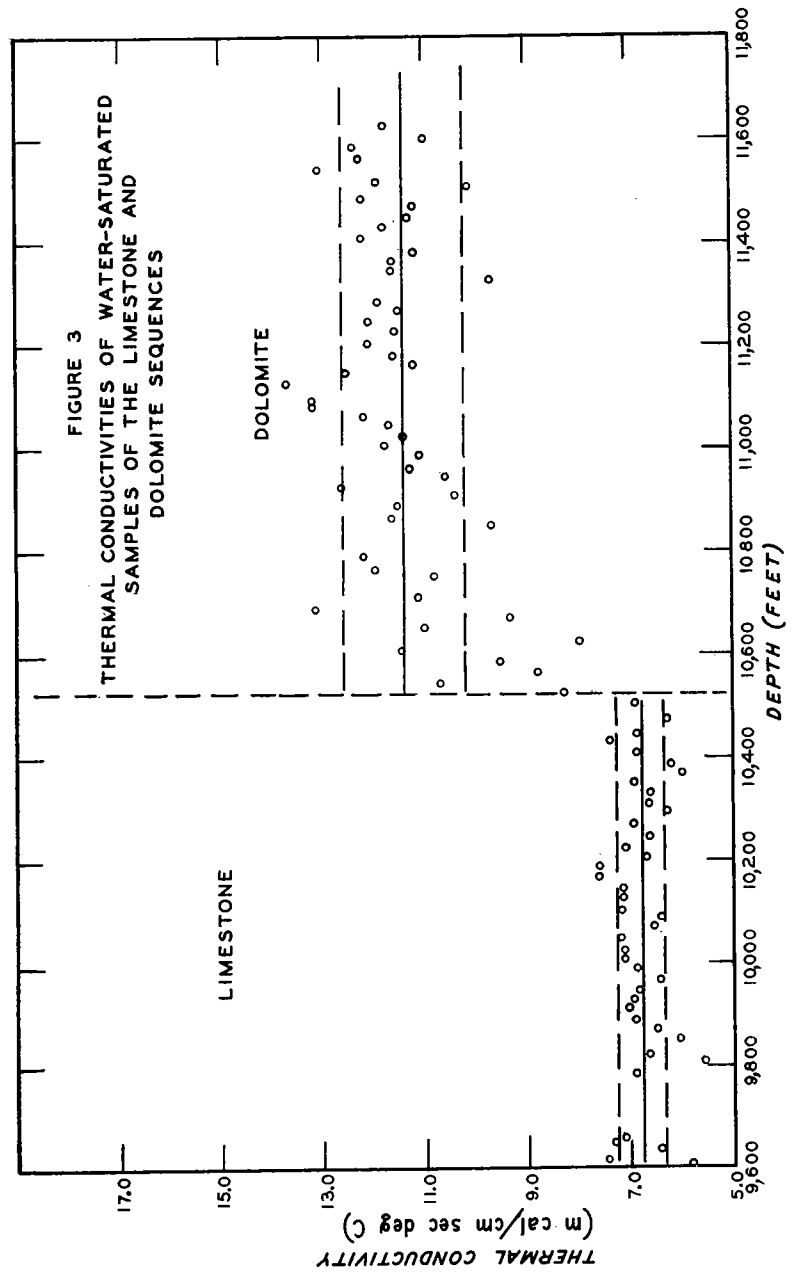


Figure 3. Thermal conductivities of water-saturated samples of the limestone and dolomite sequences.

ing measurements on the same sample. This was done both on dry and on wet samples and is expressed as the difference of conductivity between the two measurements without regard to sign: the mean difference,  $M = 0.22$  mcal/cm sec deg C,  $SD = 0.19$  mcal/cm sec deg C, was found for 20 samples of limestone, and the mean difference,  $M = 0.57$  mcal/cm sec deg C,  $SD = 0.39$  mcal/cm sec deg C, was found for 36 samples of the dolomite. The accuracy indicated by these figures is about  $\pm 5\%$ , and with the calibration error, the absolute accuracy is  $\pm 8\%$ .

Conductivities of the duplicate samples were measured both dry and saturated with water. Only the average conductivities of the saturated pairs are listed in Table 2 because the saturated samples should be more like the rock in place. The conductivities for the limestone and dolomite sequences are plotted in Figure 3, showing the uniformity within and the difference between the conductivities of the two sequences.

In terms of percentage, the scatter in the conductivities is considerably greater than that in the densities; the standard deviation of conductivity (Table 3) for the limestone sequence is 7% of the mean value, and for the dolomite sequence it is 10%; the standard deviations of their densities are 0.4 and 1.6% respectively. As the uncertainty of conductivity measurements is  $\pm 5\%$ , the actual variations in the conductivities are less than these values indicate.

The effect of water in the pores of these rocks is to increase the thermal conductivity; the means and standard deviations of this increase are shown in Table 3. Although the results indicate a water effect in limestone of 4% and in dolomite of 10%, the actual effect probably is between these two, taking the measurement accuracy into account.

The local variation of conductivity might be shown by studying the difference in conductivities of the duplicate disks, which originally were only a few inches apart: taking account of signs,  $M = 0.20$  mcal/cm sec deg C,  $SD = 0.53$  mcal/cm sec deg C, for 35 sample pairs in the limestone sequence; and  $M = 0.37$  mcal/cm sec deg C,  $SD = 1.01$  mcal/cm sec deg C, for 62 sample pairs in the dolomite sequence. In both cases, the presence of local variation is shown by the standard deviations being greater than the accuracy of measurement; statistically, the validity of some local variation is substantiated by the t-test for significance. Apparently the scatter in the conductivities is about the same on the small scale as on the large scale, because the local and long range variations shown by the standard deviations are about equal.

#### ELASTIC MODULI

Dynamic methods of measuring the elastic moduli have

two advantages over static methods: (1) they are non-destructive, and (2) only very small strains are developed,  $< 0.001$ , so that the sample remains in the elastic range. In the two dynamic techniques used in this study, measurements were made of (1) the natural resonant frequencies of vibration, and of (2) the transit time of an elastic pulse in a given length of sample. The samples were tested for transmission of both longitudinal and shear wave motions in order to determine all elastic moduli.

The resonance apparatus used is like that described by Born (1941); it was modified and built by L. Peselnick in his laboratory at the U. S. Geological Survey, Washington, D. C. The method consists in forcing a circular cylinder of rock, about 6 inches long by  $\frac{1}{2}$  inch diameter, into longitudinal or torsional oscillation by an alternating field, coupled electromagnetically to one end of the cylinder, and in determining the fundamental resonant frequency, which is detected at the other end with a sensitive phonograph pickup.

From the frequency measurement of a sample in longitudinal oscillation, Young's modulus may be computed:  $E = \rho(2zfL)^2$  where  $E$  is Young's modulus,  $\rho$  is the density,  $z$  is the length, and  $fL$  is the fundamental longitudinal resonant frequency. Similarly, with a sample in torsional oscillation, the rigidity modulus,  $G$ , may be determined:  $G = \rho(2zfT)^2$ , where  $fT$  is the fundamental torsional resonant frequency. From these moduli Poisson's ratio is calculated:  $PR = \frac{1}{2} \frac{E-1}{G}$

Using high frequency (50 kcy/sec) pulse apparatus designed and constructed for an internal friction study by Peselnick (p. 289-290, 1959), the velocity of longitudinal and of shear waves through the same rock cylinders were determined. The moduli are found from  $G = \rho V^2 S$ ,  $E = G(\lambda + 2G)$  ( $\lambda + G$ ), using  $\lambda = \rho V^2 L - 2G$ , where  $VL$  and  $VS$  are the longitudinal and shear wave velocities respectively, and  $\lambda$  is Lamé's constant.

In addition to the elastic moduli, the internal friction of each sample was measured by determining the frequencies,  $f_1$  and  $f_2$ , at plus and minus  $0.707 \times$  amplitude of the resonant frequency,  $f_0$ , and it is expressed as the log decrement,  $\delta = \pi (f_1 - f_2) / f_0$ . The  $\delta$  represents half the ratio of the energy absorbed per cycle to the maximum strain energy of that cycle (Peselnick and Zietz, p. 286-187, 1959).

The computed elastic moduli are given in Table 2. Fifty-one samples were measured by the resonance techniques, 11 of which were duplicates. Twelve of these 51 samples were measured by the pulse technique.

The mechanical and electronic components used in these measurements are well made and reliable. The frequency measurements are accurate to 0.01%, and the accuracies of

the density and the length are <1%.

The reliability of both sets of apparatus is indicated by comparison of results obtained by pulse and by resonance techniques on the same samples, all with good or fair values of Poisson's ratio. On the average, the pulse values are greater than the resonance values: the mean difference between the measurements of Young's modulus for 12 samples of limestone and dolomite is  $M = 0.03 \times 10^5$  bars,  $SD = 0.53 \times 10^5$  bars, and the mean difference for the rigidity modulus is  $M = 0.07 \times 10^5$  bars,  $SD = 0.30 \times 10^5$  bars. The scatter shown by the standard deviations are about 10% of the moduli, but this uncertainty is small compared to the much larger variation due to inhomogeneity in the rocks, shown by the 10% to 50% variation from good to very poor values of the moduli (Table 2).

Inhomogeneity in physical character is very important in measuring the elastic properties of rock samples. Rocks are aggregates of grains which are often not well bonded, and most laboratory specimens are so loosely compacted that they do not behave elastically according to Hooke's law. Birch (p. 60-62, 1938) found long ago that moduli must be measured on rocks while under hydrostatic pressure < 1,000 bars to obtain reliable values which would be applicable to rocks below the earth's surface. The apparatus used here did not allow the application of hydrostatic pressure, so that only the most homogeneous samples gave good results.

A sensitive measure of the reliability of these measurements is the value of Poisson's ratio, and the data have been divided according to the ratio into four groups, good, fair, poor, and very poor, in Table 4 and Figure 4.

Published data on massive, moderately homogeneous specimens gives Young's modulus as  $7 \times 10^5$  bars and  $9 \times 10^5$  bars for limestone and dolomite respectively, and the rigidity modulus as  $3 \times 10^5$  and  $3.5 \times 10^5$  bars respectively. The good values of the moduli in Table 4 are the highest, and these are about equal to the published figures. The decrease down to very poor values shows the effect of increasing looseness of the grains. Similarly, the values of the internal friction for absorption of wave motion are properly the lowest for the good samples and highest for poor samples. Visual inspection shows an increase in amount of shaly impurity from the good to the very poor samples, although even the poorest ones are quite massive and would not break easily at these inhomogeneities.

The local variation in compactness of aggregation might be indicated by comparing the resonance moduli of 10 sample pairs of limestone and dolomite taken a few inches apart; the mean differences are: for Poisson's ratios  $M = 0.04$ ,  $SD =$

Table 4.—Mean values of elastic moduli of limestone and dolomite sequences.

Quality <sup>1</sup>	Value Type	Young's Modulus (10 <sup>-5</sup> bars)	Rigidity Modulus (10 <sup>-5</sup> bars)	Poisson's Ratio (cm) (cm)	Longitudinal Internal Friction	Shear Internal Friction
<b>Limestone 9,596 ft. - 10,521 ft.</b>						
Good	Mean	7.75	2.98	0.30	0.021	0.007
	SD	0.21	0.04	0.03	0.012	0.002
	N	4				
Fair	Mean	5.58	2.39	0.16	0.031	0.023
	SD	1.28	0.57	0.08	0.018	0.010
	N	6				
Poor	Mean	4.48	2.38	0.15	0.068	0.028
	SD	1.00	0.01	0.19	0.040	0.012
	N	4				
Very Poor	Mean	3.68	2.18	—0.16	0.07	0.03
	N	1				
<b>Dolomite 10,521 ft. 11,631 ft.</b>						
Good	Mean	8.02	3.28	0.22	0.033	0.014
	SD	0.91	0.35	0.02	0.012	0.006
	N	5				
Fair	Mean	7.10	3.14	0.13	0.040	0.032
	SD	0.73	0.33	0.03	0.020	0.013
	N	10				
Poor	Mean	6.46	2.82	0.14	0.052	0.040
	SD	1.39	0.34	0.18	0.023	0.023
	N	4				
Very Poor	Mean	3.84	2.26	0.16	0.068	0.038
	SD	0.50	0.01	0.08	0.029	0.004
	N	5				

<sup>1</sup>Quality designations are based on ranges of Poisson's ratio as follows: Good = 0.18 to 0.36; Fair = 0.10 to 0.18, and 0.36 to 0.44; Poor = 0.0 to 0.10, and > 0.44; and Very Poor = < 0.0.

0.18; for Young's modulus  $M = 0.08 \times 10^5$  bars,  $SD = 1.41 \times 10^5$  bars; for rigidity modulus  $M = 0.02 \times 10^5$  bars,  $SD = 0.29 \times 10^5$  bars; for the longitudinal internal friction  $M = 0.004$ ,  $SD = 0.060$ ; and the shear internal friction  $M = 0.002$ ,  $SD = 0.019$ . There is some indication by the standard deviations that the local variation of looseness of grain aggregation is as wide as the large scale variation given by the standard deviations in Table 4, but the amount of both variations must be much smaller because the errors of measurement are about equal to them, namely about 10% of each modulus.

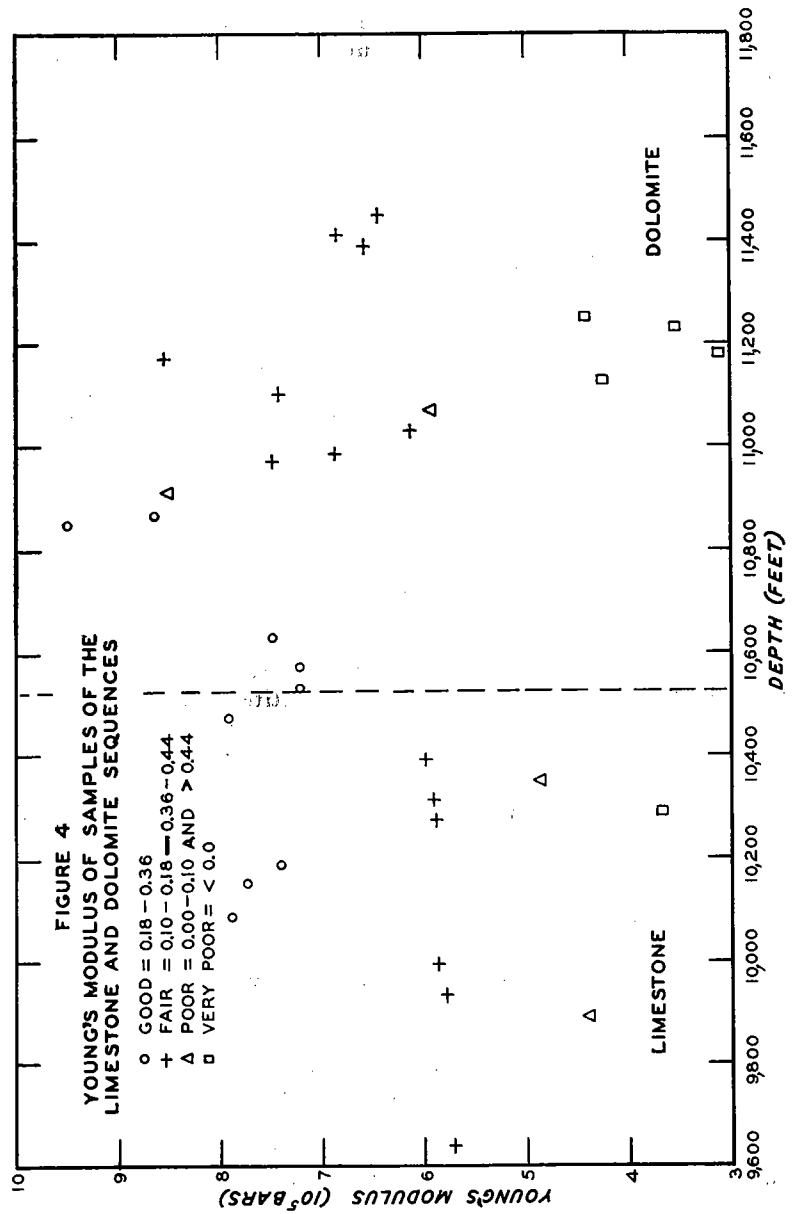


Figure 4.—Young's modulus of samples of the limestone and dolomite sequences.

In general, these meager data indicate that both the limestone and the dolomite sequences are uniform in their elastic properties, but the elastic behavior of these rocks in dynamic tests depends critically on the bonding of the grains. The results appear ambiguous because the rocks are inhomogeneous, but the results can be evaluated by Poisson's ratio because it is a sensitive measure of the perfection of the bonding and the elasticity.

#### MAGNETIC SUSCEPTIBILITY

These carbonate rocks have extremely low magnetic susceptibilities, and the measurements had to be made very carefully. The equipment used is an inductance bridge constructed by J. R. Balsley, U. S. Geological Survey, Washington, D. C., modified to improve the sensitivity from the one described by Bruckshaw and Robertson (1948). The bridge has been calibrated with ferric chloride solutions, and so the accuracy is about  $\pm 1 \times 10^{-6}$  cgs units/cc.

The observations of magnetic susceptibility are listed in Table 2, and the mean values and standard deviations are given in Table 3. Attempts were unsuccessful to find some correlation of the data with per cent.  $R_2O_3$ , insol, and with  $(100 - CaCO_3 - MgCO_3)$ .

In these sedimentary rocks, the source of magnetic susceptibility is either magnetite or hematite, but the amounts of them undoubtedly are quite variable, and not necessarily related to the amounts of the major constituents. The reason is that the amounts of either magnetite or hematite in the rocks must be extremely small.

An estimate can be made of the amounts by assuming the susceptibilities, 0.3 cgsu/cc for magnetite, and 0.003 cgsu/cc for hematite, and by computing from the mean value ( $3 \times 10^{-6}$  cgsu/cc, Table 3), the amount of either mineral that would need to be present. About 10 ppm (parts per million) of magnetite or 1,000 ppm of hematite would be sufficient. Stated in terms of an average of about 5 per cent.  $R_2O_3$ , the mean susceptibility would be observed with 0.01% magnetite in the  $R_2O_3$ , or with 1% hematite in the  $R_2O_3$ .

As the amount of magnetite or hematite is not related to the amounts of major constituents in the rock, the magnetic susceptibility is not diagnostic in differentiating limestone and dolomite nor in determining the amounts of impurities.

#### DIELECTRIC CONSTANT

In these massive rocks with both porosities and maximum water contents  $<1\%$ , the conduction of electricity is predominately by displacement current rather than by ohmic current. The ohmic conduction is quite small for rocks with

< 1% water; the resistivity measurements made on these samples range from 100 megohm cm to 10,000 megohm cm, which could be accounted for by a water content of 0.01% to 0.1%. It is not possible to account for water in these small amounts, so the resistivity values are considered too uncertain and are not tabulated. The displacement conductivity is determined by the dielectric constant, which was measured. A recent discussion of these types of conduction and the measurement of the constants is given by Keller and Licastro (1959).

The dielectric constants were measured in apparatus built by Keller (p. 258, 1959) and his collaborators, U. S. Geological Survey, Denver, Colorado. The apparatus consists essentially of a bridge in which the capacitance of the rock sample is compared with that of air, which has an absolute dielectric constant of  $8.85 \times 10^{-4}$  farads/cm. The accuracy of measurement of the relative dielectric constant is about  $\pm 0.2$ , but water and other undetermined impurities in the rocks caused variations in the constant and reduced the accuracy to an estimated  $\pm 1.0$ .

The relative dielectric constants were measured on the duplicate conductivity disks after drying at  $110^{\circ}\text{C}$ , about half of them at the frequencies, 0.1, 0.5, 5, 10, and 100 kcyc/sec, and all of them at 1 kcyc/sec. Of 89 samples measured at the six frequencies, the maximum difference in dielectric constant was < 1.5 for 69 of them, but a dispersion of 5 to 10 was observed in the other 20 samples.

The average dielectric constant for each disk pair is given in Table 2 and is that measured at 1 kcyc/sec. At this frequency, the dielectric constant in most tests had an intermediate value, at about 60% of the difference from the high value at 0.1 kcyc/sec to the low one at 100 kcyc/sec.

Mean values and standard deviations for the limestone and dolomite sequences are given in Table 3; four measurements, each > 13, were left out as anomalously high. The means agree with the published values for the dielectric constant of 8 to 13 for limestone and about 8 for dolomite.

An estimate of the local variation in the dielectric constant might be made by comparing measurements of the duplicate disks. The mean difference for 21 pairs of limestone is  $M = 0.6$ ,  $SD = 2.7$ , and the mean difference for 41 pairs of dolomite is  $M = 0.6$ ,  $SD = 2.1$ . The local variation shown by the standard deviation is somewhat greater than the long range variation shown by the standard deviations of the means for limestone and dolomite, but both variations are smaller than these figures because the nearly equal measurement error must be considered. Furthermore, the errors of measurement plus the local and distant scatter are large

compared to the difference between the means for limestone and dolomite, so the dielectric constant can not be considered diagnostic for identifying these rocks.

It might be added that although electric logs of these formations would be ambiguous because of similar displacement conductivity in both rocks as shown by the dielectric constant data, this probably would be completely covered up by even more anomalous ohmic conductivity in fractures in these otherwise massive rocks (G. V. Keller, written communication, 1959).

#### GEOLOGIC IMPLICATIONS

The most important observation to be made from this study is that chemical and mineralogical compositions and the physical properties of the two great thicknesses of limestone and dolomite are remarkably uniform; the important geologic implication is that for each rock unit the original sedimentation process and the succeeding metamorphic history also were remarkably uniform. Furthermore, the abrupt change from one rock type to the other shows how completely the sedimentation process was changed. Such close geologic control both of regularity and of change in the original thousands of feet of sedimentation is all the more remarkable in view of the cyclic or widely varying nature of most sedimentary deposition.

The formation of dolomite rock is often ascribed to metamorphism of limestone, but the homogeneity of the thick dolomite sequence studied here is good evidence for its composition being determined by the original sedimentation. The variation around the average  $MgCO_3$  content shown by the standard deviations (Table 3) is small, taking analytical error into account. Such uniformity for a thousand-foot thickness of rock would not seem to be attainable by introduction of magnesium during metamorphism, but rather would seem to be more easily accomplished during the original sedimentary deposition. Although no extensive, Recent deposits of dolomite sediment are known, this is not sufficient evidence to say that such deposits could not have been laid down in the Early Ordovician.

Perfect constancy of these rocks would not be expected in nature, and the descriptions of the core by Harris in this volume seem to reveal considerable irregularity in their lithology. Some evidence of long range variation in compositions and physical properties is shown by the standard deviations around the mean values for the whole thicknesses of the limestone and dolomite sequences, and evidence for an approximately equal local variation is shown by the standard deviations of the differences of measurements on duplicate

samples taken a few inches apart. The errors of measurement of the thermal conductivity, the porosity, and the dielectric constant are only about half the indicated local and long range variations, so these variations while small may be as much as the total error, that is about  $\pm 5\%$  of the measurements. However, the errors of measurement of the compositions, the densities, and the elastic moduli are equal to or much greater than the local and long range variations, so the actual variations in these properties must be much smaller than those indicated. The chemical and physical processing which could maintain such small local and long range variation in the formation of a 1,000 ft. of limestone and a 1,000 ft. of dolomite will not be easily ascertained, but there must have been extraordinary geologic control.

Sedimentary rocks are the end products of the geologic processes of sedimentation and metamorphism, but the processes themselves occur over long periods of time and can not be observed directly. The physical, chemical, and mineralogical properties of sedimentary rocks can be very helpful in understanding their geologic history because the changes in properties in consolidating a sediment from loose particles to a moderately metamorphosed rock is quite large.

The data from this study characterize two well-consolidated sequences of carbonate rocks, at a late stage in the geologic history of such rocks. Comparison of these data with those of similar rocks at other, successive stages of development will give quantitative data for estimating the conditions under which the geologic processes of sedimentation and metamorphism occurred.

#### PRACTICAL APPLICATION

The practical use in the Appalachian Plateau region of a given physical property lies in the closeness of its correlation with geologic formations and thereby with the occurrence of oil and gas. The thermal conductivities of the Ordovician carbonate rocks can be used to differentiate limestone from dolomite very clearly, and this suggests a new exploration technique for use in wells in the region in which cores have not been taken during drilling. As necessary preliminary preparations, measurements would have to be made of (1) the regional heat flow, and of (2) the thermal conductivities of representative specimens of the strata. Then the geologic formations in new wells could be identified by logging temperature at ten-foot intervals or perhaps continuously at a very slow rate, after a delay to dissipate the temperature disturbance due to drilling.

As the flow of heat from the interior of the earth is probably quite uniform throughout the Plateau region, its

determination by measurements at two or three well-sites should be enough to fix its value adequately. To do this, temperature gradients need to be determined in the Ordovician rocks in these wells, if the conductivities of this study are to be used. (The conductivities of other cores plus corresponding temperature logs from higher formations can be used instead, of course.) The product of the temperature gradient by the thermal conductivity of the limestone equals the heat flow; a check would be given by a similar calculation for dolomite. Next, typical samples of the geologic formations need to be obtained, preferably as well cores, for measurement of their conductivities. Knowing the heat flow and average conductivities of the strata, the temperature log from a new well can be used to identify fairly easily all formations 100 feet or thicker. This technique would provide a valuable check of the electric log interpretations.

Taking a temperature log a few months after the drilling has stopped is expensive, but it seems to be necessary in order to measure the normal temperatures. The temperatures should be measured to  $0.1^{\circ}\text{C}$  or closer in order to show the gradients adequately, but attainment of this accuracy is not difficult.

As a demonstration in reverse of this exploration technique, to show how helpful it might be, a temperature log was estimated for the Sandhill well, starting with a knowledge of the geologic formations and their locations in the well. The basic assumption had to be made that the heat flow is  $1.2 \times 10^9$  cal/cm<sup>2</sup> sec, which incidentally seems to be about right. From descriptions of the formations, estimates were made of their thermal conductivities, based on published data for the rock types. With these data and an assumed mean annual temperature at the well collar of  $53^{\circ}\text{F}$ , the temperature at the base of each formation was calculated; these points were connected in the line shown in Figure 5. This operation was surprisingly successful, judging by the agreement with the temperatures actually logged between 4,000 and 7,000 feet in the well, which are also shown in Figure 5. I think this demonstrates that the forward operation of this technique in the field should be very helpful in identifying the geologic strata. The very different average temperature line in Figure 5 shows the importance in this technique of using actual temperatures to determine the temperature gradients accurately, rather than using the mean temperatures from many wells.

Birch (p. 653-655 and Figure 6, 1954) has emphasized the importance of making new heat flow measurements to increase the knowledge of the geophysics of the earth's crust, and he uses as one illustration of this a temperature log from

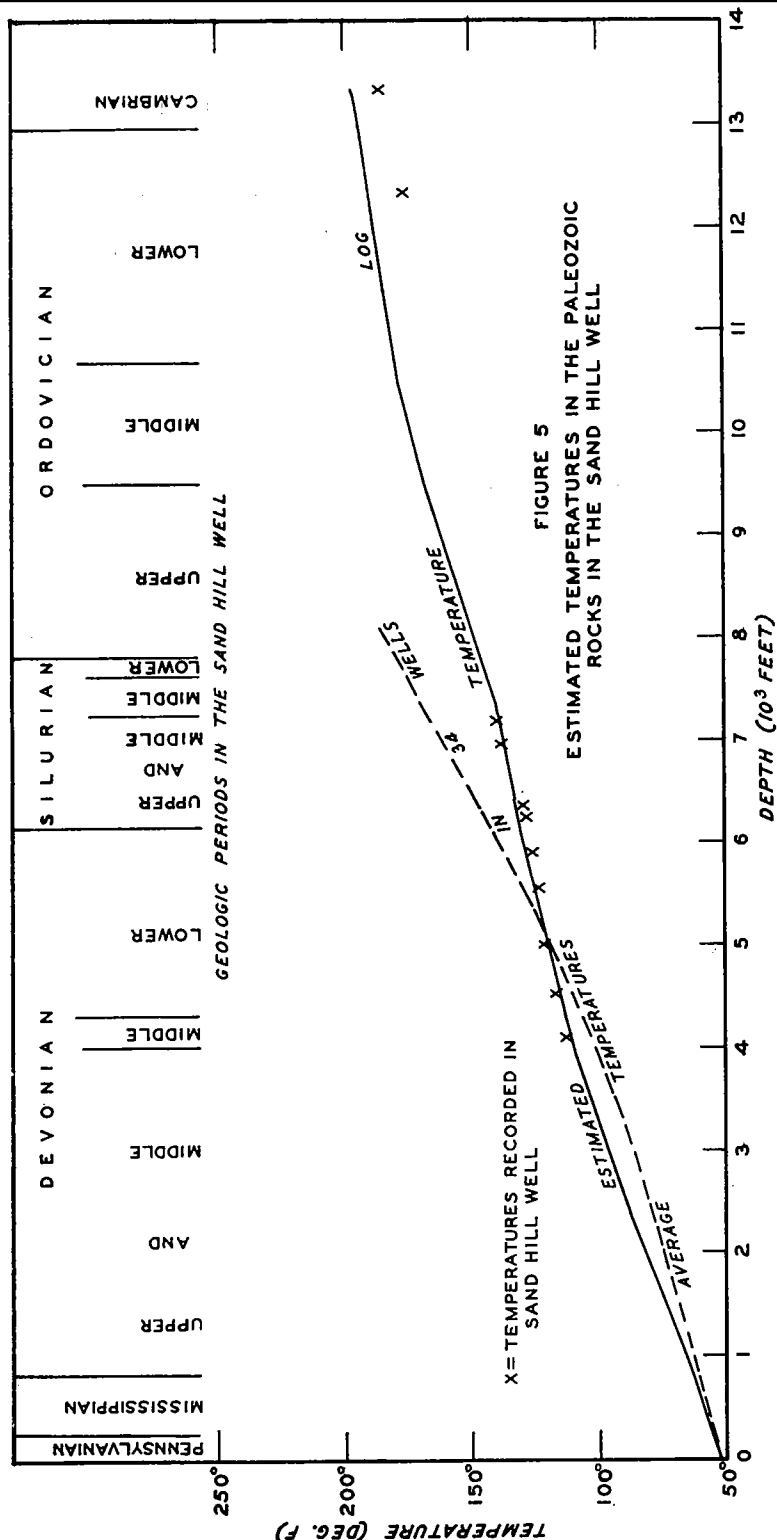


Figure 5.—Estimated temperatures in the Paleozoic rocks in the Sandhill Well.

a well in West Virginia, which needs good thermal conductivity measurements of the rocks before the heat flow computation can be made. Perhaps for practical reasons as well as for scientific ones, several good determinations of heat flow in the Appalachian Plateau will be made.

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# BASEMENT ROCKS FROM THE SANDHILL WELL, WOOD COUNTY, WEST VIRGINIA

By Manuel N. Bass<sup>1</sup>

## ABSTRACT

Pre-Cambrian crystalline rocks were encountered in the Sandhill well, Wood County, West Virginia, at a depth of 13,276 feet. The interval from 13,276 to 13,288 feet may be transported "granite wash," or, more likely, weathered crystalline rock *in situ*. Below 13,288 feet the rocks are probably relatively fresh and in place. The crystallines were cored from 13,314 to 13,331 feet (total depth).

The uppermost part of the core is an amphibolite of monzodioritic composition at least five feet thick and is believed to represent a sill or flow. An essentially identical nine-inch layer occurs between 13,327' 9" and 13,328' 6". The major part of the core (eleven feet) is a gray to red, banded and laminated gneiss of granodioritic to tonalitic (perhaps trondhjemitic) composition, with a few bands of syenite, monzonite, and granite. The gneiss is believed to represent metamorphosed sedimentary or possibly tuffaceous rocks. The structural trend is probably north-south.

The rocks were metamorphosed under conditions of the amphibolite facies. This involved intense shearing, and probably plastic flow along at least one zone in which prominent quartz veins are also found. Retrograde metamorphism led to chloritization and slight carbonatization of amphibole and feldspar. There is evidence for metasomatic effects, especially introduction of potash, so that present compositions are not necessarily those of the original rocks.

Correlation with the basal injection complex of the Blue Ridge Province is considered unlikely. More likely is correlation with Greenville-type rocks to the north-northeast or with subsurface metamorphic rocks of western Ohio and southeastern Michigan. The latter are believed to be an extension of the Greenville subprovince, but could possibly be a south-southeastward extension of the Huronian south of Lake Superior.

The age of the rocks probably exceeds 750 million years.

## INTRODUCTION

The Sandhill well, Wood County, West Virginia, also known as Power Oil Company Well No. 9634, is the only

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well to date which penetrated crystalline basement rocks in West Virginia. The nearest basement wells to the west are in central Kentucky and western Ohio (Fig. 1). No basement tests have been drilled in Pennsylvania, and the westernmost exposures of Pre-Cambrian rocks to the east are in the Blue Ridge of Virginia. The "granite gneiss" from the Sandhill well represents, therefore, the only direct information on basement crystalline rocks in an area of more than 20,000 square miles and as such is worthy of careful study.

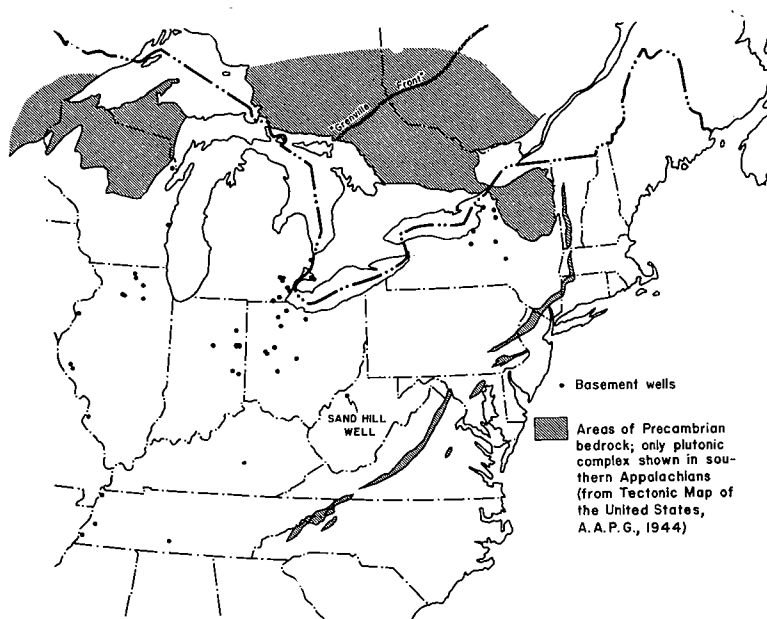


FIGURE 1.--Index map showing location of Sandhill well and other basement wells of the northeastern United States from which basement samples are available.

The gneiss was encountered at a depth of 13,276 feet (corrected depth), and is overlain by arkosic sandstone assigned (by H. P. Woodward) to the Upper Cambrian Mt. Simon Sandstone. The gneiss was cored from 13,314 to 13,331 feet (corrected depths). Some rounded fragments have been reported from the interval 13,276 to 13,314 feet, and there is some question whether part or all of this 38-foot interval is "granite wash." The writer observed no rounded fragments indicating "wash"; however, angular cuttings he observed might well be from pebbles or coarser detritus or even from small pebbles in the arkose assigned to the Mt. Simon. Though feldspar altered to clay was common in samples from below 13,276 feet, weathering was not highly pronounced in com-

posite fragments, and some of the weathered feldspar might be cavings (cavings of sedimentary carbonate were abundant in all samples of cuttings from the questionable interval). Resistivity logs indicate breaks at 13,276' (16" AM) and 13,274' (64" AM). The self-potential log registers a sharp break at 13,288 feet, with fairly constant self potential from there to total depth. The interval from 13,276' to 13,288' would seem to be either transported "wash" or weathered gneiss *in situ*. The latter is deemed more likely. The 43 feet from 13,288' to 13,331' is probably relatively fresh gneiss *in situ*.

The cored gneiss is of a type which would give the cuttings observed in the upper 38 feet, so it is sufficient to describe only the core material. The writer has seen a total of only one foot out of the seventeen feet cored, but Mr. R. E. Bayles (Hope Natural Gas Company, Clarksburg, West Virginia) said that all rock types in the core are represented in the writer's samples. Mr. Bayles, in a letter of March 23, 1956, stated that, "The top 5' 4" of the core carried a high percentage of hornblende . . . . The remainder of the core was a banded gneiss, consisting of alternating bands of a white to pink rock having a high percentage of quartz and feldspar, and the darker hornblende rock." In a letter of August 28, 1957, he stated further that a second nine-inch band of the hornblende rock occurred between 13,227' 9" and 13,328' 6".

The present study consisted of hand-specimen examination, thin-section petrographic examination and binocular microscopic examination of polished surfaces etched with hydrofluoric acid and stained with sodium cobalt nitrate. On the stained surfaces potash feldspar appeared yellow, plagioclase gray, and quartz and mafics essentially unaffected. The texture and mineral percentages, especially of feldspars and quartz, were visually estimated from the stained surfaces and checked in thin section. The stain was sensitive enough to show perthitic and antiperthitic textures, and is assumed to permit a reliable estimation of mode and description of textures. Mafics were distinguished and estimated in thin section. Due to rapid variations in relative mineral abundances, the results of accurate modal counts would not be particularly significant and hardly worth the time consumed. Hence, the reported modes are merely approximations. Plagioclase compositions were estimated from maximum extinction angle of albite twin lamellae in sections normal to (010) index relative to balsam or quartz, and/or 2V and optic sign, all as determined in thin section with an ordinary petrographic microscope.

The writer obtained six separate specimens, four from Mr. Bayles and two from Dr. Charles Milton (U. S. Geological Survey, Washington, D.C.). Three were studied in detail

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The writer obtained six separate specimens, four from Mr. Bayles and two from Dr. Charles Milton (U. S. Geological Survey, Washington, D.C.). Three were studied in detail

as described below. The others are described only as hand specimens and megascopically compared with the specimens treated in greater detail.

#### DARK-GRAY ROCK (AMPHIBOLITE)

Two specimens of this rock were studied, neither of which showed a contact with the banded gneiss. The specimens are massive at first glance, but careful examination of one specimen showed a faint foliation dipping 38°. The specimen has a thickness of two inches normal to the foliation.

The rock is dark-gray to black, equigranular, with an average grain size of slightly less than one millimeter. All visible grains appear xenoblastic.

In thin section and on the stained surface the dominant minerals are hornblende (50%, including chlorite), plagioclase (40%) and potash feldspar (10%, probably microcline). All major minerals are xenoblastic. The potash feldspar is untwinned and often includes abundant minute blebs of plagioclase. Plagioclase (calcic oligoclase or sodic andesine) is untwinned or shows albite or combined Carlsbad-albite twinning. It is rich in antiperthitic blebs, amounting in extreme cases to half the crystal. Hornblende is pleochroic in green to pale brown, and many grains are moderately to highly altered to chlorite, the bluish tinge of which between crossed nicols suggests a penninitic variety. About 1% magnetite is present as xenoblastic grains. One grain has a core of chlorite. Magnetite, partially oxidized to hematite, also forms a discontinuous, irregular veinlet averaging 0.2 to 0.3 millimeter thick. Accessory carbonate replaces hornblende and feldspar. Apatite occurs in accessory amounts as idioblastic stubby prisms and polygons. An almost opaque material, white in reflected light, resembles leucoxene, but minute prisms in the masses suggest a crystalline variety of  $TiO_2$ , perhaps rutile. A veinlet traversing the thin section irregularly is dominantly feldspar, but along its center includes quartz (with a serrate outline), carbonate, and, in spots, chlorite (penninite).

The rock has the composition of a hornblende monzodiorite and was completely metamorphosed under conditions of the amphibolite facies. Retrograde effects altered part of the hornblende to chlorite, and probably account also for the slight carbonate replacement, and at least the carbonate and chlorite in the veinlet.

#### BANDED GNEISS I

The largest specimen of banded gneiss available is about  $5\frac{1}{4}$  inches long. The banding dips for the most part 27° to 30°, but in one band (called A below) the dip of a finer foliation varies irregularly from 13° to 20° in the same direction as

the dominant dip of the specimen. The core was unoriented so strike is unknown. The thickness normal to the foliation is about  $6\frac{5}{8}$  inches. This can be divided into four bands (A, B, C, D) which are described separately below.

#### Band D:

This band is  $2\frac{1}{4}$  inches thick normal to the foliation and is composed of finer, discontinuous folia varying in color from light to medium gray to brownish gray or light pink to red, and in thickness from one to seven millimeters. The finer folia grade transversely into each other.

The stained surface shows a fine-grained aggregate with maximum grain size about 1.5 millimeters, average size less than one millimeter. Other than xenoblastic to hypidioblastic biotite, all grains are xenoblastic. The pure gray folia are composed of approximately 70% quartz and 30% plagioclase; mafics amount to about 2%; accessory potash feldspar occurs interstitially or as antiperthitic blebs. The red folia contain 30-35% quartz, 60-65% potash feldspar (perthitic), 2% mafics, and 0-2% plagioclase; accessories include magnetite, and hematite which fills cracks in quartz and feldspar. All gradations between these extreme types may be found. Quartz is sometimes poikilitically enclosed in feldspar. A quartz vein normal to the foliation contains minor potash feldspar and is about 0.3 millimeter thick.

In thin section the quartz is generally cracked, with bubble trains along the cracks, but shows only mildly undulatory extinction. Potash feldspar is generally clear and untwinned (rare grains show microcline twinning). It is peppered with minute plagioclase blebs, and rarely forms clearly lamellar or chessboard-like perthite. Plagioclase (calcic oligoclase, possibly sodic andesine) is easily recognized only when twinned (fine albite twinning). The antiperthitic blebs are usually irregularly distributed, but occasionally are strung out along alternate lamellae. The mafic is highly pleochroic brown biotite statistically oriented parallel to the foliation. Accessories include magnetite; hematite in cracks and on the edges of minerals; stubby idioblastic apatite prisms; and oval to euhedral, stubby epidote (and zoisite?) prisms.

The red folia are granitic in composition, the gray folia granodioritic, in extreme cases tonalitic (if the plagioclase is oligoclase, the extreme cases are strictly trondjemitic; this same qualification holds wherever tonalite is mentioned). The mineral assemblage is stable under amphibolite facies conditions.

**Band C:**

Band C is medium brown, massive, one to  $1\frac{1}{8}$  inch thick. It is sharply bounded on one side against D, and on the other grades over  $1/16$  to  $1/8$  inch into B.

The stained surface shows a fine-grained mass with a maximum grain diameter of one millimeter and an average size considerably less than one millimeter. It is composed of 75%-85% equant, xenoblastic potash feldspar, the remainder being dark and indeterminate under the binocular microscope.

In thin section the remainder is seen to comprise mostly chlorite (15%-20%). The potash feldspar is untwinned and perthitic. Plagioclase blebs in the perthite are few to moderately abundant, in extreme cases forming half the crystal. The potash feldspar is replaced to a slight to moderate extent by minute flakes of chlorite. Chlorite is a green, non-pleochroic variety. It is crowded with minute flakes and masses of leucoxene, some of which bristle with minute prisms (possibly a crystalline modification of  $TiO_2$ , most likely rutile). The chlorite masses are laced by an anastomosing network of phyllosilicates with a much higher birefringence (up to first-order red) than that of the host. The anastomosing strings extinguish parallel, and in plane light are pleochroic in light green when north-south (indistinguishable from host in this position) and brown when east-west. This material may be a different form of chlorite or remnants of green-brown biotite.

Quartz is very minor (less than 1%). Magnetite is a prominent accessory. Hematite occurs in and between grains. Apatite is rare. Carbonate is a prominent accessory (1%), replacing chlorite and feldspar in irregular patches.

Branching veinlets of irregular width are composed of a microcrystalline, equant to prismatic mineral with refractive indices lower than that of Canada balsam. It may be potash feldspar. A mineral of higher indices comprises about 5% of the veinlets; it occurs in irregular grains with straight edges, giving angular, serrate projections and reentrants (this texture is common in veinlets seen in other varieties of the gneiss, such as the potash feldspar-quartz veinlet in an amphibolite). A hematite stain is concentrated along edges of the veinlet.

This band is essentially syenitic in composition. The mafic mineral prior to retrograde chloritization was probably biotite, to judge from other bands in the gneiss. The extreme retrograde alteration must have been due to compositional instability because the massive nature of the band precludes its having been an avenue of preferred flow of solutions along shear planes.

**Band B:**

By a decrease of chlorite, an increase of biotite, and a slight increase of grain size, C grades into B over a distance of 1/16 to 1/8 inch. The veinlets continue from C into B but are much thinner, more discontinuous, and more irregular in trend. Band B grades into A over 1/4 to 3/8 inch. The width of B is roughly one inch. It is vaguely foliated, the dominant type being black with red spots. This grades laterally into deep-reddish brown, more uniformly colored, discontinuous folia up to three millimeters thick; these folia resemble band C more closely than the dominant type in having more potash feldspar, quartz and chlorite, and less biotite.

On the stained surface under the binocular microscope the rapidly varying mode was estimated at 25%-60% xenoblastic potash feldspar. Magnetite is a prominent accessory, leucoxene and hematite less prominent. The remainder is indistinguishable. The potash feldspar is perthitic. The guest plagioclase occurs usually as irregularly scattered blebs, but occasionally as lamellae or patches giving a checkerboard texture.

Thin section study showed a grain size up to about one millimeter, but averaging much less. Potash feldspar is perthitic and slightly replaced by irregularly distributed chlorite flakes. The extent of the replacement decreases from band C toward band A. The other major constituents are biotite and chlorite. Adjacent to band C they are in subequal amounts. Toward band A the chlorite decreases in relative amount until 2/3 across band B it is essentially gone. The change from C to B is gradational in all respects.

The chlorite is the same as in band C, forming about 15% of the rock near C and decreasing to zero near A. Biotite is brown, xenoblastic to hypidioblastic, often twisted or bent, and statistically oriented parallel to the foliation. In some folia it is interleaved with quartz. It is generally replaced from a few up to 20% by hematite (original replacing mineral uncertain), and frequently more than 75%. The extent of hematite replacement decreases somewhat from C toward A.

Xenoblastic quartz in small grains forms 2%-3% of band B.

An almost opaque accessory material, white in reflected light, is seen under high magnification to consist of minute stubby prisms with high birefringence and inclined(?) extinction. It is probably a modification of  $TiO_2$ . Apatite occurs in large idioblastic crystals some of which are almost comparable to the main constituents in size. Accessory carbonate replaces chlorite, feldspar and biotite.

Plagioclase is an accessory on the side near band A;

it apparently has the same composition (calcic oligoclase or possibly sodic andesine) as in band D.

#### Band A:

Several distinct sets of folia are included in this  $2\frac{1}{4}$  inch band, all of which are characterized by a dip of only  $13^\circ$  to  $20^\circ$ . In places the layers immediately adjacent band B have the same dip as B, but for the most part the layers of band A dip at a distinctly lower angle, the surface of discordance being essentially the zone of transition ( $\frac{1}{4}$  to  $\frac{3}{8}$  inch thick) from B to A. This zone is not marked by a fracture or fault nor any other mechanical discontinuity, rather only by a change of composition and dip of folia.

Roughly the first inch to  $1\frac{3}{8}$  inch of band A (the part adjacent B) is composed of irregular layers two to five millimeters thick, which are discontinuous over distances of one to two inches more or less. The layers have sharp to gradational lateral boundaries. The dominant color is light to medium red, the darker bands resembling megascopically the transition zone from B. A minor part is light gray in color and, together with the light-red material, resembles band D.

The etched and stained surface reveals a fine- to medium-grain size, averaging about one millimeter. All grains are xenoblastic except biotite which varies from xenoblastic to hypidioblastic. The extreme compositions, between which intermediate compositions are not well represented, are as follows. The light-red and gray folia contain 70%-90% plagioclase, the remainder being quartz except for about 1% interstitial potash feldspar. Plagioclase is antiperthitic, the inclusions being often distinctly lamellar. The medium-red bands contain roughly 50% to 90% potash feldspar, negligible to 50% plagioclase, 3-5% quartz, and 2-6% biotite. Potash feldspar is generally not noticeably perthitic, though a few grains are flecked with plagioclase blebs and some crystals are lamellar perthite. Magnetite was the only visible accessory.

In thin section the potash feldspar is seen to be abundantly peppered with plagioclase blebs. Several crystals or parts of crystals show microcline twinning; such crystals are non-perthitic. Plagioclase is calcic oligoclase. Biotite is brown, hypidioblastic to idioblastic, and highly pleochroic. In bands relatively rich in biotite it is slightly to moderately replaced by or intergrown with hematite. Quartz is slightly cracked and frequently slightly to moderately strained. Some grains show thick Boehm lamellae. Accessories include abundant large hypidioblastic to idioblastic apatite crystals, magnetite, carbonate replacing feldspar, and leucoxene (rutile?).

The thin section also shows minute veinlets composed of quartz and minor potash feldspar and chlorite. A hematite stain is concentrated along the edges. The veinlets roughly parallel the foliation but in detail are irregular in trend and thickness.

The terminal layers in the core specimen, comprising the 7/8 inch of band A opposite band B, are two quartz veins separated by a seven millimeter deep red band. One quartz vein is three millimeters thick; the other is broken, but its original thickness was at least one centimeter. The quartz veins contain potash feldspar. The deep-red layer contains abundant biotite extensively replaced by hematite. It also encloses large microcline augen, one of which is a lens 5/8 inch long and 1/4 inch in maximum thickness. The microcline is flecked with minute plagioclase inclusions, and is replaced to a very minor extent by carbonate. The large auge contained a trace of muscovite. Petrographically the deep-red band is very similar to the darker parts of band B. The grain size of the red band and quartz veins varies from fine to coarse and perhaps averages in the medium-grain size range. All grains are xenoblastic except biotite which is sometimes hypidioblastic.

Though superficially similar to band D, only the gray to light-red layers and lenses of band A resemble D compositionally. They are tonalitic to dioritic in composition. The medium to deep-red layers are similar to band C in their relatively high ratio of potash feldspar to plagioclase, their low quartz content and replacement of biotite by hematite. Their composition varies over small volumes from syenitic to monzonitic.

The discordance in dip of band A is not due to post- or late-metamorphic shearing or faulting, and is unlikely to be a relict sedimentary or igneous structure in such highly metamorphosed rocks. It probably developed contemporaneously with metamorphism by a process of plastic flow and/or lateral secretion into a low pressure zone which transgressed the main foliation at an angle of 10° to 15°, an interpretation supported by presence of quartz veins. The potash feldspar-bearing quartz veins are better explained by lateral secretion, whereas the remainder of band A would appear to have been emplaced by plastic flow.

## BANDED GNEISS II

In a second specimen of banded gneiss the foliation dips uniformly at 60°. The specimen is 4 1/2 inches thick normal to the foliation. All except a 5/8 inch band is composed of alternating, fairly continuous and uniform gray and pink layers

from three to at least 35 millimeters thick. Each of these bands is composed of moderately distinct laminae on a scale from two to less than one millimeter thick. In gross aspect these layers resemble closely those layers of similar color in band D of specimen I, and lack only the darker red portions of D. On a stained surface grains up to three millimeters diameter are seen, but they average one to two millimeters (medium-grained); this is coarser than band D of specimen I. In thin section the present specimen is seen to contain traces of muscovite and has much more abundant microcline-twinning potash feldspar and perhaps less quartz on the average than band D. The composition is probably granodioritic to tonalitic with little if any true granite.

The 5/8 inch band mentioned above is included between layers having the description immediately above. This band is very similar to band C of specimen I, but is reddish rather than brown, somewhat coarser (maximum grain size three millimeters, average one to 1.5 millimeters), and has more abundant microcline-twinning potash feldspar and no carbonate. This band resembles band B of specimen I in the presence of a few per cent. of hematite apparently after biotite (only one small crystal of green pleochroic material was seen which might be remnant biotite). The composition is syenitic. Retrograde alteration probably accounts for the abundant chlorite.

### BANDED GNEISS III

This specimen of banded gneiss was studied only in hand specimen. Its foliation dips uniformly 45°. It is 2¾ inches thick normal to the foliation, and is composed of continuous and uniform bands which are alternately light pinkish gray and medium or dark pinkish gray. The bands vary from one to 21 millimeters thick, and the thicker bands are finely laminated on the order of a fraction of a millimeter to 1.5 millimeters. The major bands are relatively sharply bounded against each other. Megascopic comparison indicates a similarity to the grayer layers of band D, specimen I. The pinkish tinge suggests the presence of a small amount of microcline, whereas the dominant minerals are apparently quartz and plagioclase. The only recognizable mafic is biotite, which varies from zero in the lightest bands to about 50% in very dark laminae. The core is bounded by two biotite-rich laminae which are apparently surfaces of weakness. Notable is a faint lineation almost in the dip direction along these two surfaces, a lineation determined by shape orientation of inequidimensional light and dark materials.

The composition is probably granodioritic to tonalitic, and differs from all other specimens examined of like com-

position in the presence of laminae rich in biotite and in the dominant gray rather than pink color. At first glance the biotite-rich laminae might be mistaken for amphibolite.

In an attempt to orient the core in order to determine the strike of the foliation, the writer submitted this specimen to Dr. Lynn G. Howell (Houston Research Center, Humble Oil and Refining Company). His measurements of remanent magnetism showed the magnetization oriented along the axis of the core barrel, a result neither surprising nor useful. Therefore, excluding the unlikely coincidence of the true direction of magnetization with the core barrel axis, the core can not be oriented by this method.

#### GNEISS IV

This small core specimen is a uniform light grayish pink, finely laminated but not banded, and with foliation dipping 60° or slightly more. It probably has a granodioritic composition.

#### SUMMARY OF PETROGRAPHIC RESULTS

The basement rock from the Sandhill well is a "granite gneiss" only in the broadest sense. In specimens available to the writer, the dominant rock type is granodioritic to tonalitic; considerably less abundant is a syenitic type, while monzonitic, dioritic and granitic bands are very minor or rare. These rocks are fine- to medium-grained, and composed of microcline (generally perthitic, uncommonly microcline-twinned), plagioclase (oligoclase-andesine; generally antiperthitic, commonly twinned on the albite law), quartz (highly variable in amount, unstrained to quite undulatory), and biotite (the only mafic silicate other than chlorite, and frequently replaced by hematite). Accessories include magnetite, hematite and apatite with lesser carbonate, leucoxene (rutile?) and epidote.

The amphibolite has a monzodioritic composition. It is now composed of green to pale-brown hornblende (extensively chloritized), oligoclase-andesine and microcline. The accessories include magnetite, hematite, apatite, carbonate and leucoxene (rutile?).

#### ORIGIN AND METAMORPHISM

The amphibolite belongs to the amphibolite mineral facies, and the mineral assemblages of the banded gneiss, allowing for retrograde effects, are stable too under the conditions of this facies. Retrograde effects include chloritization of hornblende and feldspar; replacement of hornblende and feldspar by carbonate; development of leucoxene (rutile?), probably as a result of release of  $TiO_2$  from biotite during

chloritization; and rare replacement of microcline by muscovite. Replacement of biotite by hematite (original mineral may have been magnetite) might have occurred under amphibolite facies conditions or during retrograde metamorphism.

Veinlets indicate that the constituents of quartz, carbonate, chlorite and potash feldspar were mobile. The veinlets probably formed under retrograde conditions.

The 5' 4" at the top of the core and the nine inches lower down of dioritic or monzodioritic amphibolite reported by Mr. Bayles suggest original flows or sills of intermediate composition. Mr. Bayles stated that amphibolite also occurred interbanded with white to pink layers of the banded gneiss. The writer's studies failed to reveal such interbanded amphibolite in the four specimens of banded gneiss he examined. Though the presence of interbanded amphibolite is not hereby excluded, its absence would support an interpretation of the thicker amphibolite masses as igneous bodies in that it is difficult (though not impossible) to imagine intrusion or extrusion of dioritic magma on the scale of the banding in the gneiss. On the other hand, small masses of dioritic rock might have been drawn out into narrow bands during shearing; however, this is inconsistent with the almost massive appearance of the thicker amphibolites and their apparently competent behavior. The biotite-rich bands of banded gneiss specimen III might be mistaken for amphibolite on casual examination. Tentatively, therefore, the writer assumes that the thicker masses are the only amphibolite encountered in the well. They are interpreted as originally flows or sills, the thicker exceeding five feet.

The recent trend is to interpret gneisses of the type here studied as granitized sedimentary rocks. Among the criteria for such an interpretation are composition, structure and evidence for replacement. The banding of the gneiss immediately suggests an original layering, perhaps sedimentary, modified by shearing, high temperature and pressure, and metasomatism. That granitization (essentially feldspathization in its early stages) was operative is suggested by the highly varying proportions of potash feldspar and plagioclase in the perthite and antiperthite, indicating replacement, unmixing of original mixed feldspar (or feldspars) or more uniform composition, or both. Either alternative involves mobility of some or all constituents of feldspar, and the presence of potash feldspar veinlets suggests that potash was relatively more mobile than soda. The source of the mobile constituents might have been within the original rock, from a relatively restricted mass around the site of replacement, or from sources far removed. There is no evidence at hand by which to judge the extent to

which the system was open or closed. Some of the potash in the veinlets might have been released during chloritization of biotite. The evidence indicates that metasomatism was an active process, though its extent can not be estimated.

The writer is inclined to interpret the banded gneiss as a granitized sedimentary or tuffaceous rock. The bands and laminae might or might not coincide with original sedimentary layering; they might be parallel to but non-coincident with such layering; or they may not parallel original sedimentary structures. The last interpretation is regarded as least likely. The present composition would suggest a relatively acid arkosic sandstone. However, not knowing the types of material introduced or removed during possible metasomatic alterations, neither a relatively basic rock (graywacke or tuff) nor an alumina-rich argillaceous sedimentary rock is excluded.

Likewise, in ignorance of the extent of metasomatic effects, the original composition of the igneous rock can not be estimated. If its potash was largely introduced, it might originally have been dioritic, possibly, though less likely, gabbroic.

It is unknown too whether the dominant trend during metamorphism of the banded gneiss was in the direction of homogenization or differentiation or neither. The relatively sharp boundaries between bands of widely varying composition in rock subjected to such intense metamorphic conditions would suggest either little lateral transfer of material across the boundaries of the bands, or a tendency toward differentiation. The biotite-rich laminae of banded gneiss specimen III may reflect mechanical differentiation of biotite onto surfaces of intense shearing, thus possibly accounting for the essentially down-dip lineation in these laminae.

#### AGE AND CORRELATION

The author measured a rubidium-strontium age on biotite from banded gneiss specimen III at the Department of Terrestrial Magnetism, Carnegie Institution of Washington. The result,  $940 \pm 20$  million years, is within the range found for Grenville rocks of Canada (Wilson, et al., 1956, p. 354-357) and the Adirondack Mountains, and for the Baltimore gneiss and old crystalline rocks of the Blue Ridge (Tilton et al., 1958). On the basis of lithology and this age measurement, the Sandhill basement rocks are correlated with rocks of the Grenville and Blue Ridge Provinces. Further age measurements will be made to confirm this correlation.

#### CONCLUSIONS

Basement rocks encountered in the Sandhill well were metamorphosed and granitized under conditions of the am-

phibolite facies. The dominant types are banded gneiss of granodioritic to tonalitic (perhaps trondjemitic) composition with intercalated syenitic, monzonitic and granite bands, and amphibolite of monzodioritic composition. The banded gneiss is believed to be of sedimentary origin, while the amphibolite may represent intercalated flows or sills of intermediate composition up to more than five feet thick. The grain of the basement is probably north-south. On the basis of lithology and rubidium-strontium age of 940 million years, the rocks are correlated with those of the Grenville Province.

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# STRUCTURAL INTERPRETATIONS OF THE BURNING SPRINGS ANTICLINE

By Herbert P. Woodward

## GENERAL STATEMENT

The Burning Springs Anticline is located in the eastern portion of the Eastern Interior Plateau, where it separates what have been called the Pittsburgh and Parkersburg (or Huntington) Coal basins that otherwise would be continuous in a northeast-southwest direction. The fold is not central either to the present Appalachian structural basin or to the ancient Appalachian sedimentary basin, for it lies on the west flank of both depressions<sup>1</sup>.

It is not a typical "Appalachian Mountain" fold by comparison with the position and trend of familiar folds of the eastern mountain belt. Nor is it a typical "foreland" fold, as it differs both in sharpness of folding and also in trend from the low undulating structures of the Allegheny plateau to the east. Indeed, its acuity and N-S trend clearly separate it from almost all other structures in the region. (Figure 1). This difference will later be seen to extend also to the structural complexity of the fold below ground.

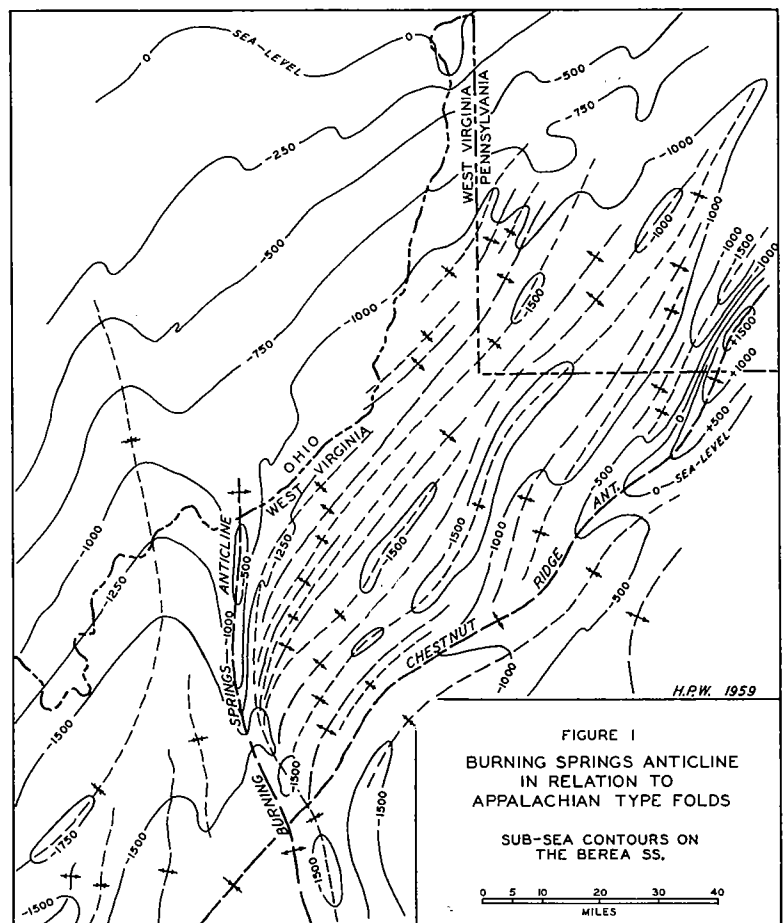
Some geologists have extended the Burning Springs Anticline into either the Cambridge arch or into the Chaseville Anticline, both of which trend northwest in southwestern Ohio; but the exact surface indications of such extensions are not completely identified. In the other direction, the fold may continue south of Chestnut Ridge Anticline into the Mann Mountain Anticline of south-central West Virginia, which also maintains a north-south trend. If so, the Burning Springs axis should cross Chestnut Ridge and some doming effect should be expected where the two folds intersect. None such is yet known from surface evidence, and the degree of kinship between the Burning Springs Anticline and the Mann Mountain structure has not yet been entirely established.

Northeast of the Burning Springs Anticline in north-

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<sup>1</sup>For recent general descriptions of the Appalachian basin as a whole, see:

- a. Lafferty, R. C., Central basin of Appalachian geosyncline; Bull. Amer. Assoc. Petroleum Geologists, vol. 25, pp. 781-825, 1941.
- b. Fettke, C. R., Oil and gas developments in the Appalachian basin, past and present; Bull. M37, Pennsylvania Topo. and Geol. Survey, 1953.
- c. Woodward, H. P., Some problems of the deep Appalachian basin; Amer. Petroleum Institute, Proc. for 1954, pp. 68-80, 1955.
- d. Woodward, H. P., A review of the deep Appalachian structural basin; Trans. New York. Acad. Sci., vol. 17, ser. II, pp. 83-98, 1954.



central West Virginia, there are a number of small folds that parallel the Chestnut Ridge structure in a northeast-southwest direction. These smaller folds plainly die out against the Burning Springs Anticline, and they do not reappear west of it. Indeed, on a map showing all folds of the region, the Burning Springs Anticline is seen to be shadowed to the west by an area wherein small Appalachian foreland folds are absent or are greatly subdued.

There is both surface and subsurface indication that the anticline has been considerably faulted, but reliable dimensions can not yet be given to these breaks. Probably those reaching the surface have small displacements; those crossed by the well have much greater magnitude. Surface indications suggest high-angle faults with planes inclined toward the

east. The log of the well being studied suggests a much more complicated fault pattern, for it is clear that the bed-rock can be separated into three segments, as follows:

- A. Surface (elevation 1,050' A.T.) to depth 4,022' (top of the Huntersville Chert). This portion of the well passes through flat or nearly level strata on the crest of the anticline. Save for the steep anticlinal slopes a half-mile away on either side, there is no internal indication of deformation, effective distortion, or other dislocation.
- B. Between 4,022' and a top of the Oriskany Sandstone at 5,865', a distance of 1,843 feet, the section is visibly disturbed. There are indications of steep dips, repetition of key beds, faulting, and dislocation of strata. From regional relations and other wells near by, the true thickness of this interval can be estimated as 185 feet; hence this segment is 1,658 feet thicker than normal.
- C. From 5,865', top of the Oriskany, to the bottom of the Paleozoic section at 13,272', the record shows rocks that are essentially level with no indication of any critical deformation.

Obviously the 1,658 feet of thickening in Segment B is a result of deformation, but it is significant that this increase almost precisely matches the observed closure on top of the anticline, as mapped by structure contours on the Washington Coal. As the overthickening of strata and the height of the fold can thus be equated, it is reasonable to believe that they are genetically related. One may conclude, as Segment C is completely undisturbed, that localized crumpling and thrusting within Segment B has somehow thickened the rocks of that segment above an undisturbed basement, with the result that Segment A, also unaffected by crumpling, was sharply arched upward to the same vertical amount that Segment B was thickened. In short, anticlinal arching of the top of the fold is no more nor any less than that needed to compensate for the thickened bed-rock section. (See Fig. 2).

The mathematics of this situation can be pursued further, and the following table condenses the critical figures:

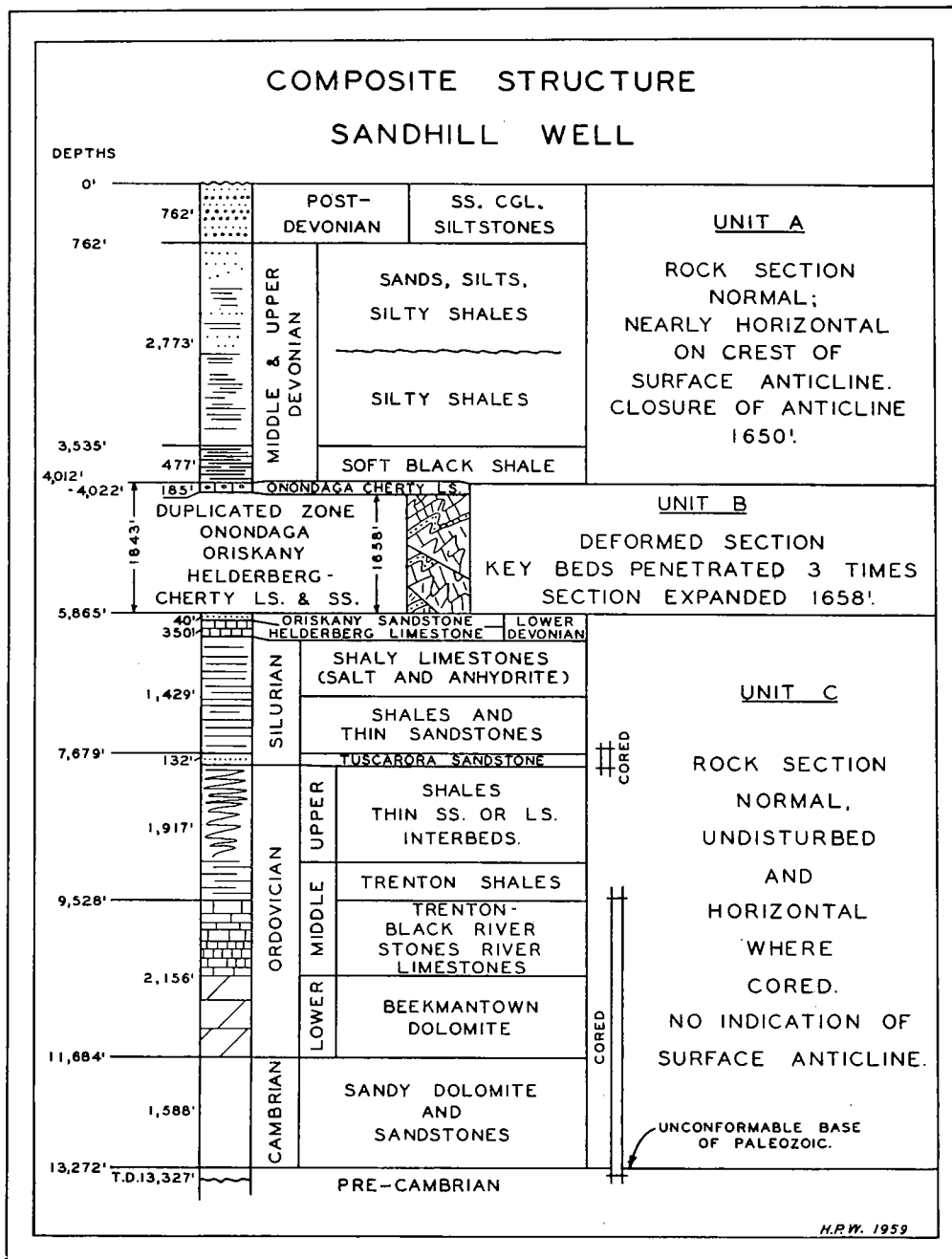


FIGURE 2

## Comparative Elevations on the Oriskany Surface

Intervals or elevations	10 miles	Sandhill	10 miles
	West	Well	East
Elevation, Washington Coal	525' A.T.	2400' A.T.	850' A.T.
Elevation, Berea Sandstone	-1618' A.T.	288' A.T.	-1218' A.T.
Berea-Huntersville interval	2900'	3260'	3600'
Elevation, top Huntersville	-4518' A.T.	-2972' A.T.	-4818' A.T.
Thickness, Huntersville	175'	185'	195'
Excess thickness, Segment B	—	1658'	—
Elevation, top of Oriskany	-4693' A.T.	-4815' A.T.	-5013' A.T.

This table compares the elevation of the Oriskany Sandstone in the Sandhill well with computed elevations of the same horizon beneath the shallow basins that lie about 10 miles east and 10 miles west of the Burning Springs Anticline. Allowance is made for a regional eastward increase of the Berea-Huntersville interval, and for a slight thickening of the chert itself. The significant point is the congruence of elevations on the Oriskany surface and the apparent disappearance at depth of any major trace of the sharp Burning Springs Anticline. There is an expectable rise of the bed-rock toward the west (i. e., toward the Cincinnati Geanticline), but the surface flexure seems to have vanished as a critical structure at levels below the Oriskany Sandstone.

One can challenge these data in several ways. First, it is possible to assume that Segment B is also thickened in the marginal basins, a situation that would restore the anticline at depth; but this hardly seems in keeping with the known surface habit of these basins. Second, one can question the writer's selection of 5,865' as a reference point for these calculations. Yet analogous figures are derived if any other horizon below 5,865' is used as a reference point and one ends up with the same conclusion as that evinced by the present table, namely that no marked arching is apparent in Silurian or older strata. Third, one can assume that although the well probably descended vertically, the anticlinal axis may have slipped downward laterally, so that the crest of the fold below 5,865' could be east (less likely west) of the hole. This reasoning surely requires crossing a zone of steeply inclined rocks on one flank of the fold as the well descended from the surface high to a position entirely off the structure; but the disturbed zone in question seems not to be of this type.

Finally, one can argue that the anticlinal arch contains keystone faulting, with a central graben-like trough developed along the crest of the fold. It is true that such structures are found at Oriskany levels in many foreland folds of New York and northern Pennsylvania; but it has already been indicated that the Burning Springs axis is not such a fold. More devastating to this argument is the necessity for the trough of the graben to be completely level and to have dropped exactly the

amount that the unfaulted arch must have risen. There remains, therefore, the surprising possibility that the Burning Springs Anticline—at least in the form of its surface appearance—may not be maintained to great depths.

The writer has not seen any of the seismic maps or other geophysical data that have been developed for this fold. He has been told, however, that the seismic picture does not appear to support the theory that the fold is essentially shallow, and that the seismic image is that of a structure folded all the way to the basement. Such a seismic profile is one that might be normally expected, for the geophysical work preceded the deeper drilling, and there was then no reason to anticipate that the well itself would suggest a shallow fold. It may be prudent to reshoot the structure as a check on the geophysical interpretation.

As matters thus stand, structural interpretations made from the well itself do not confirm earlier interpretations of reflections detected by geophysical means, and until more information is available it is difficult to reconcile the conflicting data. It is even possible that both sets of interpretations are partly correct; but it would be premature to prolong the present discussion until more tangible evidence turns up.

Another matter, however, is worthy of consideration in this connection. The writer has previously studied thicknesses of many beds that cross the surface fold, with an eye to determining whether or not any of them show a thinning that would reveal the presence or movement of the fold while the sediments were being laid down. Once he thought the Catskill facies (absent on the anticline itself) extended around it; now he thinks the red beds do not anywhere reach west to this longitude.

Both Heck and the writer have independently mapped a thinning of the Greenbrier-Berea interval across the fold, but both sets of data come from drillers' logs that are not too reliable. Indeed, as various Devonian and younger Silurian rocks are examined, no clear-cut indication of any thickness change can be established where these beds cross the anticlinal axis.

Such a thinning does seem to occur in the Tuscarora Sandstone which is forty to fifty feet, or about one-third, thinner than it should be in this well—at least as interpreted by Woodward. If this estimate is right, then there was, in fact, an ancient structural line at the point where the Burning Springs Anticline is now located. Probably it was a broad low arch in Tuscarora time, having a small positive impetus that elevated it slightly before early Silurian time began or immediately thereafter so as to permit non-deposition or erosion of some part of the sand.

One can not be more specific at this point, but an analogy can be found in western New York where a similar ancient structural line, with thinned basal Silurian sandstones, extends in a roughly north-south direction starting at Lake Ontario a short distance west of Rochester, and extending at least as far south as Geneseo. The line is there offset to the west by about 10 miles, but it can be traced south with the same trend into eastern McKean County of northern Pennsylvania. The interesting part of this analogy is that there, too, in surface rocks of Devonian and Silurian age, occurs a parallel sharp fold or fault that continues the southern offset northward, passing near Clarendon and Batavia.

This feature was examined in the field by the writer and G. H. Chadwick<sup>2</sup> in 1919 long before the underlying Tuscarora trend-line was suspected. It is now regarded by Woodward as an ancient structure having a trend inherited from the basement complex; thus it is a partial counterpart of the Burning Springs fold.

In a significant paper of 1922, Ruedemann<sup>3</sup> conceived the grain of the Pre-Cambrian basement under the Eastern Interior to run roughly east-west; this writer, nevertheless, has always assigned to it a general north-south strike. A recent provocative article by D. B. McLaughlin<sup>4</sup> adds strong confirmation to the north-south hypothesis, for he suggests the existence of a buried line of Pre-Cambrian deformation that trends west of south from the Grenville area of Ontario to the Mississippian Embayment.

McLaughlin thinks this belt was the site of an ancient mountain range that was uplifted, invaded by Killarney granite, eroded, and perhaps peneplaned. He reasons that such an orogenic belt typically develops a deep "root" of sialic material that is persistently buoyed up by the underlying sima while being reduced by erosion. The Cincinnati Dome, the Findlay Arch, and the Nashville Dome were alternately shallowly submerged and slightly exposed above the sea throughout the Paleozoic Era, while areas to the east and west more consistently sank and received thicker deposits of sediments. McLaughlin believes that the Grenville orogeny may have been an ancient sponsor of these anticlines which continued to rise isostatically or, at least, refused to sink as rapidly or as fully as the basins on either side.

<sup>2</sup>Chadwick, G. H., Large fault in western New York, *Bull. Geol. Soc. America*, vol. 21, p. 117-120, 1919.

<sup>3</sup>Ruedemann, Rudolph, The existence and configuration of Pre-Cambrian continents; *N.Y. State Museum Bull.*, Nos. 239-240. pp. 65-152, 1922.

<sup>4</sup>McLaughlin, D. B., Suggested extension of the Grenville orogenic belt and the Grenville front; *Science*, vol. 120, No. 3112, August 20, 1954, pp. 287-9.

The present writer concurs with much of this hypothesis, and believes that a persistent positive behavior characterized the line of the Cincinnati Geanticline, with an origin buried deep in Pre-Cambrian history. A north-south grain, he believes, was very early impressed into the crystalline basement of the Appalachian and Eastern Interior regions, later to be effective in controlling the site of early structures developed overlying Paleozoic sediments.

Such an inheritance, the writer believes, was responsible for the early existence and orientation of such low positive folds in Lower Paleozoic rocks as the basement arch along the site of the present Burning Springs Anticline, the deeply buried arch at Clarendon, New York, the so-called Tazewell-Adirondack axis, and others yet to be discovered. Intermittent elevation along these ancient lines was responsible for their continuation and for various sedimentary and younger structural features connected with them. The energy responsible for the uplift was a type of kinetic energy imparted during the events experienced by the sites in question.

In short, he postulates a low but definite anticlinal uplift along the line of the present surface fold, and he believes this uplift was sufficiently positive to affect early Paleozoic sedimentation. For example, this line could have been competent to prevent early and middle Cambrian rocks from crossing it from the east. In consequence, the western edge of some of these beds may now lap upon the eastern flank of this deeply buried arch, with appropriate facies development. On the other hand, as west-derived sands of the late Cambrian do cross the fold, there must have been epochs during which it had little or no sedimentary effect.

If he is correct in regarding the Tuscarora Sandstone to have been influenced by this fold, then there is the distinct possibility that basal Silurian sands may likewise show deep favorable facies development on the east side of the ancestral Burning Springs Anticline rather than on the present crest of a younger arch.

Gradually, he believes, the positive energy that was locked along the line of the anticline in the Pre-Cambrian basement ran down, and at some early Devonian time, probably before the Oriskany was deposited, the axis became relatively inert, but not until the roots of the Burning Springs Anticline had been definitely established. Doubtless the Taconic revolution near the close of the Ordovician was responsible for some rejuvenation or uplift of the Pre-Cambrian trend-line.

Lockett<sup>5</sup>, who associates the Burning Springs Anticline

<sup>5</sup>Lockett, J. R., Development of structures in basin areas of northeastern United States; Bull. Amer. Assoc. Petroleum Geologists, vol. 31, pp. 429-446, 1947.

with the northwest-trending Cambridge arch in eastern Ohio, has developed the ingenious theory that subsidence of the Michigan and other basins set up tensional strains while developing the Parkersburg-Lorain trough; the latter more or less connects the Michigan and Huntington Basins in a northwest-southeast direction. He postulates cracking or fracturing of the basement floor with "step-faults" directed northwestward. It is quite possible that a trend was thus developed that would orient the north end of the ancestral Burning Springs Anticline in that direction. Nothing presently known to the writer indicates that this could not have occurred.

Obviously, however, none of the matters so far discussed was responsible for the present sharp surface flexure along the Burning Springs axis. As early Permian rocks are folded, deformation must have occurred late in the Paleozoic, but as previously mentioned, this fold does not assume the customary northeast-southwest strike of most late Paleozoic folding, nor does it compare in dimensions or habit with such folds. It is obviously of a different type.

As the Chestnut Ridge-Warfield Anticline, one of the foreland-type folds, appears to cross the trend of the Burning Springs axis, one might conclude that the latter was an earlier structure. This writer does not hold this idea and regards the surface-visible fold at Burning Springs as one of the youngest of all of the structures in the region. As a matter of fact, he finds himself wondering if the sharp flexure may not be another structure unexpectedly dated in the early Triassic, and belonging to the same orogenic generation as the Lackawanna Syncline in northeastern Pennsylvania<sup>6</sup>.

In any event, he is convinced that both the mechanics of this fold and the time of its production are different from those of other structures in the region. He suggests that the type of force which produced the true eastern Appalachian folds and the broad open foreland folds—all with a northeast-southwest orientation—did not create this fold, either at the same general time or in the same fashion.

He thinks that the force was differently directed—in this case in a westward direction along the horizon of the resistant Helderberg-Oriskany-Huntersville sequence. He thinks the circumstances suggest a slight westward shift of the entire eastern area, the rocks of which, he believes, were already folded by the Allegheny Revolution. He regards the surface folding at Burning Springs as a sharp buckle that developed in this brittle limestone-sandstone-chert sequence above a relatively undisturbed floor and below weak Devonian shales.

<sup>6</sup>Woodward, H. P., Structural features of the northeastern Appalachian basin; *Bull. Amer. Assoc. Petroleum Geologists*, vol. 41, p. 1429-1440, 1957.

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He suspects that the fold developed swiftly, doubtless with some lateral shearing that sliced along the broken limestone and chert. At any rate, with its origin, location, and initial orientation patterned or buttressed by the low basement arch, this younger flexure struck northward and folded sharply in contrast to the normal regional pattern.

Details of this hypothesis can be considerably amplified, but enough has been outlined to give a broad picture of this concept of the history of the fold. The writer thinks the Burning Springs Anticline is of two generations: (a) a low early structure initiated by the grain of the Pre-Cambrian basement, revived by the Taconic Revolution, and possibly accentuated by later sagging of the deep basins of thick Paleozoic sedimentation, and (b) a much later flexure, sharply and rapidly developed by thrusting carried westward at this longitude by the rigid early Devonian rock section.

One of the curious features that has been discovered in the commercial development of the "mountain-type" Oriskany gas fields (as at Terra Alta, Accident, Summit, Gladly, and others) is that there is a zone of acute deformation at the general Onondaga-Oriskany-Helderberg level which is not visible at the surface. This middle-depth zone of deformation has been penetrated in the Sandhill well, where an undisturbed rock section is found below it. This raises the possibility that deeper wells in these other Oriskany gas fields might possibly pass down below the zone of deformation into undisturbed rocks, as at Sandhill.

If so, then there may well be a wide-spread zone of middle-depth deformation that has heretofore been unknown as an attribute of Appalachian basinal structure. Obviously the matter needs further study as it might have considerable economic significance as well as geologic importance.

In this connection, the writer has always made a mental comparison between the strongly faulted pattern discovered at Oriskany level in the gas fields noted above, and the broken surface pattern of highly faulted Triassic rocks in southeastern Pennsylvania and New Jersey. He suggests that very little is yet known about Triassic deformation save where Triassic rocks themselves have been visibly disturbed, and again he wonders if this post-Paleozoic deformation may not be reflected below ground in the main Appalachian basin.

In terms of such a hypothesis, then the Burning Springs Anticline differs from nearly all other Appalachian foreland folds because it is a surface expression of deformation elsewhere blanketed below ground level—perhaps by the plastic Marcellus Black Shale.

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# DRILLING APPALACHIAN AREA DEEP WELL TO THE BASEMENT ROCK

By Donald M. Corbett  
Superintendent, Southern District,  
Hope Natural Gas Company

The present paper was first presented before the Oil and Gas Division of the Engineering Society of Western Pa. at a meeting held at Marietta, Ohio April 29, 1955. The paper has been only slightly modified for publication.

Mr. Chairman, gentlemen of the Engineers Society of Western Pennsylvania, students and guests, it is my pleasure and privilege to present to you a brief account of Hope Natural Gas Company's Deep Test Well at Sandhill, Wood County, West Virginia.

On May 3, 1951 execution of the plan of the Hope Natural Gas Company for a deep test at Sandhill began when the C. F. Engle Drilling Company of Gassaway, West Virginia, commenced cable tool spudding operations. The plan was fully completed on February 19, 1955 when Pre-Cambrian rock was encountered at a depth of 13,300 feet.

A project of this kind must have a purpose. Hope's purpose, in general, was fourfold.

1. To obtain production of gas or oil in economic quantities.
2. To determine the presence and extent of adequate source beds.
3. To determine the presence and extent of porous and permeable reservoir beds.
4. To obtain other geological and engineering data necessary for future deep development in the Appalachian area.

The well location was made on the Burning Springs Anticline, approximately 14 miles east of Parkersburg, along U. S. Route 50.

The drilling operation was, of necessity, divided into two phases, cable tool and rotary.

The equipment used in the cable tool phase consisted of a standard 85-foot, 5½-inch angle iron cable tool derrick, with 6-inch rig irons. As an added safety feature, an extra brake wheel was installed on the outside of the tug wheel. The derrick was rated for a 244,000 pound load limit. The corners were set on cross ties, cribbed solid on the low side to a height of 10 feet. The cross tie corners were used in preference to solid concrete because they provided a more resilient foundation.

A 10 x 10 x 10 foot cellar was dug to accommodate the subfloor equipment such as casing spools, adapters, hangers

and control gates. The cellar was floored with reinforced concrete, 30 inches thick to provide ample support for the casing strings. The walls of the cellar were of reinforced concrete 10 inches thick. A reinforced concrete pad, 4 feet wide and 30 inches thick, extended from the top of the cellar wall to a point beyond the Samson post, and supported the nose end of the main sill.

The rig was equipped with a 6-sheave crown block consisting of 4 casing sheaves, one sand sheave and 1 crown pulley, an Oil Country chain-driven, sidewalk-type sand reel, a 7/8", 6 x 19 plow steel, left lay drilling cable, a 9/16" right lay wire sand line. Power was supplied by a model 170 Riise drilling rig motor.

Approximately 30 days were spent in clearing and grading the location, building the road, digging and cementing the cellar, erecting the derrick and rigging up.

With sights set on 10,000 feet a 20 inch hole was spudded in and the well was on its way.

The drilling progressed in the 20" hole at an average rate of about 55 feet per day. Substantial flows of fresh water were encountered in a red sandstone at depths of 65 feet and 111 feet. This water was cased off at 213 feet when 16" line pipe was welded together, run in the hole and cemented to the surface. The Big Lime was struck at a depth of 226 feet and the drilling rate decreased to about 40 feet per day.

The first of a series of drilling difficulties was encountered in a hard lime formation at a depth of 1195 feet, at which point the tools began to lead off the vertical, causing a crooked hole to be drilled. This condition was corrected by filling back with rock and junk, cementing and re-drilling. Due to the extreme hardness and dip of the formations it was essential that the bits be kept out to full gauge at all times, and the drilling motion be watched constantly for any indication of the tools leading off down dip; consequently the forge and drilling crew were in constant heat.

An average drilling rate of 70 feet per day was maintained to a depth of 1955 feet where a mixed string of 54.5 pound J and H grade 13-3/8" O.D. casing was run on a shoe, and cemented with 80 bags of cement. A 13-3/8" x 36" foundation ring, bearing on the cellar floor, was installed, to which was flanged a 13-3/8" bottom casing housing.

To insure a maximum recovery of pipe, the hole was first cleaned of drill cuttings and cavings by circulating with aquagel. A cement pump truck was engaged for this and all subsequent cementing operations.

In spite of all precautions, severe caving conditions developed at 2700 feet while drilling through a section of black, gray and brown shales streaked with sand and lime

shells. These conditions worsened progressively and, at a depth of 3975 feet, it became necessary to shut down and cement the cave. Two weeks later and at a depth only 40 feet greater, crooked hole trouble developed in the Onondaga Lime, of which the top was found at 4015 feet. Successive shots of gelatin in amounts up to 150 pounds were used to straighten the hole. An extremely hard chert formation under the lime plus heavy flows of salt water, struck at 4035 feet, added to the difficulties. Progress could only be made by shooting about every ten feet with gelatin.

At 4215 feet a bit was lost in the hole, and another bit was lost while attempting to drill by. All efforts to recover or drill by these tools failed, and on January 2, 1952, after 3½ months of fishing, the Hope released the contractor and assumed the task of cleaning the hole.

It was decided to cement the hole back to a point in the brown shale, at a depth of 3944 feet, set a whipstock and drill by the tools. Under the immediate supervision of Mr. W. L. Davis, Hope's fishing superintendent, a 45-½-foot whipstock, the longest ever run in a hole to that date, was designed by Mr. Davis, and fabricated from a solid bar of steel by the Spang Company of Butler, Pennsylvania. This stock was cemented in the hole, and the drilling-by process commenced. By keeping the bits perfectly round and to full gauge, by frequent dressing, the drilling-by job was successfully completed in 27 days.

Due to excessive amounts of salt water, again encountered at 4035 feet, and concern over the possibility of the whipstock slipping in and plugging the hole, it was decided to run casing. A string of 9-5/8" O.D., 40 pound, J, 8 R.T. casing was run on a steel shoe at a depth of 4059 feet, cemented with 100 bags of cement and hung in the 13-3/8" x 10-3/4" casing-head housing with a 13-3/8" x 9-5/8" casing hanger. A 13-3/8" x 9-5/8" casing head spool was installed, to which was flanged a 9-5/8" full opening flanged end master gate valve.

Specially designed alloy steel bits made by the Acme Fishing Tool Company of Parkersburg, West Virginia, were obtained to run in the 9-5/8" casing.

Extremely hard cherty formations and heavy flows of supersaturated salt water, encountered 19 feet below the casing, combined to slow the drilling rate to an average of 6 feet per day. Additional salt water at intervals of 169 feet, 187 feet and 247 feet below the casing further slowed the drilling rate. The Oriskany Sand was topped at a depth of 4307 feet and, after penetrating this sand 38 feet, to a depth of 4345 feet, it became apparent that the cable tools would soon reach their limit. The heavy salt water, which filled

the hole to within 1100 feet of the surface and defied attempts at lowering, so hampered the drilling motion that progress all but ceased. Despite these handicaps it would have been possible to drill the Oriskany Sand, shut off the water with 7" casing and continue drilling. But any additional water sands encountered would have necessitated the running of 5½ inch casing, which would so reduce the hole as to make progress with cable tools well-nigh impossible. With these thoughts in mind, it was decided to cease operations. On April 11, 1952, 343 days after spudding in, the cable tool phase of the deep test well came to an end.

With a new goal set at 12,500 feet, the Hope began laying plans to complete the deep test with rotary equipment. Contacts with the South Penn Natural Gas Company, the United Fuel Gas Company, The Manufacturers Light and Heat Company, and The Columbian Carbon Company resulted in an agreement for "dry hole" financial assistance from these companies in return for complete information. The next step was to secure the proper equipment and personnel. The Falcon Seaboard Drilling Company of Tulsa, Oklahoma, with whom Hope had previous experience, was selected for the job.

The use of an oil-emulsion base mud in preference to a water base mud was indicated because of its greater ability to control caving in the expected long shale zones, and its greater flexibility in controlling the unexpected.

The mud was composed of aquagel, baroid, diesel oil and water. The aquagel provided the qualities necessary to suspend the drill cuttings, form a filter cake to wall the hole and protect productive formations, and the viscosity and gel strength necessary to prevent the weight material from settling out. The baroid provided the weight material necessary to control high pressure productive zones.

The physical and chemical properties of the mud were controlled by the addition of many ingredients, i.e.: Carbonox, used as an emulsifier and mud thinner; anhydrox, used to overcome the harmful effects of anhydrite and gypsum contamination; Hydrotan, used for the alkaline-tannate treatment; Driscose, used to control the filter loss; Fibertex and Micatex, used to overcome circulation losses; and Caustic Soda and Soda Ash, used to maintain the desired P H concentration. The mud program used approximately 507 tons of dry ingredients, plus 2,494 barrels of diesel oil, plus water.

Due to the exploratory nature of the operation and the importance of obtaining correct and complete information, it was decided to engage the service of a well logging unit. This unit proved its' worth many times over. Manned by an excellently trained and competent crew of three, and

equipped with a myriad of instruments, it literally followed the bit down the hole. The following are some of the data supplied by the unit:

1. A continuous formation lithology log from the drill cuttings and core samples.
2. A continuous graph of the drilling rate and depth.
3. A continuous drilling mud analysis indicating the mud weight, viscosity, filtrate and salinity, the presence of oil by ultra violet ray, and the presence and amounts of methane and other gaseous hydrocarbons by a hot wire gas analyzer.
4. A continuous graph of the drill cuttings showing the presence of oil, the presence and amounts of methane and other gases and the presence and per cent. of porosity.
5. A complete record of all bit types and changes, drill stem tests, number of pump strokes per minute, shut downs and other rig operations.
6. Watchdog for possible blow outs.
7. A complete core analysis.

With the completion of these preliminary plans, work was resumed on June 2, 1954, two years and 21 days after the cessation of cable tool drilling.

To accommodate the equipment and prepare for rotary drilling it was necessary to enlarge and level the original location. A site approximately 270 feet long and 150 wide was bulldozed out of the hillside. A reserve pit 300 feet long by 120 feet wide by 8 feet deep was excavated in the hillside opposite the location to contain the discarded drilling mud and drill cuttings. An earthen dam was built upstream of the location to impound the water so essential to this type of operation. Two water wells were drilled and equipped with submersible electric pumps; to be used as an additional source of supply in case of a dry season. Earthen mud pits were not needed, for the rig was equipped with three steel mud tanks 30' x 8' x 6', with a capacity of approximately 250 barrels each. A bunk house, complete with beds, cooking and heating stoves, icebox and other furnishings, was installed to accommodate the tool pusher and other supervisory personnel. An electric power line was strung in from the Monongahela Power Company's line to provide A.C. current to operate the water pumps and other accessories not connected with the rig.

On June 12, 1954 the Ada Rig Company of Ada, Oklahoma moved in their derrick and commenced its erection. A foundation mat of timbers was carefully laid to support the derrick corners and substructures. The derrick was the standard 8" angle iron deep hope rotary type, 136 feet high, with a 30-foot base, and capable of suspending 15,000 feet of 4½", 17-lb. drill pipe.

The rig was equipped with three 350 H. P. Waukesha

motors, compounded to power the type U-20 water cooled air operated draw works, and chain driven rotary table. The motors were equipped with small Westinghouse air compressors and electric generators for rig use. One 175 H. P. Waukesha motor, equipped with a fluid drive torque converter to prevent drill pipe twist-offs, was used to operate (or drive) the rotary table during most of the drilling. A 7½ ton, 5-sheave Bethlehem "Gumbo Buster" traveling block and hook assembly was used to handle the drill pipe and casing. Two duplex slush pumps, a 20" x 8" Gardner-Denver and an 18" x 7½" Wheland, were used interchangeably to maintain constant mud circulation. Their capacity could be varied by changing liner sizes or rate of operation. Two 10,000-pound test Cameron ram-type blowout preventers were flanged to the well head, the upper one equipped with positive shut off rams and the lower one with rams to shut off around the drill pipe. National Tube 4½" O. D., 16.6 lb. drill pipe with Hughes "Full Hole" tool joints was used throughout. The drill pipe tool joints exposed to the open hole were banded with a hard facing material to prevent excessive wear. The drill pipe exposed to the well casing was equipped with rubber rings to prevent damage to the casing. Thirty-foot, 6¼" O. D. Baash-Ross drill collars provided the weight necessary for drilling and the rigidity necessary to drill a straight hole. A 1¼" drilling cable was used throughout.

The rigging up operation presented many problems new to this area. Equipment weighing as much as 60 tons had to be handled safely, and positioned accurately. To raise this equipment through the 12 feet from ground to derrick floor it was necessary to build a ramp of four 7" x 20" x 43' steel I-beams suitably braced with welded pipe, and floored with 3" oak lumber. The loaded trucks were then backed up the ramp with the aid of winch lines, and the equipment snaked into position. A 20 ton crane, 3 bulldozers, a boom truck and three five-man drilling crews, plus substantial help from the men of Hope's Southern District and General Teaming Department finished the job in 18 days.

At midnight, July 16, 1954 the drill pipe was started in the hole. Four drill collars, a set of Bowen hydraulic jars, a junk basket and an 8-5/8" Hughes W-7-R, 3-cone rock bit comprised the bottom section of the string. To condition the hole for drilling it was necessary to displace 3,000 feet of salt water with drilling mud and circulate out what junk might be found on bottom. A Totco Drift instrument pumped down the drill pipe showed the bottom of the hole to be 3-1/3° off the vertical.

The first few days of drilling were devoted to experimenting with such factors as weight on bit, type of bit,

rotary speed and pump pressure and speed. The Oriskany Sand was not easily drilled with standard rock bits, but by using Hughes R-1 bits with tungsten carbide button inserts it was possible to maintain, for the first 200 feet, an average drilling rate of 2 feet per hour, and an average footage of 26 feet per bit. The hard and abrasive Oriskany Sand presented the economic and mechanical problem of making the most full gauge hole with the least number of costly button bits. New bits were being worn out of gauge before reaching bottom. A three roller, side hole reamer placed above the bit contributed much toward solving this problem.

The hard cherty lime formations found between 5700 and 6150 feet were drilled with Hughes R-1 button bits; Hughes W-7-R Conventional rock bits, and Reed 4 cone button bits. Runs as high as 96 feet per bit with an average drilling rate of 5 feet per hour were made. However, the average for this type of formation ran about 30 feet per bit and 27 minutes per foot. The shaly dolomites encountered at 6700 feet were drilled with conventional rock bits, Hughes W-7 R & W7, averaging about 75 feet per bit and 15 minutes per foot. The red and green shales found at 7800 feet were drilled with longer toothed 3-cone rock bits; the Hughes O.W.S. and O.W.C. These bits averaged 135 feet per bit and about 10 minutes per foot. The best runs were made in a limy shale formation around 9200 feet where the Hughes O.W.S. bits cut as much as 320 feet per bit at a rate of 6 minutes per foot. The crystalline dolomites from 12,000 to 12,990 feet were drilled mostly with Hughes R-1 bits which averaged 65 feet per bit and 25 minutes per foot. A total of 6,425 feet of 8-5/8" hole was drilled with 114 rock bits for an average of 56 feet per bit.

The drift, or degrees off vertical, was kept within a range of from 1° to 4° throughout most of the operation. This was accomplished by careful and constant attention to drilling weight and rotary speed, and by the use of a stabilizer placed at varying distances above the bit. This was a remarkable achievement considering the type and thickness of formations penetrated.

One of the outstanding features of the whole project was the seven months of continuous rig operation with practically no down time due to mechanical failure. This was made possible mainly by the foresight, planning, know-how and constant attendance of the tool pusher, Mr. C. P. (Chet) Necessary of Elk City, Oklahoma. It is difficult to conceive the well being successfully completed to a depth of 13,331 feet without the benefit of his experience and conscientious direction.

The coring program, as set up in the original plan, was

performed by Drilling and Service, Inc. of Dallas, Texas, who furnished the diamond core bits and 50-foot core barrels, also an engineer to service the equipment and advise on operating technique. The coring was done with 8½" O.D., Truco diamond bits, cutting a 4-3/8"-core. The highly fractured and extremely hard formations made it difficult to cut and recover a full core at every run. The intermittent nature of the coring and drilling program caused many extra trips with junk baskets and magnet to clean the hole of lost rock bit teeth, buttons and bearings. These clean-up trips were necessary, since one piece of metal could ruin a diamond bit costing from \$3,300 to \$4,200. A magnet was usually inserted in the bottom of the core barrel to pick up stray metal. This magnet rose in the inner core barrel as the core entered. Despite the many difficulties encountered, 2,568 feet of core were cut and recovered by 25 bits, averaging 103 feet per hour.

The suspected producing formations, encountered while drilling, were tested by Halliburton's drill stem testers, using Halliburton's formation testing equipment. This equipment is run on the bottom of the drill pipe in a closed position. An anchor packer, set above the testing point, segregates the section to be tested from the rest of the well. The testing tool valve is then opened and only the fluids from the isolated section can enter the tool. The quantity, quality and pressures of the formation fluids are obtained by testing at the well head, by direct measurement of fluid contained within the drill pipe and by recording instruments incorporated in the testing tool. The risks involved in running drill stem tests at great depths, such as stuck drill pipe, blow-outs and test failures, have been greatly reduced by improvements in equipment and technique, but they are still present and must be considered when testing is planned.

In order to avoid missing any valuable information during the drilling operation, the well was thoroughly logged by Schlumberger Services. These services included Electrical logging, Micrologging, Gamma Ray logging, Neutron logging, Section Gauge logging and Photoclinometer and Temperature surveys.

The final stage of the operation consisted of plugging back to a predetermined depth, casing the well, displacing the drilling fluid and testing suspected productive zones. A Baker, electrically set, mechanical plug was set and topped with 50 bags of cement. A combination string of 7" O.D., 26-pound and 23-pound N 80 grade casing, with non-upset long A.P.I. threads and collars was run and cemented at 9126 feet. The string was designed and run as follows: 1927 feet of 26-pound on top, 4,202 feet of 23-pound in the middle and 2997 feet of 26-pound, with a guide shoe and cement collar on

bottom. Each section of the string was separately designed to equal or exceed the specifications necessary for its particular depth. Air operated power tongs, applying a uniform 4,200 foot-pounds of torque to each joint, made it possible to run some 434 joints of casing in the excellent time of 13 hours.

A Halliburton multistage cementing tool was inserted in the string at 7212 feet to make possible the planned two-stage cementing job. The bottom 500 feet of the string was first cemented with 90 bags of uniflow cement. The multistage cementing tool was then activated by specially designed bomb plugs and the string was again cemented with 100 bags from 7212 feet to 6330 feet.

A 6¼"-bit, run on a string of 3½" E.U., 9.3-pound, N-80 Hydril tubing, was used to drill out the cement plugs and prepare the well for testing. The 9.8-pound drilling mud was displaced with fresh water. The open hole below the casing was then tested by lowering the fluid level with swab and bailer. As no production resulted, the lower hole was filled with mud and a second Baker mechanical plug was set below the 7" casing. The formations behind the lower cemented section of the 7" casing were tested by gun perforating. The results being negative, the well was abandoned in accordance with State specifications.

The rotary phase of the operation drilled and tested 8,986 feet, and was completed in 8½ months.



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## ECONOMIC ASPECTS

By O. L. Haught

Petroleum Geologist, W. Va. Geological Survey

**Cost.**—The Sandhill well was extremely expensive. The total cost has not been made public, but may safely be assumed to exceed \$750,000. It is certain, however, that a subsequent well of like depth could be drilled in the same general area much more cheaply—perhaps for little more than half the cost of the Sandhill well. It must be remembered that this well was, indeed, a regional “wildcat”. It was drilled through rocks that had never before been penetrated in the central part of the Appalachian basin. For this reason, the operator utilized services and took extra precautionary measures which would hardly be necessary in a second test. Mr. Corbett’s paper on the drilling operations clearly indicates the nature of and the need for many expensive factors of this test which should be avoidable in future deep drilling in this vicinity. Among these are most of the cost of drilling mud, that of continuous mud logging, of drill stem tests, and of nearly all coring. This is on the assumption that air drilling will be practicable in the lower Paleozoic section of the Appalachian basin, which seems almost certainly true, provided that excessive amounts of water are not encountered in permeable vuggy zones of dolomite.

A considerable part of the cost of this well resulted directly from the repeated strong flows of salt water encountered in the lower Devonian section. As detailed in Mr. Corbett’s paper, the upper of these flows were shut off with casing, but others were encountered almost immediately below the casing shoe. Considerable hole was drilled with cable tools under these conditions, though such tools will operate satisfactorily only in a hole free from any great amount of water. After the rotary equipment had been installed, the salt water made it necessary to drill with mud rather than with air. The cost of the oil emulsion mud used is evident from the details of the amounts of materials used in its preparation, given in Mr. Corbett’s paper. Use of a rather heavy mud as a drilling fluid involved the possibility of missing potentially productive zones, and made necessary expensive and somewhat risky drill-stem tests of promising intervals.

The technique of rotary drilling has been developing so rapidly during recent years that it is certain that the future deep tests in western West Virginia will be drilled by methods and with tools somewhat different from those used in the

Sandhill well. However, the lithology of the lower Paleozoic formations in this region is such that they will always present problems for drilling other than those encountered in drilling the much younger and softer rocks found at comparable depths in the Gulf States. Here in the Appalachian region, the main problem is likely to be simply that of **drilling** — of getting reasonable footage at a reasonably rapid rate from each bit, in order to reduce the number of times the tools must be pulled and the bit changed. Every “round trip” at depths of over two miles involves hours of delay, during which no hole is made.

A drilling program for future deep tests in this region might be set up on the assumption that there is little chance of encountering much water between the bottom of the Big Injun (or of the Squaw) Sand and the top of the Oriskany. Casing could be set through the Big Injun and the well drilled with air from this point at least to the Oriskany Sand, probably even farther in case little or no water were found in this sand.

**Data of value in regard to regional prospects.**—Though the Sandhill well was not a producer, prospects for Ordovician or Cambrian production in the Allegheny synclinorium have been somewhat improved through information obtained from this well, especially when taken in conjunction with the records of the J. W. Heinzman well, located in Roane County, and of the F. D. Caldwell well (permit Wayne-465), which was drilled during 1947-1948, at a location about 110 miles southwest of the Sandhill well. Both these wells were drilled by the United Fuel Gas Company, with cable tools. The Heinzman well, drilled during 1930-1931, reached a depth of 9,104, and penetrated about 140 feet into the middle Ordovician Trenton Limestone. No shows of oil or gas were reported from any horizon below the Tuscarora Sandstone (“Clinton”), but, to judge from the records of both the Caldwell and the Sandhill wells, the Heinzman well did not reach the more promising Ordovician zone. The Caldwell well, though not so deep as the Heinzman, reached considerably lower stratigraphic levels than did the latter, as it was drilled through 3,650 feet of Ordovician beds, to a point 736 feet below the top of the Knox Dolomite. Numerous good shows, indeed, easily measurable amounts, of gas were recorded at various horizons towards the bottom of this well, especially within the Knox. In the Sandhill well too, the best shows of gas were found in lower Ordovician dolomite. In fact, shows seem to have been noted in this section wherever the rocks drilled had measurable permeability of any kind. However, these dolomites seem to be almost without intergranular permeability, but zones of vuggy permeability were en-

countered in the Sandhill well at depths between 11,238 and 11,326 feet, with a measured maximum of 2,760 millidarcies. As seems to have been the case in the Caldwell well, these zones also showed a high degree of connate water saturation.

The presence of gas in the lower Ordovician sections penetrated in both the Caldwell and the Sandhill wells has only confirmed deductions that had long previously been made from known facts of regional paleogeography and sedimentation—namely, that the Cambrian and Ordovician Systems are represented in the Appalachian plateau region by fairly thick marine sections, the rocks of which, wherever sufficiently porous, contain hydrocarbons. To many people, however, the actual presence of gas in a single drilled section is more convincing than any number of favorable deductions, no matter how well based. The one is proof positive that gas is “there”; while the other only shows that gas ought to be “there”.

The numerous good shows of gas found in the Knox Dolomite in both the Caldwell and the Sandhill wells show clearly that the Knox is a promising formation for gas production, especially if structural highs can be located in this deeply buried rock body. In fact, the results of the two wells indicate that sufficient structural relief may well be the one requisite of commercial production from the Knox. As permeable zones were found in the formation in both wells, it is probable that such zones are a general feature of the Knox, rather than merely local phases.

Questions of nomenclature are not important in the discussion of regional prospects for deep production as affected by data obtained from the Sandhill well. However, it might be mentioned that the term “Knox,” now greatly out of favor with many stratigraphers, is used here as the simplest and clearest designation for the thick mass of dolomite found in the early Ordovician, and perhaps the latest Cambrian, section of this region. A name is but a label, and “Knox” seems to be the most convenient label we can find for the easily recognized rock body in question.

Absence of sedimentary rocks older than later Cambrian in the Sandhill well indicates that near-shore belts of middle and lower Cambrian sediments are probably—indeed, almost certainly—present somewhat farther east, perhaps beginning just east of the Burning Springs structure. Upper Cambrian sandstones found in the Sandhill well appear to be too tightly cemented and too completely filled with dolomite to serve as reservoirs. Whether the same is true of older sandstones of like origin to be expected farther east can be determined only through drilling. Possibility of production from these ancient sandstones probably depends upon that of the ac-

cumulation of hydrocarbons in them during early stages in their lithification, not long after the deposition of their parent sands. Such accumulations would prevent excessive cementation of the sand in the regions they might occupy.

So far as known, the Ordovician gas found in the Caldwell well was not analyzed. However, gas from the Sandhill well, found in the interval between 11,190 and 11,274 feet depth, which includes the zone of vuggy porosity already mentioned, and lies at a distance of 483 to 567 feet below the top of the middle Ordovician, was collected during a drill-stem test, and has been analyzed. The results have been made available for publication through the courtesy of the Hope Natural Gas Company. They are as follows:

Component	Percentage by volume
Carbon dioxide	0.1
Propane and higher hydrocarbons	0.1
Oxygen	0.1
Methane	82.3
Ethane	1.4
Nitrogen	16.0
	100.0

The high percentage of nitrogen is, of course, detrimental to the value of the gas as a fuel, though by no means sufficient to make it worthless for such use, since it still leaves the calorific value decidedly higher than that of manufactured gas. Absence of hydrogen sulfide is a favorable feature of this gas, which is, in fact, essentially methane diluted with nitrogen. Natural gases that contain considerable nitrogen are also quite often high in helium, which may be present in this particular gas in quantities sufficient to pay for extraction, in case natural gas of similar composition comes into commercial production in the Appalachian region. Of course, it is as yet uncertain that the composition shown by analysis of this gas is representative of that of the deep gases yet to be found in the Appalachian region.

The brine produced with this gas has also been analyzed by Dr. A. J. W. Headlee, with the following results:

Density	1.1770
Total solids	238,730 ppm
Chlorides	138,618 "
Sodium	45,685 "
Potassium	1,291 "
Calcium	35,685 "
Strontium	1,018 "
Barium	108 "
Magnesium	6,227 "
Lithium	47 "