COMMONWEALTH OF VIRGINIA

VIRGINIA CONSERVATION COMMISSION

VIRGINIA GEOLOGICAL SURVEY

ARTHUR BEVAN, *State Geologist*

Bulletin 56

The Early Grove Gas Field, Scott and Washington Counties, Virginia

By

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Prepared in Cooperation with the Geological Survey of the United States Department of the Interior

UNIVERSITY, VIRGINIA

1941

RICHMOND:

Division of Purchase and Printing

1941

VIRGINIA CONSERVATION COMMISSION

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LETTER OF TRANSMITTAL

COMMONWEALTH OF VIRGINIA
VIRGINIA GEOLOGICAL SURVEY
UNIVERSITY OF VIRGINIA

CHARLOTTESVILLE, VA., August 5, 1941.

To the Virginia Conservation Commission:

GENTLEMEN:

I have the honor to transmit and to recommend for publication as Bulletin 56 of the Virginia Geological Survey series of reports the manuscript and illustrations of *The Early Grove Gas Field, Scott and Washington Counties, Virginia,* by Mr. Paul Averitt of the Geological Survey of the United States Department of the Interior. The field work was done during the summer of 1940. The entire project was a cooperative one with the Federal Geological Survey.

Natural gas was discovered in 1931 by drilling in the Early Grove area in northeastern Scott County, on the basis of data published in Bulletin 27 of the Virginia Geological Survey. The present report discusses in some detail the physical characteristics and structure of the bedrock formations; logs of the drilled wells; laboratory studies of the gas sands; and the gas resources and possibilities of the area. A synopsis of the report is given in the "Abstract" (page 1).

The information given in this report should be very useful in the future exploration of the natural gas possibilities in the Early Grove area.

Respectfully submitted,

ARTHUR BEVAN,
State Geologist.

Approved for publication:
Virginia Conservation Commission,
Richmond, Virginia, August 13, 1941.
R. A. GILLIAM, *Executive Secretary and Treasurer.*

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By Paul Averitt

ABSTRACT

The Early Grove gas field lies in the Appalachian Valley in Scott and Washington counties, southwestern Virginia. In addition to the main Early Grove anticline it includes a belt of slightly folded Mississippian rocks 3 miles wide and 23 miles long bounded on the southeast by the great Saltville thrust fault, which brings Cambrian limestones in contact with the Pennington shale, the youngest of the Mississippian formations in the area.

The rocks exposed in the mapped area, are, in descending order, the Pennington shale, Cove Creek limestone, Fido sandstone, and limestone of Gasper age. The rocks penetrated by wells on the Early Grove anticline are exposed at the surface northwest of the mapped area. In normal stratigraphic position below the Fido sandstone they are, in descending order, limestones of Gasper and Ste. Genevieve ages, St. Louis limestone, Little Valley limestone of Warsaw age, Maccrady shale, and Price sandstone, all of Mississippian age. In the Early Grove area the total thickness of the formations above the Price is approximately 6,800 feet.

The principal fold in the area, the Early Grove anticline, is the largest member of a series of anticlinal structures that interrupt the southeastward regional dip of 20 to 30 degrees in the belt of Mississippian rocks. Six wells, five of which have been productive, have been drilled near the crest of this anticline, and the natural gas that is being obtained is sold in the cities of Bristol, Virginia and Tennessee, 9 miles away. The producing beds are calcareous sandstones that occur in two general zones 200 feet apart in the Little Valley limestone. Examination of the well logs shows that individual sandstone beds are not continuous, but the general distribution of sands in the two zones in the belt of outcrops indicates that at least one sandstone bed may be expected to occur at any single locality.

Laboratory tests of eight sandstone samples collected from the belt of outcrop of the Little Valley limestone show an average porosity of 1.62 per cent, and correspondingly low permeability. The ratio between decline in pressure and production of the wells

also is indicative of tight sands. In consideration of this fact the behavior of one well on the flank of the Early Grove anticline, as contrasted with that of four producing wells on the axis, suggests that reservoir space on the axis may be controlled in part by jointing.

The structural relations are favorable for the occurrence of gas on the axis of the Early Grove anticline as far northeast as McCalls Gap, and at least as far southwest as U. S. Highway 58-421. The greater sand thickness, however, occurs on the northeast end of the anticline. The head of Lick Branch, which marks a point where the Early Grove axis levels off before continuing its southwestward plunge, is also a favorable structural location. To reach the sands in the Little Valley limestone, however, a well at this point would have to be approximately 500 feet deeper than wells on the higher parts of the axis.

The Wolf Run anticline, which lies northeast of the Early Grove anticline, is a small structure with limited gas possibilities. At the highest part of the axis of this fold the depth to the gas-bearing sands is approximately 5,000 feet. In view of the additional cost of pipe-line construction that would be necessary in order to dispose of the gas, and in further consideration of the limited amount of gas that is available in sands with an average porosity of less than 2 per cent, it is doubtful that a well on this structure would be profitable.

The Browder Mountain anticline at the southwest end of the series of folds is considered to be too small and too closely folded to have gas possibilities.

INTRODUCTION

PURPOSE OF REPORT

Since the discovery in June, 1931, by the Davis Elkins interests, of gas in commercial quantities on the Early Grove anticline in southwestern Virginia, five additional wells have been drilled on the structure and a four-inch pipe line has been constructed to supply natural gas to the cities of Bristol, Virginia and Tennessee. This report has been prepared through joint co-operation between the Virginia Geological Survey and the Geological Survey of the United States Department of the Interior in order to aid those interested in the further development of the region. It embodies the results of four months' field work done during the summer and fall of 1940 and contains a description of the structural and stratigraphic features of the region, together with a discussion of locations that appear to be favorable for the accumulation of natural gas.

LOCATION AND EXTENT OF AREA

The area described in this report is in the extreme southwestern part of Virginia in Scott and Washington counties. As shown in Figure 1, it extends diagonally across a block of five 7½-minute topographic maps: the Mendota, Hilton, Indian Springs, Blountville, and Wallace quadrangles of the Tennessee Valley Authority. The southeastern boundary of the mapped area is the Saltville thrust fault, which brings older Paleozoic rocks in contact with the Mississippian Pennington shale, and the northwestern boundary is the outcrop of the Fido sandstone, which is parallel to and very near State roads 615, 616, and 697, and U. S. Highway 58-421. The area thus outlined is approximately 23 miles long, and 3 miles wide in the widest parts. It is drained by tributaries of the North Fork, and to a limited extent, the South Fork of Holston River.

FIELD WORK

All of the geologic mapping was done on a scale of approximately 2½ inches to a mile on topographic maps prepared in 1938 by the Federal Geological Survey for the Tennessee Valley Authority. Because stereophotogrammetric methods were employed in their construction, the maps show a great amount of detail, and it was possible to make locations and to determine altitudes in the field by inspection. Locations at doubtful places on ridge crests

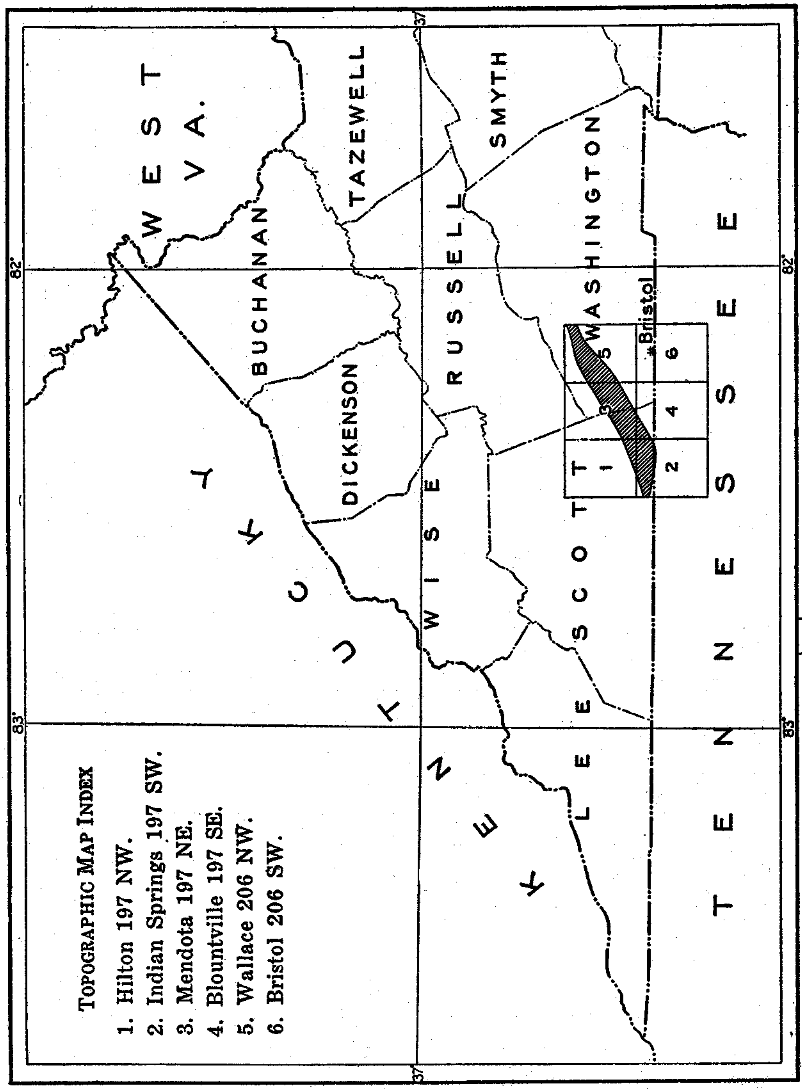


FIGURE 1.—Index map of southwestern Virginia showing, by diagonal ruling, the location of the area described in this report.

or hillsides were made by intersection methods or by hand leveling and pacing to known points. The major structural axes were followed on foot throughout their entire length in the area, and the positions shown on the geologic map (Pl. 1) are thought to be accurate within horizontal limits of approximately 200 feet. The attitude of the beds is shown by means of strike and dip symbols spaced at intervals of half a mile or less. For the sake of clarity the number is somewhat less than the total number of observations that were recorded, but no significant reading has been omitted, and it is believed that the structure is uniform between any two symbols.

ACKNOWLEDGMENTS

The writer is greatly indebted to W. O. Clarkson of the Bristol Natural Gas Corp., who provided drilling records and other data concerning the company wells and leases. Charles Butts, formerly of the Geological Survey, United States Department of the Interior, who did the preliminary geologic work in the area, and who first called attention to its gas possibilities, generously placed his field notes and maps at the disposal of the writer, and, in company with Raymond S. Edmundson of the Virginia Geological Survey, spent one day at the end of the season helping in the final check of field work. H. D. Miser of the Federal Geological Survey spent two days in the field and gave much helpful advice and criticism. Special thanks are due William M. McGill of the Virginia Geological Survey for his generous cooperation throughout all stages of the work.

EARLIER INVESTIGATIONS

The position of the Early Grove anticline in the center of a broad belt of Mississippian rocks is plainly indicated by the outcrop pattern of the Newman limestone (the name applied to the Mississippian limestones in this area before they were subdivided) on the geologic map of the Bristol quadrangle,[1] which was published in 1899. During subsequent years, however, the region was generally ignored by oil and gas operators, because of its position in the faulted zone of the Appalachian Valley, and it was not until 1927 that minor folds in the Mississippian belt were given serious consideration. At that time Butts noted the Early Grove anticline during the course of cooperative work between the State and Federal geological surveys, and published a full account of its

[1] Campbell, M. R., U. S. Geol. Survey Geol. Atlas, Bristol folio (no. 59), 1899.

gas possibilities.[2] Acting on the information contained in his report, the Davis Elkins interests drilled near the crest of the structure and in June, 1931, brought in the first gas well of commercial importance in Virginia.

Of the large body of literature that has been published on the geology of southwestern Virginia, reports by Eby,[3] Giles,[4] McGill,[5] and Butts[6] have specific bearing on the structure, stratigraphy, and gas resources and possibilities of the area.

[2] Butts, Charles, Oil and gas possibilities at Early Grove, Scott County, Virginia: Virginia Geol. Survey Bull. 27, 1927.

[3] Eby, J. B., The possibilities of oil and gas in southwest Virginia as inferred from isocarbs: Am. Assoc. Petroleum Geologists Bull., vol. 7, no. 4, pp. 421-426, 1 fig., July-August, 1923.

[4] Giles, A. W., Oil and gas possibilities in Virginia: Econ. Geology, vol. 22, no. 8, pp. 791-825, 7 figs., December, 1927.

[5] McGill, W. M., Prospecting for natural gas and petroleum in Virginia: Virginia Geol. Survey Bull. 46-B, 1936.

[6] Butts, Charles, Geologic map of the Appalachian Valley of Virginia with explanatory text: Virginia Geol. Survey Bull. 42, 1933.

STRATIGRAPHY

EXPOSED FORMATIONS

The rocks that crop out in the Early Grove area, all Chester (Mississippian) in age, are divided from base to top into the following formations: limestone of Gasper age, Fido sandstone, Cove Creek limestone, and Pennington shale. According to Butts[7] the Fido probably corresponds to the Hardinsburg sandstone of the Mississippi Valley region and to the Hartselle sandstone of Alabama; the Cove Creek to the Glen Dean of the Mississippi Valley and to the Bangor limestone of Alabama; and the Pennington to the upper Chester, including beds of Menard age, and possibly including beds of Tar Springs age. The general lithologic character and thickness of these formations are shown in the columnar section. (See Pl. 2.)

Limestone of Gasper age.—Approximately 120 feet of limestone of Gasper age is exposed along the highest part of the Early Grove anticline. The lower 100 feet of these exposures is thick-bedded, argillaceous, highly fossiliferous limestone, in which the following species determined by Butts[8] are relatively abundant: *Pentremites planus, P. welleri, Globocrinus,* n. sp., and *Talarocrinus inflatus.* The upper 20 feet lying immediately below the Fido sandstone is thin bedded, shaly, and nonfossiliferous. The boundary between these two zones is best exposed on U. S. Highway 58-421 where it crosses the axis of the anticline. Good exposures of the lower zone occur also along State road 617 near the Washington-Scott county line.

Northwest of the mapped area the full thickness of the limestone of Gasper age crops out and dips beneath the Fido sandstone in normal stratigraphic position. These beds are also penetrated by wells in the Early Grove gas field, and for this reason they are discussed in greater detail under the heading, "Concealed Formations."

Fido sandstone.—The Fido sandstone is a coarse-grained, cross-bedded, red to reddish-brown, calcareous sandstone, 35 to 50 feet thick. (See Pl. 3A.) Its outcrop forms the northwest boundary of the mapped area and it is exposed at many places along U. S. Highway 58-421 from the curve 1 mile southeast of Hilton Gap to the junction with State road 615; along State roads 615, 616, and 697, and also along the axis of the Early Grove anticline. Although it is extremely hard when fresh, it is soft and friable in

[7] Butts, Charles, Oil and gas possibilities at Early Grove, Scott County, Virginia: Virginia Geol. Survey Bull. 27, pp. 16-17, 1927.
[8] Butts, Charles, op. cit., p. 6.

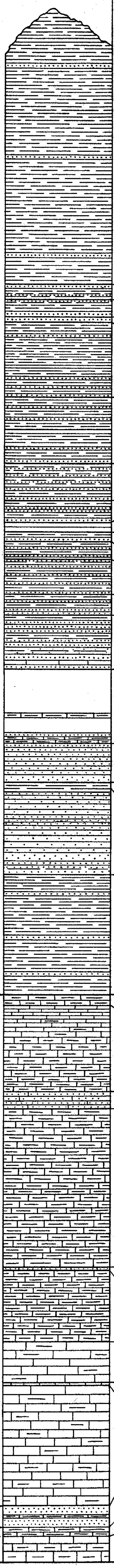
weathered outcrops and only slightly more resistant than the adjacent limestone formations. In addition to the calcium carbonate contained in the sandstone as cement, the formation generally contains one or more beds of limestone or sandy limestone. These vary considerably in position and thickness, as the following measured sections illustrate, but in general the proportion of limestone increases both northeast and southwest away from the central part of the area. This change is particularly noticeable between the section near Gardner Cemetery on Roberts Creek and the one along Fowler Branch about 3 miles to the west. West of Fowler Branch the change in lithologic character is even greater. In this area the sandstone beds of the Fido are lighter in color, finer grained, and more calcareous than elsewhere, and the position of the formation is marked only by occasional thin ledges and fragments of buff-colored, medium-grained sandstone.

Section of Fido sandstone on State road 616 near East Fork of Muddy Hollow

	Ft.	In.
Cove Creek limestone		
Fido sandstone (44½ feet exposed):		
Sandstone, red to brown, medium to coarse grained, calcareous, no cross-bedding	8	6
Concealed	2	6
Limestone, shaly, wavy bedding, contains many fenestellid bryozoa fronds	2	6
Sandstone, red to brown, medium to coarse grained, calcareous	12	6
Limestone, shaly, wavy bedding, fossiliferous in upper part, fenestellid bryozoa fronds common	10	
Sandstone, red, cross bedded, calcareous, contains some fossil fragments	8	6
Base concealed		

Section of Fido sandstone on turn in U. S. Highway 58-421 near Gardner Cemetery

	Ft.	In.
Cove Creek limestone		
Fido sandstone (38 feet):		
Sandstone, medium to coarse grained; upper part more massive	13	
Sandstone, cross bedded, calcareous, fossiliferous	1	



AGE	FORMATION	THICKNESS (FEET)	CHARACTER OF ROCKS
MISSISSIPPIAN	PENNINGTON SHALE	633	Red, yellow-green, and gray variegated shale containing a few beds of medium-grained sandstone. Weathers to smooth slopes. Outcrops rare.
		28	Gray shale and sandstone.
		38	Red shale and sandstone.
		13	Gray shale and sandstone.
		169	Red sandstone and shale containing a few beds of gray sandstone. Becomes more shaly in upper part.
		154	Gray shale and fine-grained shaly sandstone. Contains a few beds of red shale near base.
		84	Red shale and sandstone. Contains a few beds of white sandstone.
		52	Gray shale and sandstone.
		20	Light-gray shaly limestone and shale containing many fenestrated bryozoans.
		23	Gray shale and sandstone.
		41	Red shale and sandstone.
		80	Gray sandstone and shale.
		48	Red sandstone and shale. Lowest occurrence of red beds in section.
		124	Well-bedded coarse-grained sandstone becoming shaly in upper part. Contains a 6-foot bed of crinoidal limestone 12 feet below the top. Usually crops out to form a ridge.
		170	Generally concealed. Probably calcareous shale and thin sandstone.
		90	Medium-bedded, fine- to medium-grained sandstone. Crinoid stem segments common in some layers.
		20	Dark-gray shale.
		189	Medium-bedded to massive sandstone. Lower part even bedded. Middle part spheroidal. Upper part very massive and resistant with great concentration of *Diaphragmus elegans* in some layers. Crinoid stem segments abundant. *Sulcatopinna missouriensis* present.
		280	Gray shale containing thin sandstone beds. Outcrops rare. Forms landslides on dip slopes.
	COVE CREEK LIMESTONE	20	Shaly limestone, massive, somewhat siliceous. Yellow on weathered surfaces.
		200	Shaly limestone, thin bedded. Outcrops poor.
		20-60	Sandstone, coarse grained, reddish, and sandy limestone.
		366	Shaly limestone, thin bedded. Outcrops poor.
		6	Sandy limestone.
		163	Shaly limestone, thin bedded.
		94	Shaly limestone, thick bedded, less argillaceous than beds above. Purer layers white on weathered surfaces.
		5	Limestone, highly fossiliferous.
		275	Limestone, thick bedded to massive, somewhat argillaceous, white on weathered surfaces. Lower 5-10′ contains abundant *Pterotocrinus* plates.
	FIDO	50	Sandstone, thick bedded, coarse grained, red to red brown, calcareous, weathers soft. Contains one or more beds of shaly limestone.
	LIMESTONE OF GASPER AGE	20	Shaly limestone, thin bedded, nonfossiliferous.
			Shaly limestone, thick bedded, highly fossiliferous; *Pentremites planus, P. welleri, Talarocrinus inflatus*.

GENERALIZED COLUMNAR SECTION OF EXPOSED FORMATIONS IN THE EARLY GROVE GAS FIELD, SCOTT AND WASHINGTON COUNTIES, VIRGINIA

	Ft.	In.
Concealed, probably calcareous sandstone	5	
Limestone, sandy; contains ¼- to 1-inch streaks of medium-grained red sandstone	2	6
Sandstone, red to brown, medium to coarse grained; beds 6 inches to 3 feet thick	16	6

Limestone of Gasper age

Section of Fido sandstone on State road 697 near Fowler Branch

	Ft.	In.
Cove Creek limestone		
Fido sandstone (35 feet exposed):		
Sandstone, very calcareous, red to brown on weathered surfaces	5	
Limestone, gray, few fossils	5	
Limestone, shaly, fossiliferous, somewhat red at base	8	
Sandstone, medium grained, calcareous, yellow-brown	8	
Shale, sandy, red	2	6
Sandstone, calcareous, beds 1 to 3 inches thick, upper 1½ feet somewhat reddish	3	6
Shale, calcareous, light-colored, occasional ¼- to ½-inch lenses of sand	3	
Base concealed		

Cove Creek limestone.—The Cove Creek limestone is typically a highly argillaceous, nonfossiliferous limestone approximately 1,150 feet thick. The lower 375 feet is thick bedded and compact with distinct laminations one-eighth to one-fourth inch thick, in addition to the bedding. This part of the formation weathers white and crops out conspicuously on the flanks of the Early Grove anticline and on the northwest boundary of the area parallel to the outcrop of the Fido sandstone. The upper 775 feet of the formation is thinner bedded, more argillaceous, darker than the lower part, and does not form conspicuous outcrops.

Although the Cove Creek generally is not fossiliferous, several fossiliferous beds occur within the formation. At the base, immediately overlying the Fido sandstone, is 10 feet of massive, dark-colored argillaceous limestone containing many *Pterotocrinus* plates, bryozoa fragments, and *Pentremites*. Another zone 5 feet thick and 275 feet above the base is so highly fossiliferous that it can be distinguished from other beds in the Cove Creek on this basis alone. Excellent exposures of this bed occur on State road 630 near McCall Gap, and on U. S. Highway 58-421 near Muddy Gap School. Fossils collected at the latter locality were identified by J. S. Williams of the U. S. Geological Survey as follows:

Pentremites, fragments of two species
Fenestrellina? sp. indet.
Orthotetes? sp. indet.
"Productus" (Linoproductus) ovatus Hall
"Productus" (Diaphragmus) elegans Norwood and Pratten
"Productus" inflatus McChesney
"Productus," immature individuals of two species
Spiriferina sp. indet.
Eumetria? cf. E. vera (Hall)
Cliothyridina sp. indet.

This bed is shown on the geologic map (Pl. 1), near both ends of the plunging Early Grove anticline.

A zone containing two or more sandstone beds and generally underlain by a 3- to 5-foot bed of coarsely crystalline crinoidal limestone occurs 200 feet below the top of the Cove Creek limestone. On State road 630 in Cove Creek southeast of McCall Gap it is 34 feet thick. In a section measured on U. S. Highway 19,[9] 15 miles to the northeast, a sandstone, 10 feet thick, occurs at approximately the same stratigraphic position. South and west of U. S. Highway 58-421, however, the sandstone in this zone thickens, becomes coarser grained, and the crinoidal limestone disappears from the base. The zone is conspicuous in Gouldman Branch, Dry Branch, and in Bright Hollow where the following section was measured:

Section of sandstone member in the upper part of the Cove Creek limestone

	Ft.	In.
Sandstone and shale, thin bedded	12	
Sandstone, coarse grained	8	6
Limestone, argillaceous	2	
Sandstone, coarse grained; contains several 1- to 2-inch zones of pebble conglomerate	39	6
	62	

A line representing the top of this sandstone appears on the geologic map (Pl. 1) to indicate closure on the Browder Mountain anticline.

[9] Butts, Charles, op. cit., p. 5.

Elsewhere in the area, however, its proximity to the base of the Pennington shale made mapping unnecessary.

The upper 20 feet of the Cove Creek limestone is a massive, argillaceous, somewhat siliceous limestone, which is yellow on weathered surfaces and which is further characterized by the presence of wavy bedding planes. This bed is slightly more resistant than the beds below and much more resistant than the thin-bedded sandstone and shale of the overlying Pennington.

The following section of the Cove Creek limestone, except for the lower two units, the thicknesses of which are given as the average of several observations, was measured on State road 630 in Cove Creek southeast of McCall Gap:

Section of Cove Creek limestone on State road 630 southeast of McCall Gap

	Feet
Pennington shale	
Cove Creek limestone (1154 feet):	
Limestone, shaly, somewhat siliceous, massive, yellow on weathered surfaces	20
Limestone, shaly, weathers to thin slabs, outcrops poor	198
Sandstone, coarse grained, reddish	6
Limestone, fragmental	1
Limestone, sandy; contains many beds of calcareous sandstone (1 to 3 inches) thick	10
Limestone, shaly	7
Sandstone, medium to coarse grained	10
Limestone, shaly; weathers to thin slabs	359
Limestone, sandy	6
Limestone, shaly, thicker bedded than beds above	163
Limestone, shaly, thick bedded with thin laminations; more resistant than beds above	94
Limestone, highly fossiliferous (see fossil list, p. 10)	5
Limestone, shaly, generally purer than beds above, thick bedded, weathers white	265
Limestone, shaly, thick bedded, highly fossiliferous: *Pterotocrinus* plates, bryozoa fragments, *Pentremites*	10
Fido sandstone	

Pennington shale.—The greater part of the Pennington is nonfossiliferous shale and sandstone. Many beds in the lower part of the formation are highly calcareous, and a few contain abundant fossils. In contrast to the lower half, the upper half of the formation is less calcareous, less fossiliferous, and the presence of ripple marks and occasional macerated plant fragments give evidence that it was deposited nearer shore. The full thickness of the formation is not known because the top is concealed by the Saltville overthrust block, but approximately 2,250 feet is exposed in the Early Grove area.

For purpose of discussion the formation can be separated into several lithologic units, which, although distinct, have indefinite boundaries that cannot be traced precisely in the field. The lower 250 to 300 feet is composed of alternating thin beds of dark-gray shale and sandstone. These beds commonly do not crop out on the lower slopes but good exposures may be seen near the crests of the hills surrounding the Early Grove anticline. Dip slopes in this unit, as, for example, the north side of lower Wolf Run and the north side of Ridgeway Hollow, are characterized by landslides. Above this typically nonresistant unit is about 300 feet of resistant, steel-gray, generally massive, medium-grained sandstone, the lower beds of which exhibit spheroidal structures on weathered surfaces, as illustrated on Plate 3B. Many beds in this unit are fossiliferous. The following species are the most characteristic fossils: *Diaphragmus elegans, Chonetes chesterensis,* and *Sulcatopinna missouriensis.* Next in sequence is about 180 feet of light-colored calcareous shale and gray shale, which as a rule weathers to smooth slopes with few outcrops. Above this unit is a fairly resistant unit approximately 100 feet thick, consisting of massive coarse-grained sandstone in the lower part, and sand and shale in the upper part. This, in turn, is overlain by a unit in which red sandstone and shale occur in about equal proportions with gray sandstone and shale. This unit, which is between 175 and 200 feet thick, marks the first occurrence of red beds in the section. The next higher unit, a light-colored calcareous shale 20 feet thick, containing in some beds fairly abundant bryozoa fronds, is distinctive enough to be recognizable in road cuts, but it is too soft to make mappable outcrops. Excellent exposures of the calcareous shales and all lower beds except the basal shales may be seen on U. S. Highway 58-421 between Wright Hollow and Ridgeway Hollow.

The calcareous shale is overlain by 575 to 600 feet of alternating sandstone and shale, the lower half of which is nearly 50 per cent red beds, and the upper half of which is 75 per cent red beds. This part of the section is well exposed in Timbertree Branch, in the head of Wolf Run, and in the head of Nordyke Creek. The highest unit of the Pennington consists of alternating red, yellow-green, and gray shales with occasional beds of sandstone. The top of this unit is concealed by the Saltville overthrust block, but it is at least 590 feet thick. Exposures may be seen near the fault between Benham and the eastern boundary of the mapped area, particularly in the head of Gaspard Creek on State road 625.

The lithologic character of the formation is given in greater detail in the following composite section, the lower half of which was measured on U. S. Highway 58-421, and the upper half in the head of Gaspard Creek on State road 625. Correlation between the two locations was established by the 20-foot bed of highly calcareous shale containing abundant bryozoa fronds mentioned above.

Section of Pennington shale

	Feet
Top concealed by Saltville thrust fault	
Shale, alternating red, yellow-green, and gray with occasional beds of red sandstone; weathers to smooth slopes	590
Gray sandstone, medium grained; contains several thin beds of gray shale	5
Red shale and sandstone	40
Gray shale and sandstone	28
Red shale and sandstone	38
Gray shale and sandstone	13
Red shale; contains thin-bedded red sandstone	102
Gray sandstone, fine grained	4
Red sandstone and shale; contains some gray beds	63
Gray shale and fine-grained shaly sandstone; contains occasional thin bed of red shale	154
Red shale and sandstone; contains occasional bed of white sandstone	84
Gray shale and sandstone	52
Light-gray shale, highly calcareous, bryozoa fronds in some layers	20
Gray shale and sandstone	23
Red shale and sandstone	41
Gray sandstone and shale	80
Red sandstone and shale	48
Sandstone, massive, beds 1 to 5 feet, coarse to medium grained; contains shale which becomes more abundant towards top	75
Sandstone, fine grained, shaly, and shale	31
Limestone, massive	6
Sandstone, massive, fine grained, and shale	12
Concealed	100
Shale, highly calcareous	10
Shale, calcareous, and thin sandstone, largely concealed	60

	Feet
Sandstone, fine to medium grained, beds 1 to 5 feet thick; crinoid stem segments common 10 feet above base	90
Shale, dark gray	20
Sandstone, massive, steel-gray, medium to coarse grained; contains occasional thin beds of gray shale; crinoid stems abundant in some layers	41
Sandstone, fine grained, medium bedded, spheroidal structures on weathered surfaces; grades into unit above	38
Sandstone, massive, fine to medium grained, great concentration of *Diaphragmus elegans*	7
Sandstone, medium bedded, spheroidal structures on weathered surfaces; contains occasional thin bed of shale	69
Sandstone, even bedded, 1- to 3-foot beds, fine grained, blue gray, weathers reddish	34
Shale, gray, containing 1- to 3-foot beds of sandstone; outcrops poor; landslides formed on dip slopes	270
	2,248

Cove Creek limestone

CONCEALED FORMATIONS

The rocks that are penetrated by the wells in the Early Grove gas field are also exposed in normal stratigraphic sequence northwest of the mapped area where they dip southeast toward the axis of the Cove Ridge syncline. The best continuous exposure of these beds, which consist of limestones of Gasper, Ste. Genevieve, St. Louis, and Warsaw ages, is to be seen on U. S. Highway 19 southeast of Holston River where the following section, modified after Butts,[10] was measured:

Section of limestones of Gasper, Ste. Genevieve, St. Louis, and Warsaw ages on U. S. Highway 19, southeast of Holston River

	Feet
Fido sandstone	
Limestone of Gasper and Ste. Genevieve ages (2,379 feet):	
Limestone, thin bedded, argillaceous, nonfossiliferous	20
Limestone, thick bedded, somewhat argillaceous, highly fossiliferous; *Pentremites planus, P. welleri, Globocrinus* n. sp., *Talarocrinus inflatus*	160
Limestone, somewhat argillaceous, lower part crinoidal, *Pentremites planus*	115

[10] Butts, Charles, Oil and gas possibilities at Early Grove, Scott County, Va., Virginia Geol. Survey Bull. 27, pp. 5-8, 1927.

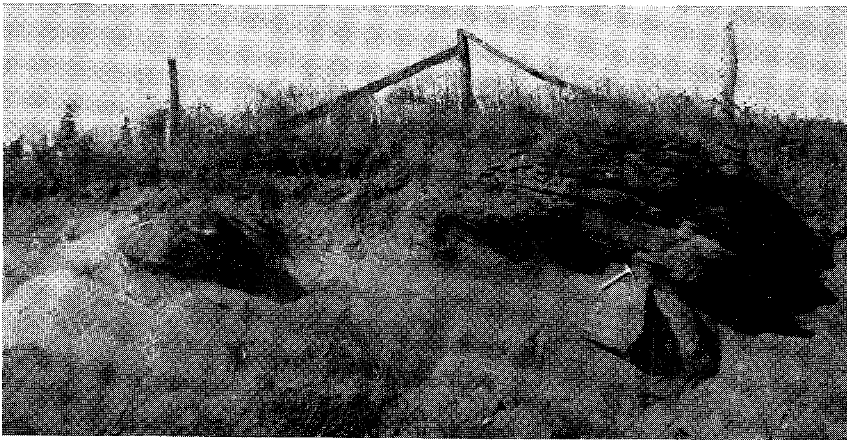
	Feet
Limestone, thick bedded, ferruginous, reddish, highly crinoidal	30
Limestone, highly argillaceous, some layers crowded with fenestellid bryozoa, weathers to smooth slopes	700
Limestone, thick bedded, gnarly, ferruginous, red, sandy; composed mostly of matted fenestellid bryozoa fronds	60
Limestone, argillaceous, shaly	10
Sandstone, soft, brown, stained red on joint surfaces	30
Limestone, shaly	15
Limestone, sandy, with coarse crinoidal layers	30
Limestone, thick bedded, argillaceous, shaly	165
Sandstone, bluish, fine grained, calcareous	2
Limestone, argillaceous	280
Mostly concealed, probably argillaceous limestone	50
Limestone, thick bedded, argillaceous	50
Limestone, coarse grained, crinoidal, *Platycrinus penicillus* (*huntsvillae*)	30
Limestone, thick bedded, argillaceous	82
Limestone, shaly	30
Shale	15
Limestone, thick bedded, argillaceous, weathers easily	30
Limestone, medium to thick bedded, rather coarse grained, with quartz grains, *Platycrinus penicillus* bases in bottom	80
Limestone, coarse, crinoidal, cross bedded, *Hydrieonocrinus* spines	15
Limestone, argillaceous, shaly	5
Sandstone, even bedded, soft, reddish	30
Limestone, sandy, *Platycrinus penicillus* bases	5
Limestone, medium to coarsely crystalline, in part fragmental and crinoidal, bluish-gray	110
Mostly concealed, probably weathered argillaceous limestone	150
Limestone, full of platy chert nodules arranged in layers 1 inch thick	15
Limestone, thick bedded, coarsely crystalline, with nodules of black chert. *Platycrinus penicillus* bases and spiny stem plates abundant; *Cystelasma;* small *Productus* apparently related to *P. parvus*	65

St. Louis limestone (330 feet):

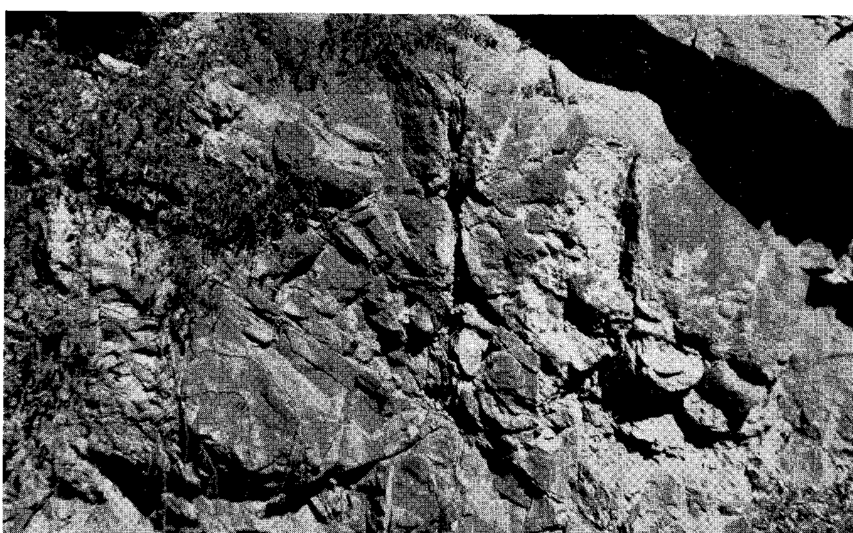
Shale	50
Limestone, very dark-colored to black, thick bedded, medium to coarse grained. *Syringopora* common; *Melonites* plates and *Archeocidaris* spines; spiny stem plates similar to those	

	Feet
of *Platycrinus penicillus* rare, observed only 65 feet above bottom; *Productus* and *Orthotetes*	264
Limestone, argillaceous, shaly	16
Limestone of Warsaw age (Little Valley limestone) (452 feet exposed):	
Shale, dark-colored, soft	14
Shale, black	1
Limestone, argillaceous, shaly; more resistant layers weather yellowish	90
Concealed, probably black shale	30
Shale, black	10
Limestone, argillaceous, compact	28
Limestone, shaly	17
Limestone, thick bedded, compact, argillaceous	5
Limestone, shaly, thin bedded	7
Limestone, thick bedded, compact, argillaceous, black on fresh surfaces; strong odor of petroleum when struck with hammer; upper 4 feet fossiliferous	12
Limestone, laminated	5
Sandstone, hard, medium grained	5
Limestone, compact, thick bedded	22
Limestone, shaly, fossiliferous in upper part	50
Limestone, coarse to medium crystalline, bluish; contains flint nodules	22
Sandstone, even bedded, fine to medium grained	12
Limestone, argillaceous	32
Sandstone, coarse grained, cross bedded, calcareous	20
Concealed	60
Limestone, argillaceous	10
Concealed in river valley, including Little Valley and Maccrady formations	185
Price sandstone	

The limestones of Gasper and Ste. Genevieve ages and the St. Louis limestone are quite uniform in thickness and lithologic character, both in the region northwest of the Early Grove gas field and in the wells drilled in the field. Together with beds of Warsaw and Maccrady ages, which will be discussed in greater detail below, they outcrop in a broad belt of relatively low relief between the Price sandstone in Pine Ridge and the Fido sandstone which forms the northwest boundary of the mapped area shown on Plate 1.

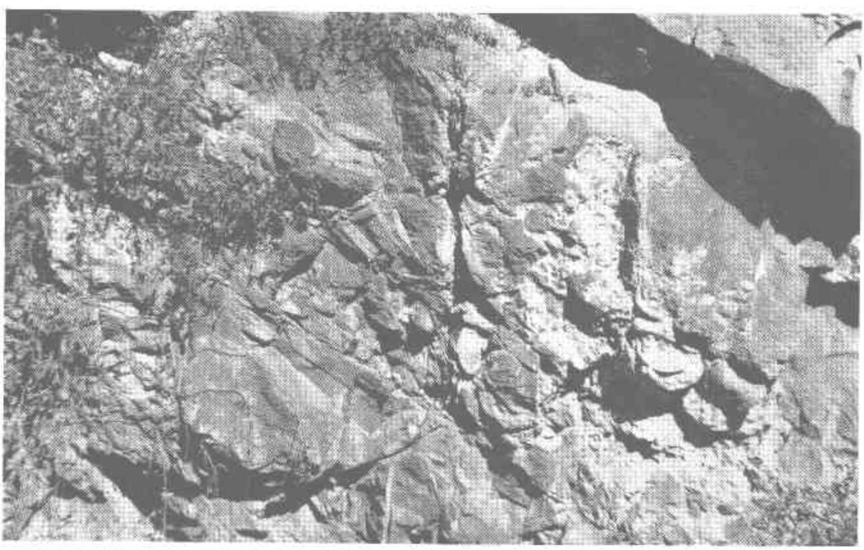


A. Fido sandstone, U. S. Highway 58-421 near Miller Church, Scott County.



B. Spheroidal structures in the Pennington shale, U. S. Highway 58-421 near Ridgeway Hollow, Scott County.

A. Fido sandstone, U. S. Highway 58-421 near Miller Church, Scott County.



B. Spheroidal structures in the Pennington shale, U. S. Highway 58-421 near Ridgeway Hollow, Scott County.

Limestones of Gasper and Ste. Genevieve ages.—In the measured section above, as in the records of the wells in the Early Grove field and in the area north of the field, the limestones of Gasper and Ste. Genevieve ages are approximately 2,380 feet thick. Of this thickness, the upper 325 feet is thick bedded and fossiliferous, containing *Pentremites planus, P. welleri, Globocrinus* n. sp., and *Talarocrinus inflatus,* which give definite evidence of Gasper age. The underlying 700 feet of beds are less massive, more argillaceous, and generally nonfossiliferous. Below this unit is 60 feet of red, sandy limestone containing matted fenestellid fronds in such abundance that the zone is easily recognizable both in the field and in well records. For this reason the top of the red limestone is the most distinctive lithologic break in the section, and it probably is the most suitable place for a formational boundary between beds of Gasper and beds of Ste. Genevieve age. Ten feet lower is a 30-foot bed of soft, iron-stained sandstone, which is also distinctive. The 600 feet of beds below this distinctive sandstone resemble the unit above the red limestone in appearance and in the absence of fossils. Below this 600-foot unit is another unit, 660 feet thick, which contains abundant *Platycrinus penicillus* stem plates in some layers. This fossil is sufficient evidence of the Ste. Genevieve age of this part of the section. The beds in this 660-foot unit are generally medium bedded and argillaceous. The lowest 65 feet, on the contrary, is thick bedded, coarsely crystalline, and contains nodules of black chert.

St. Louis limestone.—The St. Louis limestone consists of 265 feet of very dark-colored, thick-bedded, crystalline limestone containing *Lithostrotion canadense, L. proliferum, Syringopora,* and *Melonites,* overlain by 50 feet of shale and underlain by 16 feet of argillaceous limestone. The main body of the formation is distinctive lithologically at the outcrop where it commonly forms a low rounded ridge, and in well logs where the contrast between the hard dark-colored limestone and the overlying and underlying shale and light-colored argillaceous limestone is quite marked.

Because the formations described above are uniform in thickness and lithologic character over the entire area, and because all the gas in the Early Grove field is obtained from sandy zones in the limestone of Warsaw age, which is not uniform over the area, further discussion of the stratigraphy of the formations encountered in drilling will be confined to beds below the base of the St. Louis.

Little Valley limestone.—The beds in the interval between the base of the St. Louis limestone and the upper sandstone members of the Price are approximately 700 feet thick where they crop out southeast of Pine Ridge. The upper 640 feet consists mostly of argillaceous limestone containing one or more beds of fine-grained sandstone that are the gas-producing zones in the Early Grove field. The lower 60 feet consists of red and yellow-green shale and light-colored sandstone. The entire interval is correlated with the Maccrady shale of Stose[11] at the type locality two miles northeast of Saltville, Va. According to Butts,[12] however, the lower red beds contain *Taonurus caudigalli* and other New Providence species at Sunbright, at the south end of Powell Mountain, Scott County, where they lie immediately beneath the St. Louis limestone. On the other hand, the limestone beds lying between the red beds and the base of the St. Louis in the Early Grove area contain a typical Warsaw fauna, including *Anisotrypa tuberculata, Fenestralia sancti-ludovici, Hemitrypa proutana,* and *Productus altonensis,* which are confined to the Warsaw, and *Spirifer bifurcatus,* which is not known to occur in formations older than Warsaw. Because the absence of beds of Keokuk age indicates that a disconformity occurs between the red beds and the overlying limestone of Warsaw age, Butts[13] suggests that the name Maccrady be restricted to the lower 60 feet of red beds, and this usage will be followed in the present report. The limestone of Warsaw age, therefore, is a distinct lithologic unit that can be distinguished from the St. Louis limestone above and the restricted Maccrady shale below on both lithologic and faunal grounds. In order to facilitate discussion this limestone of Warsaw age is hereby named the Little Valley limestone because of its typical topographic expression in Little Valley, Scott County, Va. It is well exposed on U. S. Highway 19 near the Holston River bridge (sec. 10 of Fig. 2); at Horseshoe Bend of Holston River, Wallace quadrangle (sec. 11 of Fig. 2); and on the knoll at the west end of Little Valley near State road 689, one-fourth of a mile east of Hilton Gap (sec. 19 of Fig. 2).

Sections of the Little Valley, Maccrady, and upper Price beds were measured at every available exposure in the belt of outcrop northwest of the Early Grove gas field. The number of sections was somewhat limited because the North Fork of Holston River, throughout most of its course, flows directly in the outcrop belt of the Little Valley and Maccrady, which probably constitute the softest part of the Mississippian series. The sections that were obtained, however, give the general lithologic details of these formations. The locations of the measured sections, except for No. 10, which is northeast of the mapped area, are shown on Plate 1 as follows:

No. 10. U. S. Highway 19 at Holston River bridge, Brumley quadrangle.

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[11] Stose, G. W., Geology of the salt and gypsum deposits of southwestern Virginia: U. S. Geol. Survey Bull. 530, pp. 232-255, 1913; also Virginia Geol. Survey Bull. 8, pp. 51-73, 1913.

[12] Butts, Charles, Oil and gas possibilities at Early Grove, Scott County, Va.: Virginia Geol. Survey Bull. 27, pp. 12-14, 1927.

[13] Idem.

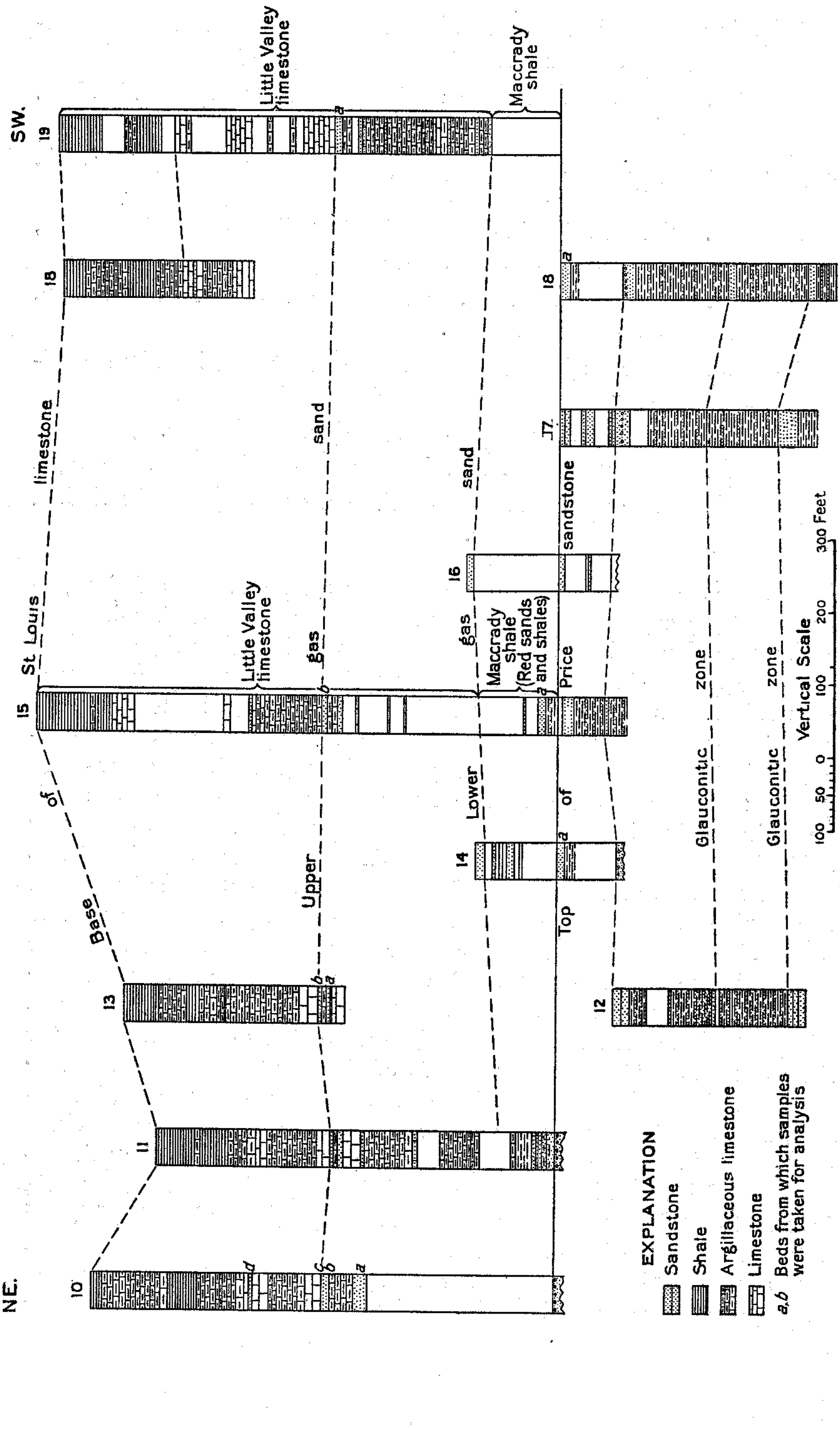

FIGURE 2.—Correlation of Little Valley, Maccrady, and Price formations in belt of outcrop northwest of the Early Grove gas field.

No. 11. Horseshoe Bend, 1.5 miles east of Wooten Gap, Wallace quadrangle.

12. Wooten Gap, State road 623, 6 miles east of Mendota, Wallace quadrangle.

13. State road 614-622, opposite mouth of Nordyke Creek, Wallace quadrangle.

14. State road 614, one-fourth of a mile east of Pine Grove, Mendota quadrangle.

15. Southern Railroad, half a mile southeast of Mendota, Mendota quadrangle.

16. State road 689, near New Hope School, Mendota quadrangle.

17. Jett Gap, State road 690, Hilton quadrangle.

18. Hilton Gap, U. S. Highway 58-421, Hilton quadrangle.

19. State road 689, one-fourth of a mile east of Hilton Gap, Hilton quadrangle.

Figure 2 shows the correlation between these sections and the general lithologic character of the three formations at each locality. In addition, section 10 is given in detail on pages 14-16. In these sections the Little Valley limestone is seen to consist of an upper dark-colored shale unit 100 to 150 feet thick that is generally divided into two parts by beds of argillaceous limestone, and a lower argillaceous and fossiliferous limestone unit approximately 500 feet thick that contains two distinct zones of sandstone. The upper of these two zones, which is the main gas-bearing zone in the Early Grove field, is approximately 200 feet above the base of the formation. It consists typically of two beds of sandstone separated by 15 to 30 feet of argillaceous limestone. The total thickness of the two sandstone beds ranges between 10 and 32 feet. The lower zone lies near the base of the formation, a few feet above the red shale and sandstone beds of the Maccrady, and the total sand thickness is less than that of the upper zone. The rocks in this part of the section weather easily and only two exposures of the Maccrady shales and three exposures of the overlying sandstone were observed. The wide spacing of the three exposures of the sand, however, indicates that it may be present everywhere in the outcrop belt.

A fact that is brought out very clearly in Figure 2 is the thickening of the Little Valley limestone that takes place between sections 10, 11, and 13 in the northeastern part of the area, and sections 15, 18, and 19 in the central and southwestern part. It can be seen by examination of the sections that this thickening takes place in the interval between the upper sand zone and the base of the shales that lie immediately below the St. Louis limestone. A further increase in the thickness of this interval occurs between the outcrop and the wells in the Early Grove field. This is illustrated in Figure 3, which shows the logs of several wells in the field as compared to a generalized section of the Little Valley limestone from the outcrop. In the well logs some additional thickening also occurs at the base of the formation below the lowest sand zone.

Maccrady shale.—The thickness of the Maccrady shale probably ranges between 50 and 100 feet. At the only locality where these beds could be observed in detail, along State road 614, one-fourth of a mile east of Pine Grove, Mendota quadrangle (sec. 14 on Fig. 2), the following section was measured:

Section of Maccrady shale near Pine Grove, Washington County, Virginia

	Feet
Top concealed	
Sandstone, coarse grained, friable, somewhat weathered	12
Maccrady shale (99 feet exposed):	
Shale, light-colored, weathered yellow	10
Sandstone, red	6
Shale, red and yellow beds alternating	5
Sandstone, red, coarse grained, soft	2
Shale, red	3
Shale, light-colored, weathered yellow	6
Sandstone, coarse grained, medium bedded	10
Shale, sandy, yellow	7
Shale, red	4
Concealed, upper portion probably contains red shale	46
Price sandstone	

Because of the sandstone above the Maccrady shale and because of the presence of sands in the red beds, drilling in the Early Grove field should always be continued until the hard uppermost Price sandstone bed is encountered.

Price sandstone.—The Price sandstone, which underlies the Maccrady, outcrops on Pine Ridge, northwest of the North Fork of Holston River, and is the lowest formation that has been encountered in the wells in the Early Grove field. It is approximately 800 feet thick in the belt of outcrop, but the base, which grades into the underlying Devonian shale without appreciable change in lithologic character, has not been precisely defined; hence the stated thickness is subject to revision. The upper 100 feet of the formation is composed of hard, well-cemented, thick-bedded, medium-grained sandstone, which as a rule contains one or two conglomerate layers in the lower portion. These layers, which range between 1 and 6 inches in thickness, are not continuous, and apparently are not confined to a single sandstone bed. The beds below the thick sandstone are dominantly sandy for an interval of approximately 230 feet, but, as they consist of thin sandstone layers interbedded with dark-gray sandy shale, the unit is relatively soft. Two glauconite zones occur within this unit, one 230 feet below the top of the formation, and the other approximately 330 feet below the top. These may be correlated for a considerable distance in the belt of outcrop, as shown in Figure 2, but no single bed of glauconitic sand is more than 6 inches thick, and the total in any one zone is probably no more than several feet. The lower 500 feet of the formation is mostly shale that weathers readily to smooth slopes on the northwest side of Pine Ridge. In common with the red beds of the Maccrady the Price contains many New Providence fossil species,[14] including *Taonurus caudigalli,* and it is, therefore, equivalent to the New Providence shale of eastern Kentucky and Tennessee, and the Cuyahoga and Logan formations of Ohio.

The following section measured in Jett Gap, State road 690, Hilton quadrangle (sec. 17 on Fig. 2) is typical of the upper 360 feet of the formation:

Section of Price sandstone in Jett Gap, Scott County, Virginia

	Feet
Top concealed	
Sandstone, steel-gray, hard, thin to medium bedded	17
Concealed	14
Sandstone, thin bedded	6
Sandstone, massive, fine to medium grained	21
Concealed	20
Sandstone and sandy shale, thin bedded	9
Sandstone, medium bedded to massive; contains a conglomerate zone 6 inches thick in middle	20
Concealed	25
Sandstone and sandy shale, thin bedded	80
Shale containing thin sandstone beds. Glauconite zones 6 inches thick occur 3 and 13 feet above base of this unit	24
Sandstone and sandy shale, thin bedded	77

[14] Butts, Charles, op. cit., p. 12.

	Feet
Sandstone, massive in upper part, thin to medium bedded in lower part; contains a 1-foot bed of glauconitic shale at the top	27
Sandy shale	26
Base concealed	
	366

WELL LOGS

The correlation between the principal wells in the Early Grove field is shown by generalized well logs in Figure 3. The formations penetrated by these wells are essentially the same in thickness and lithologic character as those that crop out northwest of the field, except that the Little Valley limestone is approximately 300 feet thicker in the wells than it is in the belt of outcrop. As shown in Figures 2 and 3, this thickening occurs mostly in the zone above the highest gas sand, but some also occurs at the base. According to the drillers' logs, the beds in the thickened interval are argillaceous limestones similar to those above the sands in the belt of outcrop. The following log of the Bristol Natural Gas Co. well No. 6, the upper part of which has been generalized, is typical of the wells in the field:

Log of Well No. 6

	Feet
Cove Creek limestone (at top)	45
Fido sandstone	64
Limestone of Gasper and Ste. Genevieve ages	2,456
St. Louis limestone	253
Little Valley limestone (978 feet):	
Shale, black, soft	21
Limestone, black, medium hard	48
Shale, black, medium soft	12
Shale, brown, soft	57
Shale, white, medium soft	28
Limestone, black, hard	179
Limestone, black, medium hard	33
Limestone, shaly, gray, medium hard	95
Limestone, black, medium hard	23
Limestone, shaly, gray, medium hard	37
Limestone, light gray, medium hard	82
Sandstone, gray, medium hard	27

	Feet
Shale, blue, medium hard	50
Sandstone, gray, medium hard	25
Limestone, shaly, gray, medium hard	6
Sandstone, gray, medium hard	30
Limestone, shaly, gray, medium hard	105
Sandstone, gray, medium hard	45
Limestone, gray, medium hard	75
Maccrady shale:	
Shale and sandstone, red	55
Price sandstone	
	3,851

The thickening of this part of the Mississippian section in the area of the Early Grove gas field is compatible with the abrupt change in lithologic character that occurs between the Price sandstone and the overlying limestone and suggests either a change in the position of the old shore line or deepening of the Mississippian limestone basin of deposition.

The gas-bearing sands are also somewhat thicker in the well logs than they are in the measured sections at the outcrop, but they fall into two clearly defined zones, one about 200 feet above the other, as do the sandstones at the outcrop. Neither zone is continuous, but the upper zone, which is the best exposed of the two at the surface and which apparently is continuous in the belt of outcrop, is also the more persistent of the two zones in the wells. There is clear evidence in the well logs as shown in Figure 3, however, that the upper zone, which is continuous between wells Nos. 1, 5, and 6, is not present in well No. 3 to the southwest. Similarly, the lower gas-bearing zone that is present in wells Nos. 3 and 6 is not present in No. 1, and if it is present at the site of well No. 5 it lies a little deeper than the bottom of the hole.

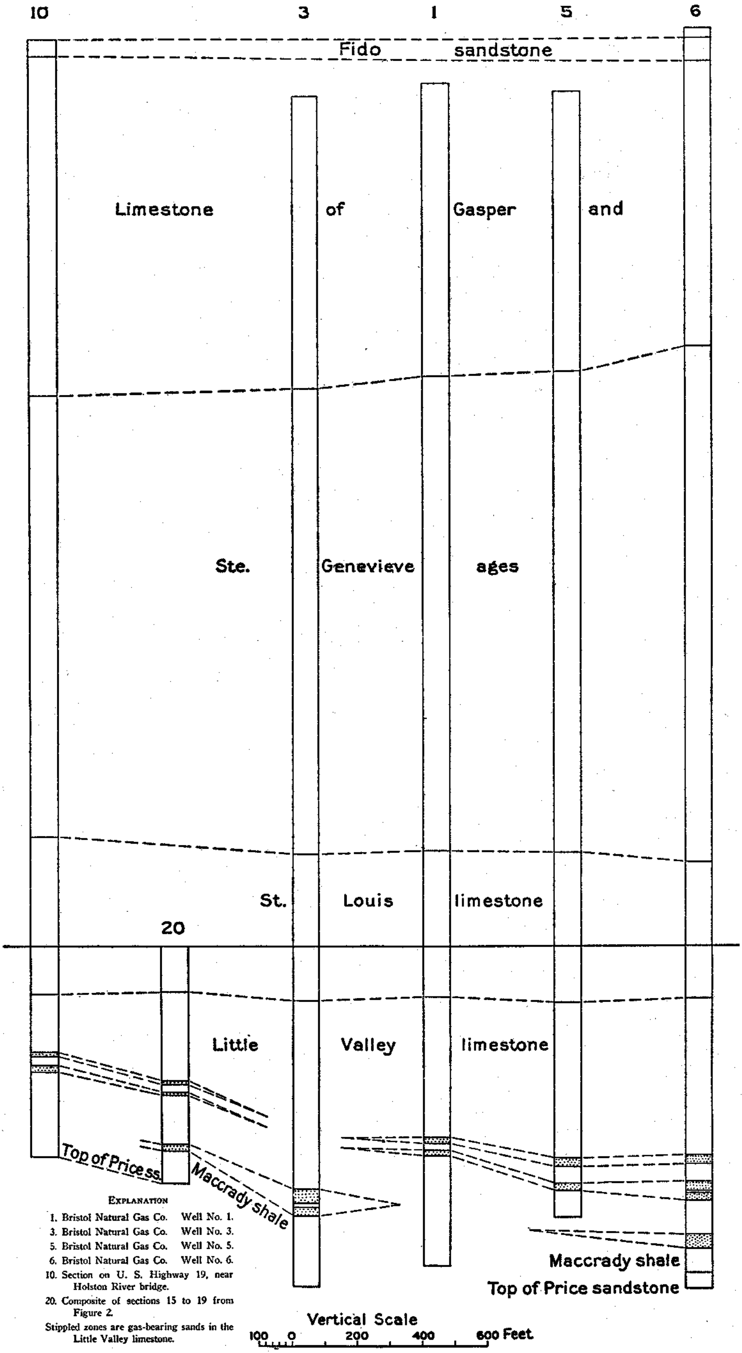

FIGURE 3—Correlation chart showing thickening of the Little Valley limestone between surface outcrops and wells in the Early Grove gas field.

LABORATORY STUDIES OF THE GAS SANDS

For the purpose of obtaining data on the porosity, permeability, and composition of the sandstones in the Little Valley, Maccrady, and Price formations, eleven samples of unweathered rock were collected in the belt of outcrop northwest of the Early Grove field. Well cuttings also were available for this study, but the rock fragments were too small to use in determining physical characteristics. The localities from which samples were taken are numbered on Plate 1 as follows:

No. 10. U. S. Highway 19 at Holston River bridge, Brumley quadrangle.

13. State road 614-622, opposite mouth of Nordyke Creek, Wallace quadrangle.

14. State road 614, one-fourth of a mile east of Pine Grove, Mendota quadrangle.

15. Southern Railroad, half a mile southeast of Mendota, Mendota quadrangle.

18. Hilton Gap, U. S. Highway 58-421, Hilton quadrangle.

19. State road 689, one-fourth of a mile east of Hilton Gap, Hilton quadrangle.

The sections measured at these localities are shown in Figure 2, and the bed in each section from which a sample was taken is indicated by a letter. As shown by Figure 2, seven samples were taken from the upper sand zone in the Little Valley limestone, one from a higher "stray" sand, and three from the top sandstone bed in the Price. The lower sand zone in the Little Valley limestone was so badly weathered in all exposures that samples of fresh rock were unobtainable.

All the tests on these samples were made by P. G. Nutting of the Federal Geological Survey, whose comments are as follows:

"All samples are exceedingly hard and tough. All appear to be medium to fine beach sand lightly cemented with silica and heavily impregnated with the carbonates of calcium, magnesium, and iron."

Porosity.—The porosity determinations were made by subtracting the lump density of the samples from the mean grain density and dividing the difference by the lump density to give percentage. The results are given in Table 1.

TABLE 1.—*Porosity of sandstones in the Early Grove gas field*

Sample No.	Formation	Lump density (grams per cu. cm.)	Mean grain density (grams per cu. cm.)	Porosity (per cent)
10a	Little Valley............	2.6629	2.6752	0.46
10b	Little Valley............	2.6043	2.6443	1.51
10c	Little Valley............	2.6329	2.6572	.91
10d	Little Valley............	2.5643	2.6987	4.97
13a	Little Valley............	2.5986	2.6211	.86
13b	Little Valley............	2.5800	2.6698	3.36
14a	Price..................	2.6093	2.6441	1.32
15a	Price..................	2.6987	2.6937	0.00
15b	Little Valley............	2.6662	2.6711	.18
18a	Price..................	2.6371	2.6938	2.10
19a	Little Valley............	2.6492	2.6689	.74

The average porosity of the Little Valley sands is 1.62 per cent, a figure that is low as compared to most gas sands. Other factors being equal, it indicates that a fairly rapid decline in pressure may be expected to follow production from the field, which, in turn, implies a relatively short life for the wells. The average porosity of the Price sandstones, which are not gas-bearing, but which are included in this study for comparison, is 1.11 per cent.

Permeability.—In determining the permeability of the samples, discs of rock 4 mm. thick and about half an inch in diameter were placed with gaskets over a hole 10 mm. in diameter and subjected to a water pressure of 75 pounds per square inch. The flow of water through none of the discs was sufficient to measure. On a few discs fine drops of "sweat" appeared after 15 minutes, but in none was the flow as great as 0.1 cu. cm. per hour. Assuming, however, that evaporation retarded flow somewhat, and that the rate of flow through the discs was 0.1 cu. cm. per hour, permeability may be computed by the following formula:

$$K = \frac{LFu}{AP}$$

where

K=Permeability in darcys
L=Thickness of disc in cm.= .4
F=Flow in cu. cm. per sec.= .000028
u=Viscosity in centipoises=1 for water at 20° C.
A=Area in cm. = .7854
P=Pressure drop in atmospheres= 5.

Substituting these figures in the formula;

$$K = \frac{.4 \times .000028 \times 1}{.7854 \times 5} = .00000285 \text{ darcys} = .00285 \text{ millidarcys}$$

The permeability of .00285 millidarcys is expressed in terms of water at 20° C. although natural gas, which has a viscosity of approximately .01 centipoise, moves through small openings 100 times faster than water. Nevertheless, the permeability of the Little Valley sands is quite low even for sands containing only 1.6 per cent pore space, and gas wells that produce from such a reservoir are likely to show a rapid decline in pressure during periods of withdrawal, and a correspondingly slow recovery after being shut in. Moreover, the amount of gas that can be taken from such a reservoir decreases as the rate of withdrawal increases, and under conditions of very rapid withdrawal well pressures can be reduced to the zero point of usefulness although a quantity of gas remains in the sands. It follows that a field producing from sands of low porosity and permeability will have a longer useful life and a greater ultimate yield if the total number of wells that are necessary to define the field are drilled in the initial stages of production so that the drain on each well can be kept at the minimum for its entire life.

Composition.—Analyses of the samples were made by using the 100-mesh material that had been prepared for grain density determinations. This was allowed to soak overnight in warm 20 per cent hydrochloric acid containing a little nitric acid. The residue after filtering was pure quartz containing a trace (2 per cent) of feldspar. Iron, calcium, and magnesium were determined in the filtrate and the calcium and magnesium calculated as carbonates. The results of the analyses are as follows:

TABLE 2.—*Composition of sandstones in the Early Grove gas field*

Sample No.	SiO_2 (per cent)	R_2O_3 (per cent)	$CaCO_3$ (per cent)	$MgCO_3$ (per cent)	Total (per cent)
10a	57.8	1.5	16.2	24.5	100.0
10b	82.1	4.4	14.1	....	100.6
10c	82.2	3.1	15.7	....	101.0
10d	62.0	3.8	18.2	16.7	100.7
13a	67.8	3.6	14.5	12.9	98.8
13b	69.0	4.0	14.0	12.5	99.5
14a	92.7	3.8	.4	....	96.9
15a	90.7	4.6	1.5	....	96.8
15b	51.0	3.0	24.5	24.7	103.2
18a	93.0	4.2	.2	....	97.4
19a	61.5	5.0	13.9	14.4	94.8

The iron, which is present in substantial amounts in all specimens, probably exists in part as a carbonate, either in the dolomite molecule or in the form of siderite, but, for the sake of convenience, it is reported above as R_2O_3, which is mostly Fe_2O_3. All samples contained some organic matter, particularly Nos. 10a, 15b, and 19a; and in addition, Nos. 10a and 15b gave a show of light oil.

The three samples of Price sandstone that were included in the tests, Nos. 14a, 15a, and 18a, stand out conspicuously in the analyses because of their high silica content, which is a point of difference between the Price and Little Valley sands that might have been anticipated in view of the hard, almost quartzitic character of the Price. The remaining specimens, however, contain a fairly large amount of carbonate material, averaging 29.6 per cent exclusive of the iron.

Thin sections of two Little Valley sand samples, Nos. 10a and 19a, showed subrounded quartz grains embedded in carbonates. Many of the quartz grains were not in individual contact, and deposition of the quartz and carbonates undoubtedly occurred simultaneously. A thin section of Price sandstone, No. 15a, showed more abundant small quartz grains cemented by very fine-grained crystalline silica and calcium carbonate.

STRUCTURE

General Features

The rocks of the Appalachian Valley in Virginia have been steeply tilted, folded into anticlines and synclines, and broken by thrust faults. The deformed beds dip southeast throughout most of the region and the planes of folding and faulting generally are inclined in the same direction. The Saltville thrust fault, which forms the southeast boundary of the Early Grove area, is one of the larger faults in the Appalachian Valley province.[15] Movement on this fault, which is overthrust from the southeast similar to others in the province, occurred in part simultaneously with folding in the adjacent Early Grove area during the regional deformation.

Northwest of the belt of folded Mississippian rocks that comprise the Early Grove area is a normal stratigraphic sequence of older Paleozoic rocks, all of which dip uniformly to the southeast. South of the folded belt on the opposite side of the Saltville thrust fault lie highly deformed Cambrian limestones and dolomites, which also dip southeast.

Methods of Representing Structure

On the geologic map of the Early Grove area (Pl. 1) faults are shown by heavy lines marked by a T on the upthrown or overthrust side of thrust faults and by the letter D on the downthrown side of normal faults. The attitude of the beds in various parts of the area is shown by dip and strike symbols and by fold axes. In order to provide a measure of the rate of plunge on the Early Grove anticlinal axis, a distinctive fossiliferous bed 275 feet above the base of the Cove Creek limestone has been mappd at the ends of the structure. Similarly, closure on the Browder Mountain anticline is shown by a line representing the top of a sandstone that lies 200 feet below the base of the Pennington shale.

Faults

The dominant structural feature of the Early Grove area is the Saltville thrust fault. Throughout most of its length in the area rocks of Cambrian age—the Rome formation, Honaker dolomite, and lower members of the Knox—are in contact with the Pennington shale of Chester (Mississippian) age, a stratigraphic displacement of approximately 15,000 feet. Northeast of U. S. Highway 58-421, however, an overturned and internally faulted block of Paleozoic formations rang-

[15] Butts, Charles, Geologic map of the Appalachian Valley of Virginia with explanatory text: Virginia Geol. Survey Bull. 42, 1933.

ing in age from Ordovician to Mississippian is exposed for a distance of approximately 4 miles between branches of the fault. The part of this block that involves beds of Gasper age, and the Fido and Cove Creek formations is shown on the geologic map (Pl. 1).

In general the plane of the Saltville fault dips southeast at an angle less than 30 degrees, and observations suggest that the minimum angle may approach zero in some places. The isolated overthrust mass, or klippe, of Honaker dolomite at Glenwood School, for example, lies one mile in front of the main body of Cambrian rocks at an altitude that is comparable to altitudes elsewhere on the trace of the fault. The outcrop pattern of the fault at the head of Venus Branch shows also that here the fault plane is very nearly horizontal.

The exact relationship between movement on the Saltville fault and structures in the adjacent Mississippian belt cannot be ascertained, but certain inferences can be drawn from a study of the position of the Glenwood School klippe, which lies on the axis of the Vineyard Ridge syncline. Between the klippe and the main mass of Cambrian rocks to the south is the topographically higher Browder Mountain, the vertical north limb of the Browder Mountain anticline, which deforms only Mississippian rocks. The trace of the Saltville fault, however, forms an arc around the south side of the anticline. Assuming that the fault extended north as far as the Glenwood School klippe, it follows that the fault plane must have arched up over the position of the Browder Mountain anticline and down to the position of the klippe on the axis of the Vineyard Ridge syncline. The folding thus assumed for the fault plane is very gentle in comparison with the folding of the underlying beds but the two sets of structural axes coincide. In addition to providing a reasonable explanation for the preservation of the klippe by assuming it to be a remnant of a syncline in the Cambrian rocks of the overthrust mass, this relationship suggests also that the Mississippian beds were deformed by movement on the fault, and that the fault plane was, in turn, slightly deformed along the preexisting axes during later stages of movement. The simultaneous deformation of beds above and below the fault is also suggested by the alinement of the axis of the Vineyard Ridge syncline with the infolded or infaulted wedge of Cambrian rocks near Shadylawn School at the head of Fowlers Branch.

A thrust fault of very small displacement is exposed at three places between Grindstone Branch and Cove Creek. At Cove Creek a cross section of the fault plane in the small quarry on State road 630 near Ketron (Fig. 4) shows clearly that the fault movement dies out along bedding planes and suggests that other similar faults might exist in the Pennington and be unrecognizable.

Another small thrust fault may be present parallel to Ridgeway Hollow between U. S. Highway 58-421 and the Washington-Scott county line, half a mile up the hollow. One exposure of vertical beds at water level on the county line in a small tributary of Ridgeway Hollow

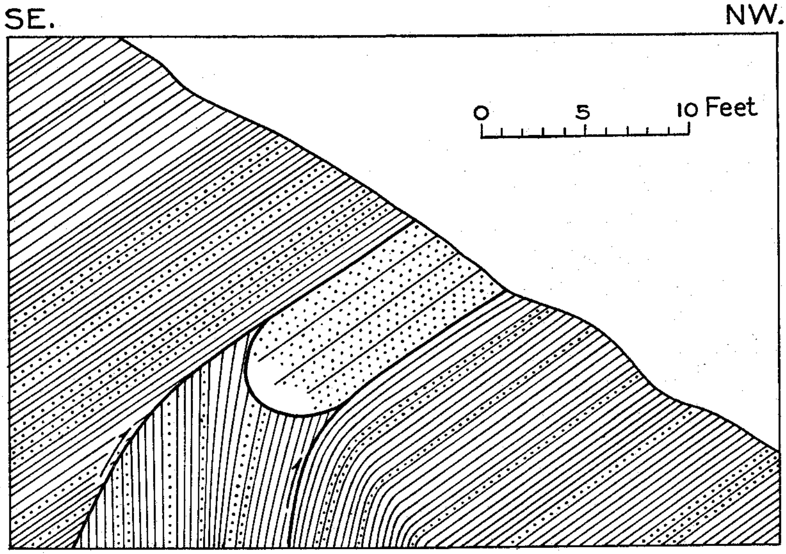

FIGURE 4.—Diagram of thrust faulting in Pennington shale on State road 630, near Ketron, Virginia.

cannot definitely be attributed to the landsliding which is characteristic of this zone in the Pennington, but in the absence of other confirming evidence no fault is shown on the map at this locality.

The only normal fault in the area occurs near Free Hill Church in Caney Valley. The Fido sandstone here is displaced upward on the east side by a southward-trending fault, which does not break the beds at the Cove Creek-Pennington contact, and which is alined with a very small anticlinal structure in the head of the East Fork of Nordyke Creek. The beds south of this locality are not deformed.

FOLDS

Fold axes in the Early Grove area are arranged in two belts roughly parallel to the Saltville fault. The anticlinal axes, which lie nearest the fault, stand out clearly on the geologic map (Pl. 1). Beginning with the Browder Mountain anticline in the southwest and extending to the Wolf Run anticline in the northeast, each successive anticlinal axis is offset to the north, and the plunging ends of adjacent structures overlap somewhat in an *en echelon* arrangement. The synclinal axes, although less definite, are alined similarly in a belt parallel to and northwest of the anticlinal belt. The beds northwest of the synclinal belt dip uniformly to the southeast.

Browder Mountain anticline.—Southwesternmost of the series of anticlinal axes is the Browder Mountain anticline, the higher parts of which are shown on the geologic map (Pl. 1) as an area of Cove Creek limestone. The northern flank of the structure is vertical and the southern flank dips south at angles ranging between 7 and 30 degrees. Closure on the axis is indicated by a line drawn on the top of a sandstone bed that lies 200 feet below the base of the Pennington shale. This structure is more closely folded than any of the others in the area, and the beds along the eastern end of the axis are slightly deformed and broken. The axis here might have been mapped as a fault had there been any significant displacement.

Vineyard Ridge syncline.—The Vineyard Ridge syncline is 0.7 mile north of and parallel to the Browder Mountain anticline with which it is complementary. It is also asymmetric, having a steeply dipping south flank and a very gently dipping north flank, which includes most of the drainage area between Roberts Creek and Fowler Branch. In addition, it is more closely folded at the western end where it disappears under the Saltville fault than it is at the eastern end where the beds rise onto the northern flank of the New Hurlin anticlinal nose.

New Hurlin anticlinal nose.—The only member of the *en echelon* series of anticlinal axes that is not typical of the group is the New Hurlin anticlinal nose, which is essentially the southwestward plunging end of the Early Grove anticline. It is separated from this main axis, however, by a very small syncline as shown on the geologic map (Pl. 1). It is separated from the Browder Mountain anticline at the west end by another small syncline, which may be observed in a tributary of Timbertree Branch near the junction of State roads 694 and 698. The axis of the New Hurlin anticlinal nose plunges southwest at an angle that is nearly as steep as the dip of the beds on the flanks, and its position is based as much on a small but constant variation in the direction of strike of beds as it is on reversals in dip.

Early Grove anticline.—The Early Grove anticline, the most conspicuous structural feature in the belt of Mississippian rocks, is 7 miles long and more than a mile wide. It is arched sufficiently to expose limestone of Gasper age along higher parts of the axis. On the geologic map (Pl. 1) its position is marked by the conspicuous oval-shaped outcrop of Cove Creek limestone. The tributaries of Cove Creek have cut deeply into the structure relative to other parts of the area and it now appears as a topographic basin which contains a few hills and ridges of low relief. The axis of the structure is marked by a very narrow zone of gentle dips. On either side of this zone the beds dip at angles ranging from 10 degrees near the axis to 25 degrees half a mile away. From the highest point on the axis in the largest outcrop area of limestone of Gasper age the plunge is gentle to the limits of the Fido sandstone outcrop at either end. Between well No. 1 and U. S. Highway 58-421, for example, the axis plunges 60 feet per mile. Beginning at Highway 58-421, however, the southwestward plunge increases to a rate of about 385 feet per mile between that point and the point where the fossiliferous bed 275 feet above the base of the Cove Creek limestone disappears below drainage. This general rate of plunge is maintained for three-quarters of a mile to a point one mile southwest of the point where the Fido sandstone disappears below drainage, but in the head of West Fork of Cove Creek the rate of plunge decreases. Farther west in Lick Branch the axis approaches the horizontal, and somewhere near the point where it is joined by the minor anticlinal axis that extends into the head of Gouldman Hollow there is a slight reversal of plunge. The Gouldman Hollow anticline is but one of several subsidiary folds that occur on the north side of the Early Grove anticline. This minor fold can be observed where it crosses the divide between the East Fork of Gouldman Hollow and Lick Branch, and in other places indicated on the geologic map (Pl. 1) by dip symbols. It is separated from the Early Grove anticline by a very small syncline about one mile long, which dies out to the northeast in the Pennington-capped ridge between Gouldman Hollow and Cove Creek. Minor folding occurs also in a tributary of West Fork of Cove Creek. This is indicated on the geologic map by a synclinal and an anticlinal axis. The beds between the synclinal axis and the axis of the Early Grove anticline are, in addition, slightly undulating. These minor structures were not observed to continue in either direction beyond the limits indicated on the map. Continuing from the head of Lick Branch, the Early Grove anticline plunges gently westward to a point on the divide between Gouldman Hollow and Timbertree Branch beyond which it ceases to exist.

The axis of the Early Grove anticline plunges very gently northeastward, the average rate of plunge between a point near the crest and a point near McCall Gap being approximately 210 feet per mile as against the average of 385 feet per mile southwestward. Northeast of McCall Gap, however, the plunge steepens greatly to an average rate of 715 feet per mile between McCall Gap and a point on the northeast side of Max Hollow. From Max Hollow to Livingston Creek the rate of plunge is 540 feet per mile. Northeast of Livingston Creek the anticline is narrow and poorly defined. It may be traced, however, as far northeast as Abrams Creek where a sharp flexure in the rocks may be seen half a mile above Abrams Falls. No minor flexures are associated with the northeast end of the axis, but several local areas of very low dip occur along Livingston Creek near the mouth of Max Hollow in a position where they might easily be mistaken for the continuation of the Early Grove axis.

Cove Ridge syncline.—The axis of the Cove Ridge syncline, which is complementary to the Early Grove anticline, crosses U. S. Highway 58-421 near Muddy Gap and Livingston Creek near the junction of the two forks. It is well exposed in both places. In Muddy Gap, however, the exact position of the axis is obscured by the presence of small scale subsidiary folding which can be observed nowhere except in the highway cuts. Folding on the axis dies out in Dry Branch to the southwest and in a tributary of Abrams Creek to the northeast. There is no reversal of dip in Abrams Creek although the Cove Ridge synclinal axis is perfectly alined with the axis of a small syncline northeast of Abrams Creek.

Wolf Run anticline.—Northeasternmost of the *en echelon* series of anticlinal axes in the Early Grove area is the Wolf Run anticline, the axis of which is well exposed in Wolf Run, one mile north of Benham near the junction of State roads 627 and 628. It may also be seen in Nordyke Creek, 2 miles to the northeast. This axis has been traced half a mile northeast of Nordyke Creek and 2 miles southwest of Wolf Run, a total of approximately 4½ miles, but for most of this distance it is a structure of very small magnitude. The highest part of the anticline is approximately a quarter of a mile west of Wolf Run, and the plunge on the axis is fairly rapid in both directions. It can be observed to end at the southwest in an area of nearly horizontal beds about a quarter of a mile northeast of Abrams Creek. The small syncline, which is parallel to the Wolf Run anticline on the northwest, dies out in this area also, and no trace of either structure is to be seen in Abrams Creek. The anticline terminates somewhat more abruptly at the northeast end in a very narrow zone of sharply folded beds.

Abrams Falls syncline.—The area between the northeast end of the Early Grove anticline and the southwest end of the Wolf Run anticline is a basin-shaped syncline. It is limited in extent on three sides by previously described folds, and on the fourth by the regional dip of beds on the south flank of the Wolf Run anticline.

Nordyke Creek syncline.—The Nordyke Creek syncline, which limits the extent of the Wolf Run anticline on the north, is also a small, unimportant structure. It is unsymmetrical in that it is broader and deeper at the west end corresponding to the higher portion of the Wolf

Run anticline, and like the Wolf Run anticline it dies out to the northeast in a narrow zone of sharply folded beds. To the west the beds close around the basin-like end of the syncline near the Wolfrun post office and there is no structural connection with the small, northeast-trending syncline to the southwest. The beds near Wolfrun post office in the zone between the two synclinal axes are somewhat distorted, but there is no evidence that faulting accompanied the change in structural trend that occurs here.

JOINTS

The best developed set of joints in the Early Grove area strikes 10 to 15 degrees north of the regional trend of the beds, and dips at high angles. The joint planes on the flanks of the Early Grove anticline are inclined towards the axis of the structure, whereas those on the flanks of the Cove Ridge syncline are inclined away from the axis of the structure. A second set of joints essentially normal to the first and also nearly vertical is much less conspicuous but is generally present. On the north flank of the Cove Ridge syncline, particularly half a mile northeast of Beech Grove School, a third, nearly horizontal set of joints striking north 65 degrees east, and dipping 10 degrees west, gives the appearance of bedding. This set, however, was not observed elsewhere.

If it can be assumed that the joints were formed during early stages of the compression that produced the folds, the divergence between the strike of strike joints and the strike of fold axes and bedding indicates that the compressive stress was not normal to the fold axes. The *en echelon* arrangement of the fold axes, moreover, in which the end of each axis is offset north of the one to the southwest (Pl. 1), suggests that movement was normal neither to the fold axes nor to the strike joints. It is probable, therefore, that compression was oriented obliquely to the fold axes and to the strike of the joints.

RELATION OF DRAINAGE TO STRUCTURE

The Appalachian Valley has been a land area for a considerable part of geologic time during which the streams have passed through several distinct erosion cycles. Evidence of the antiquity of the drainage is found in the almost perfect adjustment to rock composition and structure. Evidence of earlier erosion cycles is indicated by occasional anomalous drainage features.

The North Fork of Holston River, tributaries of which drain most of the Early Grove area, is a typical Appalachian Valley stream following a meandering course, but confined for the most part to the belt of soft Mississippian limestone and shale southeast of Pine Ridge. Some meanders, however, cut Pine Ridge with apparent disregard of the hard Price sandstone. Obviously, they were formed in an earlier erosion cycle when there was slight surface relief in the valley. The tributaries of the North Fork of Holston River that drain the Early Grove area are adjusted to a notable degree to the structure. The headwaters of Cove Creek, for example, flow along the axis of the Early Grove anticline; Livingston Creek flows parallel to the strike of beds on the northeast side of the plunging nose of the anticline; Abrams Creek flows in a zone of no deformation between the plunging ends of two structures; the major turn in the course of Wolf Run occurs at a point of disturbance in the beds. and Timbertree Branch flows parallel to the strike of the bedding throughout most of its length.

GAS RESOURCES AND POSSIBILITIES

General Considerations

The amount of deformation the rocks in the Appalachian Valley in Virginia have undergone has rendered most of the region unsuitable for the accumulation of gas and oil. The occurrence of gas in the Early Grove area, therefore, is possible only because a wide belt of relatively undisturbed rocks has been preserved northwest of the Saltville fault. The rocks in this belt, however, have dips that range from zero to 30 degrees, and are folded more sharply than the rocks in most gas fields.

The composition of the Early Grove gas, and the porosity and permeability of the reservoir rocks all give strong evidence that oil in commercial quantities does not occur in association with the gas. Studies in Pennsylvania[16] and West Virginia[17] have shown that the methane content of natural gas increases eastward on the eastern edge of the Appalachian bituminous coal field in a manner similar to the increase in fixed carbon content of the coal. The gas in the Early Grove area contains 98.2 per cent methane on a dry, inert-gas free basis. Gas of this composition occurs east of all oil-producing areas in Pennsylvania and West Virginia, and gas of slightly lower methane content occurs northwest of the Early Grove field in Wise County, Virginia, where the fixed carbon content of coal ranges between 62 and 65 per cent. The metamorphism in the Early Grove area, therefore, is comparable to that in a region where the fixed carbon content of the coal is 65 per cent or higher. This figure is well above the 60 per cent set by White[18] as approximately the highest percentage compatible with the occurrence of oil. As has been stated on page 27, the gas-bearing sands in the Early Grove field have an average porosity of 1.6 per cent and a permeability of the order of .00285 millidarcys. That migration of gas through these beds is retarded to a considerable extent by friction is evident from the behavior of the wells. If oil were present—a fact that is not borne out by a consideration of the relationship existing between the occurrence of oil and the composition of the associated gas—its migration through these beds would proceed many times more slowly than natural gas and commercial production under those circumstances would be impossible.

[16] Hamilton, S. H., Oriskany explorations in Pennsylvania and New York: Am. Assoc. Petroleum Geologists Bull., vol. 21, no. 12, pp. 1582-1591, December, 1937.

[17] Price, P. H., and Headley, A. J. W., Physical and chemical properties of natural gas in West Virginia: West Virginia Geol. Survey Bull., vol. 19, pp. 147-160, 1937.

[18] White, David, Some relations in origin between coal and oil: Washington Acad. Sci. Jour., vol. 5, no. 6, p. 210, 1915.

HISTORY OF DRILLING AND PRODUCTION

Nine wells have been drilled in attempts to find gas in or near the Early Grove area. Five of these, as shown by the records in Table 3, have produced gas and four were dry. The four unsuccessful wells all were unfavorably located with regard to geologic structure, and, with the exception of the No. 2 well of the Bristol Natural Gas Corp., no information is available for them.

The first productive well, No. 1 of the Bristol Natural Gas Corp.,[19] was drilled in 1931 near the highest part of the axis of the Early Grove anticline following the suggestions of Butts[20] in a report prepared through joint cooperation between the Geological Survey of the United States Department of the Interior and the Virginia Geological Survey. The success of this well, which had an initial yield of 1,750,000 cubic feet per day, led to the drilling of well No. 2, 1,700 feet south of the axis of the anticline. Although no gas was found in this well it gave a suggestion as to the limit of production on the south flank of the structure, and the absence of water in the gas sands indicated that there was no water drive in the field. Well No. 3, which was drilled in 1935, was located southwest of No. 1 and near the axis. It had an initial yield of 200,000 cubic feet per day, which was obtained from a lower sand zone than that encountered in well No. 1. Well No. 4, drilled in 1937, was located according to geophysical data which indicated a subsurface structural "high" 1,250 feet north of the axis of the anticline. The existence of the supposed "high" was disproved, but a small production of gas was obtained, which served to show the limits of production on the north flank of the structure. In March 1938, gas from these wells was turned into a newly constructed 4-inch pipeline built by the Industrial Gas Corp., for the purpose of supplying gas to Bristol, Virginia and Tennessee. Well No. 5, also on the axis of the anticline, but northeast of well No. 1, was completed in April 1938, with an initial yield of 1,500,000 cubic feet and well No. 6, northeast of No. 5, was completed in 1940 with an initial yield of 1,000,000 cubic feet. A new well northeast of No. 6 was being drilled during the summer of 1941.

DISTRIBUTION OF GAS SANDS

The study of the stratigraphy of the gas-bearing zones in the Little Valley limestone has revealed that, although the sandstone beds are not continuous, one or more are present in every exposure in the belt of outcrop northwest of the Early Grove area and in every well in that

[19] Wells Nos. 1 to 4 were drilled by the Davis Elkins interests, but have since been acquired by the Bristol Natural Gas Corporation. Wells Nos. 5 to 7 have been drilled by that corporation.

[20] Butts, Charles, Oil and gas possibilities at Early Grove, Scott County, Va.: Virginia Geol. Survey Bull. 27, 1927.

TABLE 3.—*Records of wells in Early Grove area, Scott and Washington counties, Virginia*

Well No. on Pl. 1	County	T. V. A. quadrangle	Farm	Operator	Altitude	Initial volume gas (cu. ft. per day of 24 hrs.)	Maximum pressure attained (in pounds)	Total depth	Completed	Remarks
1	Scott	Mendota	Earl S. Ridgeway	Bristol Natural Gas Co.	1,461.35	1,750,000	1,500	3,613	June 1931	....
2	Washington	Mendota	J. R. Smith Heirs	Bristol Natural Gas Co.	1,561.3	....	....	5,650	August 1932	Dry, abandoned.
3	Scott	Mendota	C. B. and J. H. Hunsucker	Bristol Natural Gas Co.	1,506.5	200,000	1,420	3,721	December 1935	Abandoned.
4	Scott	Mendota	G. W. Fleenor	Bristol Natural Gas Co.	1,510.9	75.000	1,465+	3,854	September, 1937	Small output, but pressure builds up quickly.
5	Scott	Mendota	E. D. Smith	Bristol Natural Gas Co.	1,459.1	1,500,000	1,500	3,435	April 1938	....
6	Washington	Mendota	Margaret Sproles	Bristol Natural Gas Co.	1,578.9	1,000,000	1,420	4,103	February 1940	Gas from four or more sandy zones.
*7	Washington	Brumley	John M. Arnold	Victor Behm	....	....	....	3,500-4,000	November 1935	Dry, abandoned. Well located two miles northeast of Greendale.
8	Washington	Wallace	W. E. Leonard	Holston Oil and Gas Co.	....	....	....	2,600±	About 1910	Dry, abandoned.
9	Washington	Mendota	Bailey Barker	Holston Oil and Gas Co.	....	....	....	2,500±	About 1915	Small pocket of gas burned rig

*Not on Pl. 1.

area. Although it is impossible to predict the extent of any one bed, the fact that as many as four are known to occur in some sections, together with the fact of the very general distribution stated above, indicates that the chances are excellent that at least one sandstone will be found in any well drilled in the area. At one place, however, the limits of two lenses are known. The major gas production from wells Nos. 1, 4, 5, and 6 is obtained from sandstone that constitutes a single lens. Not only do the zones correlate perfectly in a comparison of the well logs, but a definite thinning occurs from well No. 6 to well No. 1. (See Fig. 3.) Production from well No. 3, on the other hand, is obtained from a sandy zone approximately 200 feet lower than the sands in wells Nos. 1, 4, 5, and 6, and there is no trace of the higher lens in the log of well No. 3, and no trace of the lower one in the log of well No. 1. Further evidence of a lack of connection between these two lenses is found in the fact that there is no relationship in the pressure characteristics of well No. 1 and well No. 3, although there is apparently some relationship in pressure behavior between No. 1. and No. 5.

SUGGESTED NEW DRILLING SITES

Because the gas sands in the Early Grove area are generally fine grained and tight, it is likely that most gas will be obtained from wells near the crests of anticlines where the maximum amount of jointing has occurred. The two wells that have been drilled on the flanks of the Early Grove anticline, No. 2 and No. 4 of the Bristol Natural Gas Co., have yielded data to support this generalization. Well No. 2 was dry, indicating that gas does not extend far down the flanks of the structure. Well No. 4 is a small producer capable of yielding gas at a high pressure for a short time. It may easily be exhausted but when the well is shut-in the pressure soon builds up in a manner characteristic of a sand with small reservoir capacity. In view of these results, attempts to obtain commercial production from stratigraphic traps on the flanks of folds are likely to be unsuccessful, even though the lenticularity of the sands suggests that such traps may occur.

Well locations that appear to be favorable for future drilling on the basis of what is now known about the structure of the Early Grove area are discussed below.

A well on the axis of the Early Grove anticline, 1,500 to 1,800 feet northeast of well No. 6 of the Bristol Natural Gas Co., seems to offer a good chance of being a fair producer. The plunge on the axis is low in this direction, and the four sands that are known to yield gas in well No. 6 probably continue northeastward.

Depending somewhat upon the success of a well northeast of No. 6, successive locations between there and McCall Gap should be tested.

Because the axis of the anticline is plunging uniformly northeastward at an average rate of 210 feet per mile between a point near the crest and McCall Gap, it would be inadvisable to skip a location in the succession if the sands persist and if production is obtained in each new well. If the sands do not persist, a well might be drilled on the axis near McCall Gap as a final test of the northeast end of the structure. The axis of the anticline plunges steeply northeast of this point, however, and drilling should not be extended in this direction unless favorable results are obtained in the McCall Gap well.

The Early Grove anticlinal axis southwest of well No. 3 still must be considered as having gas possibilities in spite of the fact that No. 3 was not a large well, and in spite of the fact that the higher sandstone zones of the northeast end of the field are not present. The outcrop of limestone of Gasper age on the axis near U. S. Highway 58-421 is only 60 feet lower structurally than the outcrop at well No. 1 and is a very convenient location on which to test the southwest end of the structure. The Early Grove axis plunges steeply a short distance southwest of Highway 58-421, and there is the chance that a local accumulation of gas would be found near the point of change in dip. Furthermore, the possibility exists that sandstone will reappear at the position of the higher beds. This suggested site is slightly more than 3,000 feet southwest of No. 3, and, in the event of a successful well, there is room for an additional one on the axis midway between Highway 58-421 and No. 3, and perhaps another southwest of Highway 58-421 on the more steeply plunging part of the axis.

The well locations suggested above represent only those that would be drilled in the normal development of the Early Grove anticline, and the procedure as outlined insures that the limits of the field along the axis will be ascertained in a fairly economical manner.

Another well site that has good possibilities, but which definitely must be classed as a wildcat, is the rise on the Early Grove anticlinal axis in the head of Lick Branch. The highest point structurally in this area is obscured by the presence of the several local fold axes shown on the geologic map (Pl. 1), but it probably lies near the junction of the two anticlinal axes. A well on Lick Branch on either of the two axes will serve to test the area adequately because the intervening syncline probably does not extend to the depth of the gas-bearing zones. At either of these points the depth to the top of the Fido sandstone is approximately 700 feet; below the Fido the depth to the gas-bearing zones in the Little Valley limestone should be about 3,500 feet.

The Wolf Run anticline, the highest part of which lies a short distance west of Wolf Run, also may be considered to have gas possibilities. However, because the structure is short and narrow as compared to the Early Grove anticline, and because the depth to the gas sands is more than 5,000 feet, there is slight chance of a profitable return on the cost of an exploratory well.

The Browder Mountain anticline is too small and too intensely folded to have promise as a source of gas in commercial quantities. However, for one inclined to take the great risk involved, a location on the small knob 400 feet south of the divide between Browder Hollow and Polecat Hollow appears to be far enough south of the axis so that a well will penetrate only the gently dipping beds of the south flank and yet be in the fractured zone near the crest of the anticline.

No other structure in the Early Grove area appears to offer a suitable trap for the accumulation of natural gas.

Locations immediately southeast of the trace of the Saltville thrust fault have been considered by some to be favorable sites for wells because of the chance that gas might be concentrated in places where the broken and upturned edges of the gas-bearing zones are sealed against the fault. Movement on the fault plane, however, has been rather great, and it is impossible to predict with any certainty where, on the surface of the overriding mass of Cambrian rocks, a well would have to be placed in order to penetrate the gas-bearing sand zone of the Little Valley limestone. The isolated mass of beds of Cove Creek, Fido, and Gasper ages shown on the geologic map (Pl. 1) in the fault zone northeast of U. S. Highway 58-421 is only part of a much larger mass of internally faulted Paleozoic rocks[21] that has been completely detached from the parent body of Paleozoic rocks, overturned, and moved along the plane of the fault. This suggests that the upturned edges of the main mass are some distance back from the trace of the fault, and consequently at considerable depth below the surface.

In choosing possible well sites on the folds several general principles should be considered. The fact already mentioned that the crests of anticlines, in addition to their obvious structural advantages, appear to offer more reservoir space is the most important. If, however, a well site directly on an axis is inaccessible, or if the exact position of an axis cannot be ascertained, it may then be best to choose a location a short distance south of the axis in preference to one north of the axis. Several reasons support this view. First, if the area of rocks that rises to the crest of the anticlines is important in determining the amount of gas that might migrate upward, then a location south of an axis is better because the area in which upward migration of gas might take place is greater on the south flank of each anticline than it is on the north. Furthermore, in asymmetric folds of the Appalachian Valley type, the planes of folding curve downward towards

[21] Butts, Charles, Geologic map of the Appalachian Valley of Virginia with explanatory text: Virginia Geol. Survey Bull. 42, 1933.

the southeast, and the crests of folds underground are southeast of the axes as determined at the surface. Although there is no evidence in the outcrops to suggest that this is true in the Early Grove area, it is a possibility that weighs in favor of locations south of an axis as against locations north of an axis.

DEEP DRILLING

The beds below the Little Valley limestone—in descending order, the Price sandstone, the Devonian shale, the Onondaga limestone, the Clinton formation, and the Clinch sandstone—in general, do not have gas possibilities, and the Oriskany sandstone, which is a good producing zone elsewhere, is absent in the zone of outcrop northwest of the Early Grove area. The Price sands are more siliceous and less porous than the sandstone beds in the overlying Little Valley limestone, and the shale in the Price sandstone is not a source rock of either oil or gas. The Devonian shale, although similar in appearance and composition to the black, gas-bearing shale of the same age in Kentucky, is apparently less carbonaceous in the Early Grove area. However, if gas is obtained in the Early Grove field from beds lower than the sandstone beds in the Little Valley limestone, the Devonian shale is the most likely place of occurrence. The best and most efficient way of testing these beds would be to extend one of the wells now producing from the Little Valley sands on the crest of the Early Grove anticline at the time when it must be abandoned. The formations below the Devonian shale are not generally suitable as reservoir rocks, although gas has been obtained locally in both the Onondaga limestone and the Clinch sandstone, and in view of their great depth below the surface it is doubtful if a well to these beds would be profitable. The interval between the top of the Price and the top of the Clinch is approximately 2,845 feet, divided as follows: Price sandstone, 805 feet; Devonian shale, 1,765 feet; Onondaga limestone, 75 feet; and the Clinton formation, 200 feet. It follows that a well over 6,000 feet deep would be required to reach the Clinch sandstone on the crest of the Early Grove anticline.

COMPOSITION OF GAS

An analysis of gas from the Bristol Natural Gas Co. well No. 1, together with heating value and specific gravity determinations made on a composite sample from all wells, is as follows:[22]

Analysis of gas from Bristol Natural Gas Co. well No. 1

Carbon dioxide	0.00
Oxygen	0.00
Methane	97.89

[22] By W. W. Allerton, 1022 Watauga St., Kingsport, Tenn.

Ethane	1.57
Propane	——
Butane	.14
Pentane	——
Nitrogen	.40
Total	100.00
Moisture	None

Composite sample from all wells:

B. t. u.	at 760 mm. and 60° F.	1,028.5	
S. G.	at 760 mm. and 60° F.	.563	(Air=1.00)

The analysis was made with a Podbielniak fractional distillation column in conjunction with a U. S. Bureau of Mines mercury orsat. All items of this analysis are on a dry basis.

PRODUCTION AND PRESSURE DATA

The annual yield of metered gas, together with the estimated amounts of gas used in drilling and lost during completion of the five producing wells in the Early Grove area is tabulated below.

TABLE 4.—*Annual yield of gas from the Early Grove field, 1931-1940 (in thousands of cubic feet)*

Year	Metered yield	Used in drilling (estimated)	Lost during completion of wells (estimated)	Total
1931	....	....	200,000	200,000
1932	....	....	....	....
1933	....	....	....	....
1934	....	....	....	....
1935	....	2,000	2,000	4,000
1936	....	....	....	....
1937	....	2,400	1,200	3,600
1938	41,024	1,900	14,370	57,294
1939	66,539	2,000	3,000	71,539
1940	92,758	900	7,000	100,658
	200,321	9,200	227,570	437,091

The pressure behavior of the wells in the field has not been uniform. Well No. 3, which produced from a lower sandstone zone than the other wells, yielded very little gas, lost pressure rapidly, and was abandoned early in 1941. Well No. 4, although producing from the same sand as the remainder of the wells, shows a very rapid decline in pressure and a slow recovery following withdrawals of only a few hundred thousand feet. It apparently has a very small reservoir capacity and, due to low porosity and permeability of the sands, has no connection with the rest of the field. Pressure readings on these two wells, therefore, are not included in the field averages given in Table 5 below, although the insignificant production of each is included in the totals due to the fact that figures for the individual wells are not available.

The average initial pressure attained at the well heads of the three principal wells was 1,473 pounds per square inch. This figure, however, is somewhat lower than the true maximum because the pressure of well No. 6, the last well to be drilled, reached only 1,420 pounds, due in part to the general lowering of the pressure in the reservoir during 1938 and 1939, and in part to the fact that it was put to work before maximum pressure was attained. For this reason, 1,500 pounds, a pressure recorded at both well No. 1 and well No. 5, may be assumed to be the initial pressure of the field as measured at the well heads after approximately 200,000,000 cubic feet of gas had been lost from well No. 1.

The average pressures of the three wells at the end of June and December of 1938, 1939, and 1940, the gas production during the corresponding semiannual periods, and the cumulative production during the entire interval are given in the following table:

TABLE 5.—*Production and pressure of the Early Grove field, 1938-1940*

Date	GAS YIELD (thousands of cubic feet		Average well-head pressures at end of June and December of each year (pounds per square inch)
	Semiannual	Cumulative	
Dec. 1937	7,600	7,600	1,450 (No. 1)
June 1938	23,187	30,787	1,290 (Nos. 1 and 5)
Dec. 1938	34,107	64,894	1,025 (Nos. 1 and 5)
June 1939	28,820	93,714	1,110 (Nos. 1 and 5)
Dec. 1939	42,719	136,433	795 (Nos. 1 and 5)
June 1940	52,706	189,139	1,085* (Nos. 1, 5, and 6)
Dec. 1940	47,952	237,091	564 (Nos. 1, 5, and 6)

*Nos. 1 and 5 alone = 897.

The fact that pressures show a decrease between June and December of each year indicates that gas is being withdrawn from the field during the winter at a rate that is faster than the rate of adjustment of pressures between the wells and the areas of higher pressures around them. The pressure readings at the end of December of each year, therefore, are not indicative of the maximum pressure in the reservoir. The June pressures also are somewhat lower than maximum reservoir pressure because of the slow recovery of the wells due to continued use during the spring. A more accurate measure of the reservoir pressure was obtained during the summer of 1940 when pressures of 1,080 and 1,060 pounds, respectively, were recorded at wells Nos. 1 and 5 at the end of shut-in periods of one month duration. The pressure on No. 6 rose slowly during these periods and reached a maximum of 1,420 pounds per square inch late in the summer. The average of the three pressures is 1,186 pounds, a figure which may be taken as the minimum pressure that would have been recorded at the well heads at the end of June 1940 had there been no withdrawals during the month and had the pressures in the reservoir been equalized.

In view of the fact that no accurate measure of the reservoir pressure can be obtained from the data at hand, and that the size of the field is as yet unknown, no estimate of the total reserves of the field can be given. It should be stated, however, that the effective reserves of the field are in large measure dependent upon the rate of withdrawal. The data given above indicate that gas is now being withdrawn from the field at a rate that is faster than the rate of flow from the reservoir sands to the wells. A faster rate of withdrawal, because of the low porosity and permeability of the reservoir sands, will result in a cone of depressed pressures around each well, and a consequent decrease in production. It is conceivable under these conditions that the field might be unable to meet the demand for gas, even though an adequate amount remained in the sands at some distance from the wells. A slower rate of withdrawal, on the other hand, will result in a slower decline in pressure, greater ultimate production, and a longer useful life for the field. It is obvious, therefore, that if the size of the field is increased by the addition of new wells, and if the rate of withdrawal from the field remains constant, the reduction in the rate of withdrawal from individual wells will result in increased effective reserves in the old part of the field. Under this condition, estimates of the effective reserves of any new wells could also be based on a more favorable rate of withdrawal than that now in effect.

CONCLUSIONS

The area covered by this report has gas possibilities, outside the present gas field, along the Early Grove anticline near the highest part of the axis, and in the head of Lick Branch. There is also a fair chance that gas would be obtained in a well on the crest of the Wolf Run anticline. However, the low porosity and permeability of the sands in the Little Valley limestone and the resulting small supplies of gas that can be obtained from a single well are factors that must be considered before new drilling attempts are made in the area, for at best the margin of profit that can be expected on a single well is very small. Where a deep well is necessary to reach the gas-bearing zones, as in the case of the Wolf Run anticline, there may be no margin of profit. The cost of pipeline construction must also be added to the cost of drilling, and, at both the suggested Wolf Run and the Lick Branch sites, this would be an item of considerable magnitude. On the other hand, the fact that a pipeline owned by the Industrial Gas Corp. is in operation between the Early Grove field and Bristol, Virginia and Tennessee, assures continuing interest in efforts to increase the supply of gas, and although the demand during 1941 was being met by the Bristol Natural Gas Co., which owns wells and leases on the higher parts of the Early Grove structure, any new supply of gas that can be delivered to the line will probably find a ready market.

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IN COOPERATION WITH
U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

VIRGINIA CONSERVATION COMMISSION
GEOLOGICAL SURVEY
ARTHUR BEVAN, STATE GEOLOGIST

GEOLOGIC MAP OF THE EARLY GROVE GAS FIELD SCOTT AND WASHINGTON COUNTIES VIRGINIA

Geology by Paul Averitt - 1940

Scale $\frac{1}{24000}$

Contour interval 20 feet with 10 foot contours shown by broken line

Datum is mean sea level

Topographic base compiled from quadrangle maps of the Tennessee Valley Authority
Control by USC & GS, USGS, and TVA
Topography by Geological Survey from aerial photographs by stereophotogrammetric methods
Field examination by Tennessee Valley Authority 1938-39