DEVELOPMENT OF GAS-BEARING RESERVOIRS IN THE TRENTON LIMESTONE FORMATION OF NEW YORK

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IN THE TRENTON LIMESTONE FORMATION OF NEW YORK

Final Report

Prepared for

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ABSTRACT

The Middle Ordovician Trenton Formation is a limestone sequence with shale interbeds that was deposited under shelf conditions that centered about a minor trough extending northwesterly across central New York State. The formation outcrops along the southern flank of the Adirondacks then dips southward in the subsurface at an average of 80 feet per mile reaching a depth of more than 8000 feet below sea level at the Pennsylvania border. Thicknesses range from an erosional and depositional feather edge to more than 800 feet in Seneca County.

The Trenton contains organic shales and is overlain by the dark Utica Shales. It is underlain by dark limestones and is up dip from the organic sequences of the main Appalachian Basin. The organic shales form the source beds and minor tectonic movements have caused jointing and fracturing in the limestone beds, that have resulted in the formation of extensive fracture reservoirs that contain quantities of sweet natural gas that is almost pure methane.

The Trenton Limestone Formation is prospective for new reserves of natural gas with the most promising areas being the northeastern counties of central New York where the reservoirs are shallow enough to be readily tested and where the structures formed during the Adirondack uplift have created extensive reservoirs. With careful drilling and completion techniques and with closely monitored reservoir pressures during production, Trenton gas can be a valuable fuel resource for New York State.

CONTENTS

Section Page

ILLUSTRATIONS

SUMMARY

The Trenton Limestone Formation in New York State is limestone sequence with zones of shale interbeds that, when jointed and fractured, form reservoirs for natural gas. Reservoir quality depends largely on the number and frequency of open fractures and, these in turn, depend on the proximity of tectonic flexures. The reservoirs appear to be large and capable of sustained production providing production rates are regulated to maintain reservoir pressures and not set according to estimated open flow potential.

Wells testing the Trenton have shown evidence of natural gas in all areas where the formation is present. However, when the reservoir volumes are considered along with the high rate of discoveries and the minimum drilling costs, wells with the greatest potential for both commercial and local use appear in the northeastern part of central New York. Specific counties in the region include Wayne, Oswego, Cayuga, Oneida and northern Onondaga and Madison. The best reservoir potential appears to be along the flanks of minor tectonic features that trend northeast-southwest from the Adirondack uplift. The structural trends are noticeable on the Trenton structure contour maps and on the magnetic and gravity maps of the area. Wells between the structures also produce Trenton gas but volumes are not as great.

Trenton reservoirs in this area generally contain natural gas at above normal hydrostatic pressure. This indicates that the gas reservoirs are extensive and reach considerable depths. However the reservoir is composed of fracture porosity, and thus requires careful management of production for optimum recovery.

Production tests often suggest initial production rates that, if followed, would result in a rapid decrease in pressure accompanied by a drop in production. Such reservoirs must maintain pressures fairly close to the original pressure for optimum field life. Fracture reservoirs can be depleted quickly if overproduced. However, where the Trenton reservoirs are carefully managed, they can be expected to overcome the early stigma of short field life and provide a reasonable return on investment.

Drilling and completion techniques should also be tailored for the specific type of reservoir involved. It is suggested that casing be set to the top of the Trenton. It is best to air drill the entire Trenton section and perform openhole completion. Bothdrilling and control fluids should only be used as a last resort. Mud will seal off the fractures and gas zones can be missed entirely. Treatment of the well is best when kept to an absolute minimum, at least until production history has identified the main laterally extensive and long-term gas producing fractures.

With careful drilling, completion and production procedures, the Trenton appears capable of providing a valuable natural gas resource for the future needs of homes, farms and industries of New York State. Inexpensive, local-use wells can be drilled where the section is shallow, and commercial wells where it is deeper. Potential reserves range from 3 MMcf per acre where the Trenton is near the surface to over 8 MMcf per acre where the formation is at least 2500 feet beneath the surface.

Section 1

DESCRIPTION OF STUDY

Information on the Trenton Limestone Formation of New York State was collected and examined to determine the potential for natural gas exploitation of the formation and to determine those areas most suited for exploitation. The project included a search of previously published reports in scientific journals and both published and unpublished reports prepared by State agencies. Drillers reports to the State on wells penetrating the Trenton were examined and compared to computer-processed files containing well information. Geophysical well logs from Trenton wells were set up in computer-processable form and analysed for gas potential, and the results were compared with descriptions of rock samples obtained from the Trenton Formation.

From these data, a uniform set of elevations, thicknesses and economic potentials of the Trenton Limestone as it exists in New York State was evolved. The results are displayed as the maps, logs and analytical descriptions contained in the body of this report.

SOURCES OF INFORMATION

Information for this project was collected from the New York State Library, Syracuse University and State University libraries, State and Federal geologic reports, New York State Museum bulletins and other publications. Some excellent information on the older fields was obtained from Public Service Commission records compiled by William Lilley and from old newspaper articles collected by local historical societies.

Much of the recent well data was obtained from the computer-processable New York State Oil and Gas Well Information File. These data were originally compiled by the New York State Geological Survey, and the file is being maintained at Syracuse University. The file was used to search for Trenton wells and gas shows or production and to make preliminary computer maps of the project area. Well logs were obtained from the New York State Department of Environmental Conservation and digitized at Syracuse University for computer processing. Well sample descriptions were obtained from the Geological Sample Log company of Pittsburgh, Pennsylvania.

All computer processing was carried out at Syracuse University using programs available to the Department of Geology. Final maps and interpretations were made by Joseph E. Robinson, Certified Petroleum Geologist.

AREA EVALUATED

The project included the evaluation of the natural gas potential of the Trenton Limestone Formation as it exists in the subsurface of New York State. The area includes that portion of the State south and west of the Adirondack uplift and west of the Hudson Valley. Well information from 33 counties was examined, compiled into maps and interpreted.

Section 2

GEOLOGIC BACKGROUND

INTRODUCTION

With the exception of surficial glacial deposits, all of the sedimentary rocks of western New York are of Paleozoic age. Silurian and Upper Ordovician rocks crop out in east-west trending belts across western New York. Middle and Lower Ordovician and Cambrian strata are exposed around the flanks of the Adirondack uplift. Devonian outcrops cover the southern portion of central New York. The sedimentary section (Figure 2-1) ranges in thickness from a feather-edge near the borders of the Precambrian outcrop area of the Adirondack uplift to more than 13,000 ft. in Steuben County in the southwestern part of the State. Devonian, Silurian, and Upper Ordovician strata are predominantly clastic, but some carbonates and evaporites are present in the Lower Devonian and Silurian sections. Middle and Lower Ordovician and Cambrian rocks are predominantly carbonate but include shale and some sandstones.

Regional dip of the surface formations in western New York is southward at about 50 ft/mi. In the subsurface, particularly in regard to the older bed , the rate of dip increases because of convergence of the section northward, but nowhere except near faults or other local structural features does the dip exceed a few degrees. Block faulting is present around the flanks of the Adirondack uplift, and large-scale structures such as the Clarendon-Linden fault of western New York and southeast trending folds in the Southern Tier are discernable as pre-Appalachian tectonic features. Minor faulting is associated with anticlinal features in southern New York.

CAMBRIAN AND LOWER ORDOVICIAN

The Cambrian section in New York consists of rocks of Early and Late Cambrian ages, lying unconformably on an eroded basement complex of granitic and metamorphic rocks. The Cambrian strata are truncated northward and pinch out against the south flank of the Canadian Shield. Regionally, they thicken basinward toward the south and southwest.

PERIOD		GROUP	FORMATION		THICKNESS
DEVONIAN	UPPER	Conewango		Sh,Ss,Cgl	700'
		Conneaut	Chadakoin	Sh,Ss	700'
		Canadaway	Undiff	Sh,Ss	1100-1400'
			Perrysburg	Sh,Ss	
		West Falls	Java Nunda Rhinestreet	Sh,Ss	375-1280'
		Sonyea	Middlesex	Sh	0-400'
	?	Genesee		Sh	0-450'
	?		Tully	Ls	0-50'
	MIDDLE	Hamilton	Moscow	Sh	200-800'
			Ludlowville	Sh	
			Skaneateles	Sh	
			Marcellus	Sh	
			Onondaga	Ls	30-235'
	LOWER	Tristates	Oriskany	Ss	0-40'
		Helderberg	Manlius	Ls	0-10'
			Rondout	Dol	
SILURIAN	UPPER		Akron	Dol	0-15'
		Salina	Camillus	Sh,Gyp	450-1850'
			Syracuse	Dol,Sh,Salt	
			Vernon	Sh,Salt	
		Lockport	Lockport	Dol	150-250'
		Clinton	Rochester	Sh	125'
			Irondequoit	Ls	
	LOWER		Sodus	Sh	75'
			Reynales	Ls	
			Thorold	Ss	2-8'
		Medina	Grimsby	Sh,Ss	76-160'
			Whirlpool	Ss	0-25'
ORDOVICIAN	UPPER		Queenston	Sh	1100-1500'
			Oswego	Ss	
			Lorraine	Sh	
			Utica	Sh	900-1000'
	MIDDLE	Trenton-Black Riv.	Trenton	Ls	0-810'
			Black River	Ls	225-550'
	LOWER	Beekmantown	Tribes Hill Chucktanunda		0-550'
CAMBRIAN	UPPER		Little Falls	Dol	0-350'
			Galway (Theresa)	Dol,Ss	575-1350'
			Potsdam	Ss,Dol	75-500'
PRECAMBRIAN			Gneiss, Marble,Quartzite		

Figure 2-1. Stratigraphic section for central New York State (After Kreidler, 1971; Van Tyne and Foster, 1979)

The Potsdam Sandstone is the basal sedimentary unit recognized in western New York State. The Potsdam generally is considered to be of Late Cambrian age. The formation crops out on the flanks of the Adirondack uplift. The type locality is near the village of Potsdam, St. Lawrence County, New York. Drill cuttings have been described as very fine- to medium-grained sandstone, in places dolomitic and calcareous. It is composed of large frosted quartz grains, with some anorthoclase feldspars and sandy dolomite.

The basal part of the Potsdam is porous and permeable. This zone has been commercially productive of natural gas in the Memphis area (1897) of Onondaga County, and west of Buffalo in the Point Abino field (1916) of Welland County, Ontario, Canada.

The Potsdam Sandstone strikes generally east-west and regionally dips southward at an average rate of 100 ft/mi. It ranges in depth from 3,000 ft in the vicinity of Buffalo, New York to 13,000 ft in southern Steuben County near the Pennsylvania state line. In Oswego County, at the eastern end of Lake Ontario, the Potsdam is 1,500 - 2,000 ft deep.

The Theresa formation is composed of sandstone and dolomite and overlies the Potsdam. It is considered to be of Late Cambrian age. The formation was described originally from its exposure at Theresa, New York. The distribution of the Theresa is general throughout the western part of the state. In the subsurface, the maximum thickness of 1,486 ft was found in the New York Natural Gas Corp. Robert Olin well in southern Steuben County. The subsurface Theresa thins to the north, sub-cropping against the Knox Unconformity. The Theresa consists of porous, sandy dolomites which grade upward into a sandstone facies. The dolomite is buff and brown; crystalline, and contains finely disseminated grains of quartz, pyrite, and biotite. The sand grains are often cemented by either calcareous or dolomitic overgrowths. The clastic section at the top of the Theresa is a white, clean sandstone with fine subrounded grains. Shows of gas are common. The section ranges from zero to 250 ft in thickness, depending on the degree of truncation and appears to be developed best in the west-central part of the State.

The Little Falls dolomite directly overlies the Theresa. Its distribution is restricted generally to the southern half of western New York. A maximum thickness of 950 ft is found in the New York State Natural Gas Corp. No. 1 Kesserling well in Chemung County.

In the subsurface, the Little Falls consists of crystalline dolomite containing quartz sand and, in places, thin bedded siltsones. Lithologically, it appears to be fairly uniform throughout the study area.

The Lower Ordovician Beekmantown Dolomite is the youngest of the Cambrian-Lower Ordovician formations preserved in Central New York State. It appears to be transitional with the underlying Little Falls Dolomite and is made of dark gray dolomites interbedded with gray to black pyritic shales. The Knox Unconformity is at the top of the Cambrian-Lower Ordovician sequence. This stratigraphic break is widespread in the Appalachian basin and eastern United States. During the Knox hiatus, the Cambrian strata were truncated in New York, Michigan, Ohio, Kentucky, Tennessee, Virginia, and other states as well as in Ontario, Canada.

The Tribes Hill formation unconformably overlies the pre-Knox Cambrian/Lower Ordovician section. In the subsurface, the Tribes Hill consists primarily of light gray to crystalline, pyritic limestone interbedded with dolomitic siltstones, thin stringers of shale, and clean, fine-grained calcareous sandstones. Basinward, to the south, the limestone grades into dolomite with interbeds of shale, and white, fine-grained calcareous sandstones.

MIDDLE AND UPPER ORDOVICIAN

Sedimentary rocks of Middle and Upper Ordovician age outcrop in the northern part of the State and dip southward into the Appalachian Basin. Thickness ranges from zero around the Adirondack uplift to more than 3,700 ft in southern Steuben County near the Pennsylvania border. Dip is southward at less than 100 ft/mi. The Ordovician rocks can be divided into two lithologic units: an upper clastic unit consisting of shale, siltstone, fine-grained sandstones and very minor amounts of carbonate rock, and a lower carbonate unit containing a few thin calcareous shale and dolomitic sandstone beds.

The Middle Ordovician

The Black River Limestone unconformably overlaps older rocks from south to north. This Formation consists of dark gray cherty limestones with various amounts of shale. The thickness varies due to erosional relief on the depositional surface. The Black River displays very little intergranular porosity but locally appears to be moderately fractured.

Transitionally overlying at the Black River is the Trenton Limestone consisting of light to dark gray limestone beds with alternating thin, gray, calcareous shale beds. The Trenton Limestone which is described in detail later in this report, contains fracture porosity that has been exploited as a natural gas reservoir for more than a century.

The Trenton Limestone is capped by the Utica shale which is black, carbonaceous, with an abundance of graptolite fossils. In the subsurface, the color ranges from gray to black. Siltstone and mica are present in places, particularly in the western counties.

The Upper Ordovician

The Lorraine Shale, which overlies and is transitional with the underlying Utica Shale, ranges in thickness from 500 to 800 feet. It is present in the subsurface in most of western New York and crops out in the northern parts of the area. The Lorraine grades upward from a dark gray, pyritic shale at the base to a fine-grained, interbedded sandstone, shale, and siltstone at the top. The Lorraine Shale is transitional with the overlying Oswego Sandstone, where the latter is present.

The Oswego Sandstone is regarded as the sandstone facies of the Queenston Shale. It is present in most of western New York and crops out in the northern part of the area. Thickness ranges from zero in the west, to about 900 feet in Chemung County. It is a monotonous sequence of fine-grained sandstone, shale and siltstone. The sandstone is quartzose, and usually cemented with silica cement. The Oswego Sandstone is overlain by the sandstone, siltstone and shale of the Queenston formation with the only distinction being a color change from gray to red. In the easternmost counties of western New York, the Oswego Sandstone is absent because of pre-Silurian erosion. In eastern Madison County, the Oswego is overlain unconformably by the Silurian Oneida Conglomerate.

The Queenston formation is a thick sequence of reddish shales, siltstone, and fine-grained sandstones. In the eastern and central parts of western New York, the Queenston is predominantly siltstone and sandstone; westward it grades into a red silty shale. In general, the clastic material becomes finer from east to west. The Queenston Shale is about 800 - 900 feet thick in most of western New York and crops out in the northern part of the area.

SILURIAN

In central New York State, the Silurian consists of numerous lithologic units characterized by erosion, nondeposition and variations in depositional environments. The basal unit is the Medina series of sandstones, siltstones and shales. The Whirlpool or "White Medina" is the basal sandstone member of the Medina Series and is an almost pure, white quartzose sandstone. It extends from western to central New York where it pinches out by onlap.

The Cabot Head Shale overlies the Whirlpool Sandstone in western New York, but disappears eastward.

The Grimsby or "Red Medina" Sandstone overlies the Cabot Head Shale in western New York. It is approximately 100 ft thick in west-central New York and consists of red shales, and pink to red fine-grained sandstones. In central New York, where the Whirlpool Sandstone is not present, the contact between the base of the Grimsby Sandstone and the top of the underlying Ordovician Queenston Shale is difficult to recognize from well data because of the sandstone development of the Queenston in that area. The youngest Medina formation is the Thorold Sandstone, which overlies the Grimsby. It is light gray, fine-grained, sandstone. The Thorold Sandstone is identified in well cuttings because it is the first sandstone found below the Lockport Limestone. The overlying Clinton Group consists of basal shale members locally named Bear Creek and Sodus Shales and averaging a total of 100 ft in the project area. They, in turn, are overlain by the Reynales Limestone.

The Reynales is a true limestone in central New York State but becomes dolomitic in the west. The Rochester Shale overlies the Reynales and is approximately 100 ft thick. It becomes dolomitic toward the top and appears to be gradational with the overlying Lockport dolomite.

Immediately overlying the Rochester shale is the Lockport Group. The Lockport consists of a dark gray, crystalline, dolomite containing some interbedded shale. It is dolomite in the western area but becomes more calcareous in east-central New York and grading into limestone. Above the Lockport is the Salina group of interbedded evaporites, carbonates and shales. The generally recognized lower member, the Vernon Shale is composed of red and green shales and siltstones with minor dolomitic stringers. West of Seneca Lake, several salt beds occur in the middle Vernon attaining a maximum thickness of 75 feet.

The Syracuse Formation comprises the middle Salina. It has been called the "Syracuse Salt" although it contains numerous interbeds of shale, dolomite and anhydrite along with the salt section that may total as much as 800 feet in the south-central portion of the area. The Bertie Formation, consisting of a thin sequence of dolomites and shales, is the uppermost Salina member in the general project area. Silurian formations outcrop in an east-west band across central New York at the approximate latitude of Syracuse. Dip of these formations is generally south at 75 ft/mi.

DEVONIAN

In the southern portion of central New York, the Lower Devonian consists of the Helderberg Group of transgressive limestones topped by the Oriskany Sandstone. The thickness of the Lower Devonian Series, including the Oriskany Sandstone, ranges from a feather edge in southwestern New York to possibly 800 ft in the southeastern part of the state. The Oriskany is a quartzose sandstone that ranges in thickness from a wedge edge up to 70 ft or more in the south-central part of New York. The Middle Devonian Series is composed of the Tully Limestone at the top, the Onondaga Limestone at the base, and an intervening shale section. The Onondaga Limestone comprises 85 to 95 feet of limestone that is often cherty at the base. The overlying Hamilton Shale Group consists of calcareous shales and silts with minor limestones. The sequence is capped by the Tully Limestone which is a distinctive electric log marker. Regional dip is generally southward with the rate increasing from about 60 ft/mi in western New York to over 100 ft/mi in south-central New York. The Upper Devonian Series consists of interbedded shales, siltstones, and sandstones. They form the bedrock of the southern half of the project area.

Section 3

GEOLOGY OF THE TRENTON LIMESTONE FORMATION

The sequence of rocks in New York State designated in this report as the Trenton Limestone Formation, has varied in other descriptions and publications. At times, all the limestones and shales from the base of the Black River to the top of the Utica Shale have been included in a Trenton Series. Other publications designated a Trenton Group that included limestone and shale sequences above the Black River Limestone to the top of the Utica Shale. The component formations were defined by the faunal content discovered in the outcrops. However, where the sequence is in the subsurface and based on geophysical well logs, the Trenton is usually considered to be a single sequence of limestones lying entirely between the underlying Black River Limestone and the overlying Utica Shale.

The Gamma Ray log and the Neutron log both give responses that indicate that the Trenton Limestone is essentially one formation that can be divided into three members: a lower member, a middle member and an upper member. These units do not relate to the more formal designations in outcrop but are suitable for a subsurface, natural gas-oriented, study. When future drillers obtain cores, the two differing designations can be resolved.

OUTCROP DESCRIPTION (after Johnson, 1971)

The evolution of the Trenton nomenclature is complex (Kay, 1937, 1942; Chenowith, 1952). The limestone phase of the Trenton group as considered in those published accounts, comprises five formations which are from base to top: the Rockland, Kirkfield, Shoreham, Denmark, and Cobourg limestones. There is, however, difficulty in delineating these units in the subsurface. The lithologic similarity of much of the Trenton Limestone frequently requires the use of faunal evidence as a basis of recognition; lithologic characteristics are not distinguishable.

The Rockland Limestone

The Rockland Formation is primarily composed of dark to medium gray, fine calcilutites interbedded with minor (5 to 10 percent) gray to olive gray medium-grained calcarenites. The grays lighten a shade when weathered. Black to dark gray, smooth and flat, paper-thin, limy shale partings separate the limestone beds. Zones of limy shale, up to 2.5 in. thick, are locally common. The shale may account for as much as 20 percent of the rock. The individual limestone beds measure 0.5 in. to 8 in. thick and average 2.5 to 3 in. thick. The calcilutites are usually the thicker beds. Layering coincides with bedding.

The Rockland Limestone carries the ubiquitous Trenton Limestone fauna, although the forms are not as prevalent as in the overlying carbonate divisions. There are present fossils of Columnaria halli Nicholson, Praspora orientalis Ulrich, Phragomolites compressus Conrad, Rafiniesquina alternata (Conrad), and Flexicalymene scenaria (Conrad). A faunal list has been provided by Kay (1937, pp. 251-256). The calcarenites are the most fossiliferous of the rock types in the Rockland Formation. The distinctive brachiopod Triplesia cuspidata (Hall) is restricted to the Rockland Formation. The distinctive brachiopod Triplesia cuspidata (Hall) is restricted to the Rockland (Napanee member) Formation. Any bed containing T. cuspidata is considered Rockland. The brachiopod Parastrophina hemiplicata (Hall) normally is common in the lower part of the Kirkfield and rare in the top of the Rockland; its presence aids in distinguishing the formations. The distinctive trilobite Enrinurus cybeliformis Raymond is present in lowest Kirkfield but absent in the Rockland Formation.

The Kirkfield Limestone

In contrast to the underlying Rockland Limestone, the Kirkfield Limestone consists mainly of medium gray to yellowish brown, frequently crossbedded and ripple-marked coarse coquinal calcarenites (40 to 80 percent of the formation) which are interbedded with lesser amounts (10 to 25 percent) of gray calcisiltites. The finer limestones are more abundant in the lower and upper portions of the formation, which accounts for some of the difficulty in placing the formational boundaries. The colors generally lighten a shade on weathering. Olive black to dark gray limy shale partings and thinly laminated zones of limy shale up to 3 in. thick separate the limestone beds.

The calcarenites vary from 0.5 in. to 15 in. thick with most of the calcarenites between 4 and 10 in. thick. The thicker beds of calcarenite are in the minority, but because they resist erosion and give rise to the prominent ledges and waterfalls in which the Kirkfield is commonly observed in the field, they are readily seen and serve as a guide to the formation. The calcisiltites are not over 6 in. thick, generally averaging 2 to 3 in. thick. Layering coincides with bedding. The calcarenites appear to increase in quantity westward.

The Kirkfield has a large and abundant fauna. Among the distinctive forms are the trilobites Bathyurus ingalli Raymond, Enchrinurus cybelformis Raymond, Hemiarges paulianus (Clarke), Flexicalymene senaria (Conrad) and Isotelus gigas DeKay. All but the two latter forms are not present in the Trenton limestones above the Kirkfield.

The Shoreham Limestone

The Shoreham Limestone consists almost wholly of thin- to medium-bedded limestones ranging from gray to yellowish brown, coarse calcarenites. The yellowish brown color is characteristic only of the coarsest calcarenites. The gray colors are a shade lighter on weathered surfaces.

The limestone beds range in thickness from 0.5 in. to 7.5 in. They rarely measure over 5 in. thick, however, and average 1 to 3 in. thick. The calcarenites tend to have wavy surfaces which give the beds an irregular lensing appearance, but they are rarely ripple-marked or cross-bedded. Dark gray shale partings separate the limestone beds and compose 20 to 25 per cent of the formation.

The Shoreham Limestone contains Trenton fauna which are largely restricted to the calcarenites. There are present the common brachiopods, Rafinesquina, Paucicrura, and Sowerbyella, and the trilobites Flexicalymene and Isotelus. Pelmatozoan stem fragments and bryozoans are abundant. The frondescent bryozoan Subretipora is characteristic of the lower half of the formation. The Shoreham contains species of the distinctive trilobite Cryptolithus. C. tessalatus appears restricted to the Shoreham but C. quadrillineus is present in the Denmark as well. These forms are generally difficult to find. Sinuites is present in both formations, but Trocholites (very rare) in combination with Sinuites is restricted to the Denmark.

The Denmark Limestone

The Denmark Limestone primarily contains (60 to 80 percent) medium gray to light gray thin-bedded coarse fossiliferous calcarenites which are sometimes cross-bedded and ripple-marked. The very coarse crystalline varieties often have a pale red to moderate red cast. Calcilutites are found every few feet. Gray limy shale partings separate most of the limestone beds. The amount of shale is variable; it ranges from less than 5 percent of the rock in some portions of the Denmark to a maximum of 25 percent in other portions.

The Denmark is best exposed at Trenton Falls, and its most common fossils are the brachiopods Dinorthus, Rafinesquina, Paucicrura and Sowerbyella and the trilobites Flaxicalymene and Isotelus.

The Cobourg Limestone

The Cobourg Limestone consists of a sequence of a thick-bedded limestone with gastropod fauna and an underlying thinner-bedded limestone with Rafinesquina deltoidea. The latter consists of bedded calcisiltites with thin seams of dark gray shale. The top of the Cobourg is sometimes marked by a conspicuous bed of limestone conglomerate.

Rafinesquina deltoidea is present throughout the Cobourg but is abundant and most characteristic of the upper part. Hormotoma trentonensis and Fusispira fusiformis frequently appear in the calcarenites.

SUBSURFACE DESCRIPTION

The Trenton Limestone is continuous in the subsurface across Central and Western New York State (Figures 3-1, 3-2) and extends southward and westward into Pennsylvania, Ohio and southern Ontario, Canada. It reaches its greatest thickness of over 800 feet in Seneca County of central New York and averages 400 feet elsewhere. To the east and southeast, the limestone thins and becomes increasingly shaly and silty finally pinching out towards the lower Hudson Valley. The Trenton outcrops in southern Ontario along the north shore of Lake Ontario and in the Watertown area of New York State. It has been truncated by erosion along the southern edge of the Adirondacks where there are also some excellent outcrops.

Unfortunately, the wells drilled into the Trenton close to the outcrop areas are very old ones. There were no geophysical logs, and any sample record has been lost. Consequently, the outcrop sections cannot be directly related to the individual subsurface logs. However, the lithological descriptions can be used along with the logs to indicate a general designation for the Trenton in the subsurface. There are lithologs in existence for many of the more recent wells. The careful descriptions provided on these sample logs by the Geological Sample Log Company of Pittsburgh, Pennsylvania have been utilized in all log formation member interpretations. Trenton wells used in this study are located on Figure 3-3.

From outcrop, sample, and geophysical log descriptions, the Trenton Limestone appears to be a dense limestone with numerous interbeds of shale. Outcrop descriptions suggest that the individual beds may be on the order of a few inches thick. Intervening shale beds appear to be approximately of the same order. On this scale, the logs do not resolve the individual beds but they do give an indication of the average limestone and shale content. Interpretation of the density log, which is a sidewall log and provides the most detailed response, is hampered by the fact that the compact indurated limy shales have almost the same density as the limestones so that discrimination is difficult. Drilling samples are commonly taken every 10 feet and thus do not discriminate between thin beds, but they can provide an average limestone/shale content.

The Trenton Limestone is fractured--often highly fractured. These fractures are readily apparent in outcrop and are indicated on the geophysical logs and by the type of gas production.

The Density log is the best fracture indicator of all the standard logs. The Gamma Ray log and the Neutron logs are not good indicators of fractures in the formations. They look at a relatively large volume of rock. However, in air- or gas-filled boreholes, they can be interpreted to distinguish between enlarged holes and shale content in the formation. Results are best when the porosity logs are interpreted along with a Caliper log which shows caved sections but which often will miss small fractures.

A reasonable estimate of the physical characteristics of the subsurface Trenton can be determined from a comparison of the characteristics of the suite of logs. The actual subdivisions of the Trenton are best displayed by the Gamma Ray and the Neutron logs. These react well to the change from the overlying Utica Shale to the limestones of the Trenton and again to the underlying Black River Limestone.

Variations in the lithology of the Trenton permit the formation to be divided into three members each having distinctive characteristics. The basal member, (Trenton A) contains considerable shale interbeds but becomes cleaner toward the top. The member is variable in thickness but can be traced throughout most of the prospective gas-producing area. The middle member (Trenton B) is the most uniform of the Trenton members. It consists of a sequence of interbedded limestone and shale layers with a distinctive neutron log response. It is fractured, often caved, and at times produces a false impression of neutron porosity. The upper member (Trenton C) is usually the cleanest of the Trenton members. However, it does thicken locally with the additional section occurring at the top.

The Trenton members and their spatial configurations are illustrated in the accompanying set of cross-sections, Figures 3-4 to 3-7. All members continue to the west and southwest beyond the borders of New York State but lose their identity to the southeast where the Trenton Limestone pinches out and is replaced by a shale sequence.

Trenton A

The basal Trenton member represents a set of thinly bedded limestones and shales deposited over the surface at the relatively clean Black River Limestone. The depositional center was along a trough running southwest from Oswego County through to Seneca County. This member is a distinctive Neutron log unit but can also be picked on the Gamma Ray log. The limestone is most abundant towards the top which is designated by a clean limestone bed that can be followed through the area. The "A" member roughly coincides with the Rockland and Kirkfield members of the traditional Trenton classification. However, because the subsurface designation is exclusively based on log-derived facies and the outcrop designation is based on faunal content, no direct relationship can be assumed.

Trenton B

The middle Trenton member is more or less uniform in thickness over central and western New York. It is a relatively clean limestone at the base with the frequency of shale interbeds increasing upward. An abrupt break to cleaner limestones indicates the top of this member. Trenton "B" is a good Gamma and Neutron log unit. It is roughly equivalent to the Denmark zone. This "B" member is remarkably uniform in appearance and thickness across central New York State including those areas where both the underlying and the overlying members show considerable variation. There is some minor thickening southward toward Pennsylvania, and the member pinches out to the southeast along with all the limestone section.

Trenton C

The upper member, Trenton C, is the least shaly limestone of the three and is approximately equivalent to the earlier Cobourg designation. Its base represents a break from the underlying interbedded limestones and shales to a relatively pure limestone. It is recognizable in all locations except for the southeastern portion of the study area. This member is thickest in Wayne and Ontario counties where the uppermost portions have an added section consisting of interbedded limestones and shales. The area of thicker Trenton C lies to the west of the Trenton A trough and actually overlies one of the thinner Trenton A areas. The Trenton C continues uniformly westward into Pennsylvania but thins southward and pinches out to the east.

The appearance and geometric variations in the three Trenton members can be seen in the four cross-sections, Figures 3-4 to 3-7.

Section 4

WELL LOGGING

INTRODUCTION

"Well Logging" denotes any operation wherein some characteristic data of the formations penetrated by a borehole are recorded in terms of depth. This record is called a log. The log of a well, for example, may simply be a chart on which abridged descriptions of rock samples are written opposite the depths from which the samples were taken. A log may also be a graphic plot with respect to depth of various characteristics of these samples, such as porosity, permeability and residual oil or natural gas.

It has become general practice, when a hole has been drilled, or at intervals during the drilling, to run geophysical surveys for the purpose of quickly obtaining a complete record of the formations penetrated. This recording is of immediate value for the geological correlation of the strata, and for the detection and evaluation of potentially productive horizons.

In New York State, standard varieties of well logs measure the natural radioactivity of the formations (Gamma Ray Logging), the secondary effects due to the bombardment of the formations by neutrons (Neutron Logging), the electron density of the formation (Density Logging), the sound-velocity across the formations (Sonic Logging), the diameter of the base hole (Caliper Logging), the temperature of the fluids in the bore hole (Temperature Logging) and occasionally, the resistivity or conductivity of the formation (Induction Logging).

In electrical and sonic logging, the measurements are performed in the uncased portions of the borehole only. With radioactivity logging, the measurements can also be recorded in cased holes.

The Neutron, Density and Sonic logs are known as porosity logs.

The general information provided by the logs is essentially the following:

- Differentiation between shales, other rocks to define their individual beds, and for well-to-well correlation. Log data make possible the delineation of structural features and the determination of the thickness and lateral extension of potential reservoirs.
- In most cases, qualitative discrimination between oil- or gas-bearing and water-bearing beds, as well as location of oil-water contacts. In favorable cases, quantitative evaluation of porosity and water saturation.

LOG NOMENCLATURE

Gamma Logs

- Gamma Ray
- Gamma-Gamma
- Scintillometer

Neutron Logs

- Compensated Neutron
- Porosity
- Neutron Porosity
- Sidewall Neutron Porosity

Density Logs

- Formation Density
- Formation Density Compensated
- Borehole Compensated Density

Electric Logs

- Shallow Induction
- Medium Induction
- Deep Induction
- Dual Induction
- Induction Spherically Focused

Sonic Logs

- Sonic
- Borehole Compensated Sonic
- Velocity

Caliper Logs

Temperature Logs

PROPERTIES OF LOGS COMMONLY RUN IN NEW YORK STATE IN ORDER OF THEIR USE AND FREQUENCY

The Gamma Ray Log

Description and Calibration. The Gamma Ray is the most common and probably the most useful log from New York State wells. It is a measurement of the natural radioactivity of the formations. The log is, therefore, useful in detecting and evaluating deposits of radioactive minerals such as potash or uranium ore.

In sedimentary formations, the Gamma Ray Log normally reflects the shale content of the formations. This is because the radioactive elements tend to concentrate in clays and shales. Clean sandstone or carbonate formations usually have a very low level of radioactivity, unless radioactive contaminants such as volcanic ash or granite wash are present or when the formation waters contain dissolved potassium salts.

The Gamma Ray Log can be recorded in cased wells, which makes it useful as a substitute for self or spontaneous potential (SP) in cased holes where the SP is unavailable or in open holes where the SP is unsatisfactory. In both cases, it is useful for the location of the non-shaly beds and for correlation.

The Gamma Ray Log response, after correction for borehole, casing, etc., is proportional to the weight concentration of the radioactive material in the formation. Two formations having the same amount of radioactive material per unit volume but having different densities will show, on the Gamma Ray Log, different radioactivity levels with the less dense formations appearing to be more radioactive.

The number of gamma rays reaching the counter fluctuates even when the sonde is stationary in the hole; the phenomenon is statistical in nature. The fluctuations are more noticeable for lower count rates. However, the number of gamma rays counted per second over a sufficiently long period of time will be practically constant. The period of time required to obtain a good average value is appreciable, usually a few seconds.

In order to average out the statistical variations, condenser-resistor smoothing circuits are used in the measuring circuits. Various "time constants" may be selected according to the radioactivity level measured.

The smoothing circuits introduce a lag in the recording, and, in order to avoid excessive curve distortion, the recording speed is chosen so that the counter will not travel more than about one foot during the time constant. For a time constant of 2 seconds, the logging speed is 1800 ft/hr.

Gamma Ray Logs are now usually calibrated in American Petroleum Institute (API) units. The radioactivities observed in sedimentary formations range from a few API units in anhydrite or salt, to 200 or more in shales.

Prior to the API calibration procedure, Gamma Ray Logs were scaled in micrograms of radium equivalent per ton of formation.

The API calibration is based on the use of a permanent calibration facility to establish standard units for nuclear logs.

The gamma ray deflection is a function not only of the radioactivity and density of the formations, but also of hole conditions (hole diameter, mud weight, casing, etc.) since the materials interposed between the counter and the formations absorb gamma rays. The corrections can be important in large holes and in cased holes.

Applications of the Gamma Ray Log.

- The Gamma Ray Log is particularly useful for defining shale beds when the SP curve is rounded in very resistive formations, or or flat, or when SP curve cannot be recorded (non-conductive--empty holes--cased holes).
- The Gamma Ray Log reflects the proportion of shale and, in some regions, can be used quantitatively as an indicator of shale content.
- The Gamma Ray Log is used for the detection and evaluation of radioactive minerals, such as potash or uranium ore. The gamma ray may also be used to detect and to evaluate uranium deposits, but in this case there is no simple proportionality between gamma ray deflection and the "richness" of the deposits.
- The Gamma Ray Log can also be used for the delineation of non-radioactive minerals including coal beds.

- The Gamma Ray Log is used for correlations in cased holes. The simultaneous recording of the gamma ray and of a casing collar locator makes it possible to position perforating guns very accurately. As compared with the corresponding open-hole log, the deflections on the cased-hole log are somewhat attenuated due to absorption of the gamma rays in the steel casing and cement.

- The Gamma Ray Log is sometimes used in connection with radioactive tracer operations.

Gamma Ray Log Response Standards Computed at Syracuse University. The Gamma Ray Log is the most common correlation and lithological log run in New York State. There have been many service companies performing the logging operations and there have been changes in calibration within as well as among companies. Log responses thus display considerable variation in amplitude and cannot be used directly for lithologic identification in a well-to-well comparison. Fortunately the Gamma Ray Log is a direct record of the radioactivity within formations and can be considered as constant for identical rocks. Thus, where formations are known to have uniform levels of radioactivity, the logs can be adjusted to a uniform response to these formations. Gamma Ray Logs can be standardized to a uniform amplitude response to formations known to have a uniform level of radioactivity. The standard logs are useful for accurate well-to-well correlations and lithologic determinations.

Modern Gamma Ray Logs are recorded to uniform scales and uniform responses to test conditions. Many are now recorded digitally and are amenable to between well standardization. However, the older logs are not uniform and can only be transformed to a uniform lithologic response when corrections are applied by computer to digital log values. Each log must be examined on an individual basis, and average response to clean formations must be determined for the entire area. Then correction parameters must be measured and then applied via computer programs to produce standard logs that show a uniform response over a region. The standard logs can then be used in a comprehensive program to compute the percentage of shale present in the section.

Standardization measurements were made on all Gamma Ray curves used in this project. The values were entered into computer programs that computed and displayed standard gamma curves for use in correlation and for entry into programs that computed lithology corrected porosities. Computer programs used in this project were written at Syracuse University.

Shale Fractions Computed at Syracuse University

Once Gamma Ray logs are corrected to a standard response to known zones of clean shale and clean limestone, the shale fraction can be computed:

$$\text{Shale Fraction} = (1.0 \times ((G-Gsh)/(Gcl - Gsh)))^{1.1}$$

where:

cl = clean limestone formation
sh = pure shale
G = Gamma reading

The exponential (1.1) was experimentally determined for maturely compacted shales in New York State. Because shale content directly relates to effective porosity, porosity calculations must be corrected for any contained shale.

Neutron Logs

Description and Calibration.

Neutron Logs or neutron derivative, porosity logs are normally run with the Gamma Ray Logs in New York State.

Neutrons are electrically neutral particles, each having a mass almost identical to the mass of a hydrogen atom.

High-energy neutrons are continuously emitted from a radioactive source which is mounted in the sonde. These neutrons collide with nuclei of the formation materials in what may be thought of as elastic-type collisions. With each collision, a neutron loses some of its energy. The amount of energy lost per collision depends on the relative mass of the nucleus with which the neutron collides. The greatest energy loss occurs when the neutron strikes a nucleus of practically equal mass. Collisions with heavy nuclei do not slow the neutron down very much. Thus, the slowing down of neutrons depends largely on the amount of hydrogen in the formation. Within a few microseconds, the neutrons have been slowed down by successive collisions to thermal velocities corresponding to energies of around .025 electron volts. They then diffuse randomly, without losing any more energy, until they are captured by the nuclei of atoms such as chlorine, hydrogen, silicon, etc. The capturing nucleus becomes intensely excited and emits a high-energy gamma ray of capture. Depending on the type of Neutron Logging tool, either these capture gamma rays or neutrons, themselves, are counted by a detector in the sonde.

When the hydrogen concentration of the material surrounding the neutron source is large, most of the neutrons are slowed down and captured within a short distance of the source. On the other hand, if the hydrogen concentration is small, the neutrons travel farther from the source before being captured. The counting rate at the detector varies according to the hydrogen concentration.

The natural gamma rays and those emitted by the source generally have much lower energies than the captured gamma rays. Hence, it is possible, by proper design and shielding of the detector, to eliminate the natural gamma rays and those coming directly from the source, and to reduce the effect of these scattered by the formations to a very small amount.

Neutron Logs are used principally for delineation of porous formations and determination of their porosity. They respond primarily to the amount of hydrogen present in the formation. Thus, in clean formations whose pores are filled with water or oil, the Neutron Log reflects the amount of liquid-filled porosity.

Gas zones can often be identified by comparing the Neutron Log with another porosity log or a core analysis. A combination of the Neutron Log with one or two other porosity logs yields even more accurate porosity values and lithology identification, including evaluation of shale content.

The concentration of hydrogen in gas is usually much less than in oil or water; so for equal porosity values, a formation which contains gas will give a higher counting rate than a formation free of gas.

In a shaly formation, the volume fraction occupied by shale does not contribute to the effective porosity, because shale is practically impervious. On the other hand, shale contains a great amount of hydrogen because of the water which is either occluded in its pores or combined chemically in its molecules. The interstitial shale accordingly contributes to the hydrogen content of the formation; and for equal effective porosities, the number of counts per second will be less for a shaly formation than for a clean formation.

Besides the hydrogen content of the formation, the Neutron Log also may be affected by the chemical composition of the minerals which constitute the rock and by the borehole conditions such as diameter, nature of borehole fluid and presence of casing.

If the borehole conditions are about the same throughout the second survey the intervals with a lower counting rate will correspond to higher porosity and/or to greater shale content. The deflections of the log which correspond to variations of porosity can be differentiated, to a great extent, from those corresponding to variations of shale content, by means of the gamma ray curve and/or the SP curve. In particular, these curves usually indicate pure shale beds without ambiguity.

Empirical approaches make possible the derivation of fairly reliable porosity values from the Neutron Logs in many cases, at least in open holes and in essentially clean formations. Appreciable errors, however, may occur even in clean formations, because of the influence on the Neutron Log readings of the borehole conditions. Test results indicate that the influence of hole diameter variations is important and should be taken into account in the interpretation of the logs. The presence of casing and cement has an appreciable effect, which depends on the positions of the casing and of the sonde in the borehole. It is difficult to correct for this effect, since the exact geometry of casing and cement is rarely known. The variations of borehole fluid density can be neglected, but increasing salinity increases the counting rate, all other conditions being the same. This effect, nevertheless, is not important except when the salinity becomes very high.

In the case of empty holes and with the type of logging instrument used at present, the interpretation of the Neutron Logs becomes difficult for hole diameters greater than 6".

The position of the logging instrument with respect to the wall of the hole is a critical factor, and sidewall neutron tools use a device to hold the sonde against the borehole wall.

The Neutron Log is a useful tool for the delineation of formations, and for correlation, in wells filled with water-base mud, oil-base mud, in empty holes, in open holes or in cased holes. The Neutron Log and Gamma Ray Log provide a qualitative record of shales, tight formations and porous sections in cased wells, valuable for workover jobs or for the surveying of old wells.

Determination of porosity by means of the Neutron Log is probably one of its most important applications. For equal porosity values, a gas-containing reservoir will show a higher counting rate than an oil- and/or water-bearing formation, provided the gas in the volume of formation penetrated by the neutrons has not been flushed by mud filtrate. The Neutron Log, therefore, can be used under favorable conditions for the distinction between oil and gas.

Neutron Response Standards Computed at Syracuse University. Early Neutron Logs were scaled in counts per second according to each logging company's instruments and logging rates. Scales varied over a considerable range, and only recently has a standard API scale been used. However, even the standard scale logs show considerable variation due to hole parameters and operator idiosyncrasies. Fortunately, Neutron scales are linear and the logs can be standardized to a uniform response to clean formations. Again, it was necessary for Syracuse University personnel to examine Neutron Logs and determine the average response to clean formations, pick the connections for each log, then use the computer to generate standardized Neutron Logs for correlations and for use in computing lithologic neutron porosity logs.

Neutron Porosity Logs and Syracuse University Computer Computations. The Neutron tool responds largely to the concentration of hydrogen ions in the formations and borehole. If corrections are made for borehole fluids, then the response is proportional to the water or oil that is contained in the rock pores. Thus, formation porosity can be computed from the Neutron Log, providing compensations are made for borehole effects and rock type. Because of this porosity response, logging companies began computing formation porosity and displaying it as an additional curve along with the neutron response. These porosity curves were a linear dependent form of the Neutron and thus were only correct under specific borehole, lithology and formation fluid conditions. Later, specific neutron porosity tools were developed such as the Side Wall Neutron Porosity Log which applies a neutron tool to the borehole wall by means of a spring-loaded skid. With these logs, the neutron response was no longer displayed and the logs report porosity only. Such porosities are borehole corrected and are more accurate than older versions but still are only correct for specific lithologies and non-gas reservoirs.

Where both neutron and dependent-porosity curves were displayed, only the neutron was digitized because it is more efficient to compute the porosity curve. However all, porosity-only curves were digitized. Curves where a direct neutron response was available were recorded and standardized.

Although the neutron porosity parameters are complex, they can be reduced in practice to functions that are derived empirically from actual porosity measurements. Logging company computations usually consider porosity to be a logarithmic function of the neutron response. However, detailed comparisons of log and core porosities have shown that the most accurate porosities are a linear function of the natural log of the Neutron values. The Syracuse Algorithm uses the log of a Neutron response, applies a rock matrix adjustment, and corrects for shale:

Øls = (-(m * lnN) + k) * 100
Øss = Øls - 2.5
Ødol = Øls + 3.0
Ø = (Ø)ss, dol or ls * sh fraction

where:

N = neutron log response
Ø = porosity
ls = limestone
sh = shale (fraction from Gamma Ray Log)
ss = sandstone
dol = dolomite.

m and k are constants which have been empirically determined to be 33.04615 and 43.39889, respectively, in western New York State.

Lithology-corrected porosities were computed from standard Neutron Logs using this formula as applied by computer programs written at Syracuse University.

Formation Density Logs

Next to the Gamma-Neutron Logs, the Formation Density Logs are the most popular and useful logs run in New York State boreholes.

Description. A radioactive source, applied to the hole wall in a shielded sidewall skid, emits medium-energy gamma rays into the formations. These gamma rays may be thought of as high-velocity particles which collide with the electrons in the formation. At each collision a gamma ray loses some, but not all, of its energy to the electron, and then continues with diminished energy. This type of interaction is known as Compton scattering. The source and detector are so designed that the tool response is predominantly due to this phenomenon. The scattered gamma rays reaching the detector, at a fixed distance from the source, are counted as an indication of formation density.

The number of Compton-scattering collisions is related directly to the number of electrons in the formation. Consequently, the response of the Density tool is determined essentially by the electron density of the formation. Electron density is related to the true bulk density, Db, in gms/cc, which in turn depends on the density of the rock matrix material, the formation porosity, and the density of the fluids filling the pores.

A correction is needed when the contact between the skid and the formations is not perfect, due to mud cake or roughness of the borehole walls. Two such measurements are used in borehole-compensated log calculations and the distance between the face of the skid and the extremity of the centering arm is recorded as a caliper log, from which it is possible to assess the quality of contact between the skid and the formation.

The FDC tool may not follow the same track up the side of the hole on subsequent overlap and/or repeat runs. If the formations are quite heterogeneous, having, for instance, more vugs and/or fissures on one side of the hole wall than on the other, the two runs may disagree slightly. Disagreement between runs is infrequently encountered, however, because the heavy skid tends to ride the downhill side of the hole, which seldom is vertical.

If residual hydrocarbons exist in the region investigated by the FDC, their presence may affect the Density Log readings. The effect of oil may not be noticeable, since the average fluid density of both oil and filtrate may be close to unity. But if there is appreciable residual gas saturation, its effect will be lower than Da (apparent DB value), resulting in a superfluously large, computed porosity.

Interpretation of the Density Log may be affected by the presence of shale or clay in the formations. Although the properties of shales may vary with the formation and the locality, a typical density for shale beds and laminar shale streaks is of the order of 2.2 to 2.65. Shale densities tend to be smaller at shallow depths where the compacting forces are not as great. Dispersed clay or shale disseminated in the pore spaces may have a somewhat smaller density than the interbedded shales.

Formation Density Logs are effective in uncased, air-filled boreholes and are popular in the gas exploration areas of central New York State. Where lithology is known, formation density can be related to porosity. However, the accuracy of the porosity computations is dependent on knowledge of the density of both the rock framework and the pore-filling fluids. Density logs generally display the corrected density curve, the applied correction curve and possibly a density-derived porosity curve. Because the corrections have been incorporated into the density values and porosity is a direct transformation, only the density curve has been digitized.

If Density porosity and Neutron porosity are displayed on the same log, the differences can be interpreted directly to indicate the presence of natural gas. This is an immediate advantage to the versatility of digitized logs that can be displayed to any format and in any combination, because most logging companies have tended to present these important curves on different logs and to different scales. The natural gas determination is based on the density-calculated porosity which considers the rock pores to be filled with a fluid; consequently, porosity is overestimated. Conversely, neutron porosity is based on contained hydrogen, and gas-filled porosity is underestimated. Where both logs are available and lithology is known, the errors can be corrected, and an accurate porosity can be obtained. Density values used for this project are the raw bulk density values displayed on the original log and digitized at Syracuse. New York State lacks the rock sample-derived density necessary to determine parameters for computing standard density curves.

Density Porosity Logs and Syracuse University Computer Computations. Syracuse uses standard density porosity calculations with a correction for shale content:

$$Dma = ((1-Sh\ fraction) * Dcf) + (Sh\ fraction * Dsh)$$
$$\emptyset = (Dma-Db)/(Dma-Df)$$

where:

D = density
cf = clean formation
Ø = porosity
ma = rock matrix
f = pore fluid
b = measured bulk density.

Matrix is corrected for shale fraction.

Sonic Logs

Description. The Sonic Log is a recording versus depth of the time required for a compressional sound wave to traverse one foot of formation. Known as the interval transit time, the recorded value is the reciprocal of the velocity of the compressional sound wave. The interval transit time for a given formation depends upon lithology and porosity. Its dependence upon porosity, when the lithology is known, makes the Sonic very useful as a porosity log. Integrated Sonic transit times are helpful in interpreting seismic records.

Variations of velocity in different types of rock produce a Sonic curve with some correlatable character. In addition to this, the very good vertical definition of the Sonic Log and the reduced hole effect on the BHC tool make this log excellent for correlation use. It is very helpful in some cases where other lots give poor results. Moreover, some types of formations, evaporites in particular, can be identified from their sonic values:

- The relationship between interval time and porosity is somewhat complex, but good values can be found for formations containing intergranular porosity.
- With the Borehole Compensated (two receiver) system the quality of the measurement is very good with accurate calibration, no borehole effect, and excellent vertical definition.
- The Sonic Log is useful for correlation. In many cases where other logs give poor results, some lithologies are identified by the magnitude of the reading.
- The Sonic Log can be used in combination with other porosity logs to evaluate shaly sands, determine formation lithology, and determine the amount of secondary porosity.
- The integrated travel time is useful in seismic interpretation.

Sonic logs require a fluid-filled borehole and are only occasionally run in Central New York State. Their sparseness prevents their use as a correlation log but the interval and total travel times are necessary for seismic formation identification. Sonic curves that have been recorded in a satisfactory manner have been digitized.

Sonic Porosity Computed at Syracuse University. Sonic Porosity is calculated according to standard formulae with a correction for shale fraction:

d(t)ma = (1-sh fraction) * d(t)cf + sh fraction * d(t)sh

Ø = (d(t) -d(t)ma)/(d(t)f - d(t)ma)

Where:

$d(t)$ = delta (t), sonic time in milleseconds per foot.
sh = shale
cf = clean formation
ma = rock matrix
$\emptyset$ = porosity
f = pore fluid
t = time.

Formation travel times are for clean well indurated Paleozoic formations and shale times are averaged from known clean shale zones in the area.

Temperature Surveys

Description. Temperatures encountered in drill holes are dependent not only on the natural geothermal gradient, but also on the circulation of the mud or other borehole fluid. In a strongly circulated well, the mud is thoroughly mixed, and its temperature tends to become uniform. When the drill pipe is removed and the well is allowed to stand, the mud in the hole at each depth gradually comes to the temperature of the formation around it. The mud temperature at each level changes at a rate which depends on the heat conductivity of the surrounding formations and on the volume of mud, which itself is a direct function of the hole diameter. Almost all temperature surveys in mud-filled holes are made during the transition period before thermal equilibrium has been reached. In air-drilled holes where the borehole is dry, thermal equilibrium is attained considerably faster than with conventional mud. Where the borehole is filled with formation fluid, the pre-equilibrium temperature relates to the water reservoir temperature.

Applications. At the present time, temperature measurements in gas and oil wells are primarily used for:

- Locating gas-producing horizons.
- Locating the depth of lost circulation
- Locating the height of the cement behind the casing, and the possible zones of channeling.
- Correlation with the electrical log for depth control in perforation operations.

- Estimating potential gas production.
- Computing formation temperature and geothermal gradients.

The survey is made by lowering the instrument into the hole slowly in order that the thermometer may have time to come to the temperature of the surrounding fluid. Surveying speeds up to about 5,000 feet per hour may be used. Measurements are made while going down in order to eliminate the perturbing effect of the presence of the cable. If another run must be made in the hole, it is necessary to wait from 6 to 12 hours so that the stable temperature conditions will have been re-established.

During the process of gas production, the temperature in the borehole is strongly affected by cooling due to the expansion of the gas. The drop of temperature opposite a gas-producing zone may attain 20 degrees F or more. Under these conditions and using special thermometers with high sensitivity and short time, constant temperature surveys show the points of entry of gas into the hole with great precision. In favorable cases, it is possible to derive from the temperature log an approximate estimate of the amount of gas produced by each separate horizon. Temperature surveys in open air-filled boreholes are very effective in indicating gas zones even in very tight and fractured reservoirs.

Differential temperature logs incorporate two thermistors vertically spaced a fixed distance apart. The difference between the temperatures measured by these thermistors is recorded. This difference is the slope of the fluid temperature gradient. The differential temperature curve reads a constant value except where the gradient changes. The effect is to accentuate small changes in the gradient that may be unnoticed on the regular temperature log.

Quantitative Temperature Log Interpretation. The production rate of gas (V) into an empty wellbore is:

$$V = C\,(T_e - T_g)/(dT_g/dh).$$

Where T_e is the earth temperature, T_g is the gas temperature, dT_g/dh is the change in gas temperature with depth, and C is the proportionality constant.

C is a function of the type of flow (streamline or turbulent), length of time gas has been flowing, hole diameter, casing, and cement.

C is usually determined empirically for individual formations and areas.

The bracketed expression is referred to as Delta (Δ), thus the equation can be restated as:

$$V = C \times \text{Delta}$$

The average geothermal gradient on the temperature log past the gas entry point is constructed as follows: A tangent to the temperature log is drawn below the top of the gas gradient break and above the gas entry point (point of minimum temperature). This tangent line should extend over 100' of depth. An example of delta determination is illustrated in Figure 4-1.

For example

where delta = (87.35 - 82.40)/((88.15 - 77.80)/100) = 47.8

Known gas volumes from four-point or other gas volume flow tests are compared to computed deltas and charts constructed for the interpretation of other temperature logs. Account must be taken of borehole size, multiple gas-bearing zones and fluid in the borehole. Because there are only a few wells in New York State where there are good flow tests and temperature logs, the chart used (Fig. 4-2) is an adaptation of a standard chart.

Sibilation Logs

The Sibilation Log is used to detect the movement of gas into the borehole. It is a passive device consisting of a transducer that picks up the vibrations caused by the movement of gas. Unfortunately, there are not enough Sibilation Logs in New York to quantify their response to gas volume, but they are an excellent indicator of the zones that produce gas.

Caliper Logs

Caliper Logs utilize expanding arms to make a record of borehole diameter. Because variations in borehole size and roughness can have a major effect on the calculation of formation parameters from well logs, caliper curves have been digitized for this project at Syracuse University for all the wells for which they were available.

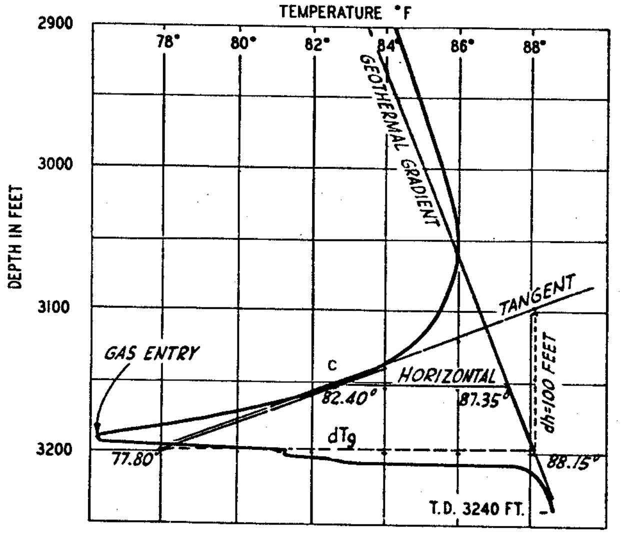

Figure 4-1. Delta Determination (From Birdwell, (1973)

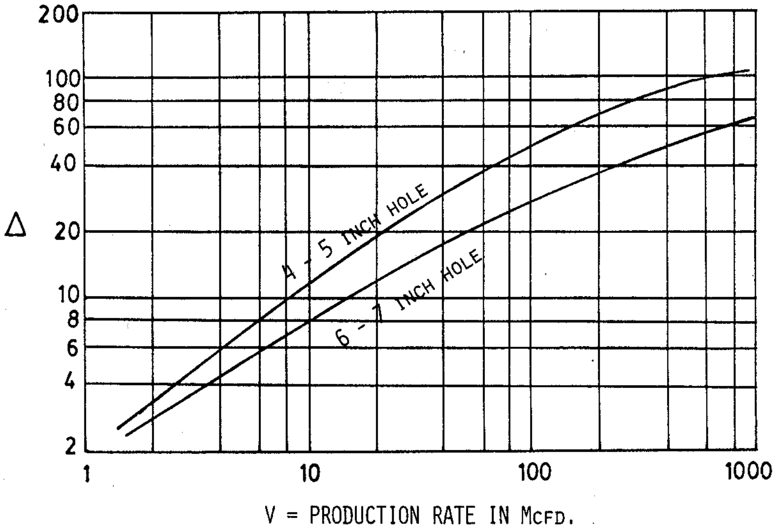

Figure 4-2. Production Rate Chart (After Birdwell, 1973).

Induction Logs

Induction Logging makes use of currents induced in the surrounding formations to measure their resistivity and conductivity. By proper design and placement of the coils mounted on the sonde, the response is confined by a horizontal slice of formation of limited thickness. The effects of the mud column and of adjacent beds are minimized or even rendered negligible in many cases.

With the present equipment, the Induction Log works best in soft or moderately consolidated formations drilled with fresh muds, and it is generally more reliable than the conventional electrical log even in hard formations. The Induction Log operates to advantage when the borehole fluid is an insulator--even air or gas. But the tool will also work very well when the borehole contains conductive mud. Induction logs are used for correlation and for measuring water saturation in intergranular porosity reservoirs.

Induction Logs Digitized at Syracuse University. Induction Logs have been successfully used in New York State wells and are common in local areas. They make a good correlation tool, although there is not sufficient information on actual formation conductivities for any form of standardization. All good Induction Log curves from project wells have been digitized and displayed for visual formation analysis.

Section 5

RESERVOIR CHARACTERISTICS

DEFINITIONS

Porosity

Porosity is the fraction of the total volume of a sample which is occupied by pores, or voids. A dense, uniform substance such as a piece of glass, would have zero porosity; a sponge, on the other hand, has a high porosity.

Effective porosity is that in which the pores or voids are interconnected so that fluids can pass through the sample. Total or bulk porosity of a sample includes not only pores which are connected, but also those which are sealed off by cementing material.

Porosities of subsurface formations can vary widely. Dense limestones and anhydrites may show practically zero porosity; well-consolidated sandstones show about 10 to 15 percent porosity; and unconsolidated sands show up to 30 percent or more porosity. Shales and clays may contain over 40 percent liquid by volume, but they are so fine-grained that they are practically impervious to the flow of fluids. For all practical purposes, their voids are not interconnected, and their porosity is not effective.

Porosities may be classified also according to the physical arrangement of the material which surrounds the pores. Thus, in a clean sand, the pores exist between the grains. Such porosity is called "intergranular," and is inherent in sand formations since the time they were deposited. Vugular and secondary porosities are caused by the action of formation waters on materials after deposition.

Fracture porosity is that resulting from compaction and tectonic movements in brittle rocks such as limestone and refers to the open fractures and joints in the rock. Trenton porosity is largely fracture porosity.

Permeability

Permeability is a measure of the ease with which a formation permits fluids to flow through it. For a given sample of rock and for any homogeneous fluid, the permeability will be a constant, provided the fluid does not interact with the rock itself.

In order to be permeable at all, a rock must have some interconnected pores, capillaries or fractures: that is, it must have some effective porosity. There exists a rough relationship between the values of porosity and permeability. Greater permeability, in general, corresponds to greater porosity, but this is far from being an absolute rule.

Limestones may be composed of dense rock broken by a few small fissures of great extent. The porosity of such a formation would surely be very low, but the permeability of a fissure can be enormous. In fact, it has been shown that a 0.05 in. fissure will have a permeability equivalent to about 550 feet of sand of 1000 millidarcies permeability. Therefore, fissured limestones may have very low porosities, together with exceedingly high permeabilities.

Effective permeability refers to the permeability of a formation to one fluid when another fluid, immiscible with the first, is also present. It not only depends upon the rock itself, but also upon the relative amounts of the two (or more) different fluids present in the pores.

Saturation

Saturation of a formation is the fraction of its effective pore volume which is occupied by the fluid considered. In electrical logging practice, it is customary to consider the formation water as the saturating liquid because it conducts the electric currents.

Water saturation is the fraction of pore volume which contains formation waters. If nothing but water exists in its pores, a formation has a water saturation of 100 percent--the volume of water equals the pore volume.

Most rocks have a preferential affinity for water rather than oil or gas, and water was the universal reservoir fluid when the sediments were deposited. The oil and gas displace the water in the reservoirs but leave remanent water on the rock surfaces and in the smaller pores and fractures. Fractures, because they tend to be larger openings than intergranular pores, usually have relatively low saturations. Water production is not a great problem in Trenton gas production although some water can be produced where there are high gas production rates.

GENERAL LOG INTERPRETATION

Logs used in the general interpretation are the Gamma, Neutron, Density, Caliper and Temperature. Sonic logs are rare in New York but are interpreted where available. The few available Induction logs were digitized and examined. They were effective for indicating fracture zones but there was not sufficient detail available to compute water saturation.

Log interpretation of the Trenton Formation is different from that of the more usual reservoirs with intergranular porosity. Outcrops, log interpretation and a detailed examination of an experimental well drilled in the city of Auburn indicate that the Trenton Limestone is a dense, compact limestone with interbeds of thin shale stringers. The limestone is commonly fractured with the fractures providing the reservoir porosity. Production is not confined to any one zone but can vary over the entire limestone section. Only a few of the fractures produce significant amounts of gas. Zones where the limestone is thinly bedded with alternating shale, appear to have greater fracture frequency than where the limestone is more massive. The style of fractures in the subsurface was confirmed on the Auburn test well by a fracture finder log and a borehole televiewer log. These logs provided a detailed picture of Trenton fractures and by direct correlation with the more common logs, can be extended to the general interpretation.

The Gamma Ray Log indicates the amount of shale in a formation. It is also excellent for locating the Trenton top, base and the main facies members. However, the Gamma Ray tends to underestimate the shale content in the middle member, the interbedded limestone shale section, because the log integrates over a period of log movement and gives an average reading for thinly bedded zones. It does not indicate fractures.

The Neutron Log is also excellent for picking the Trenton members and, when standardized, for computing the porosity of the clean limestone zones. However, it does tend to suggest an erroneous degree of porosity in the interbedded limestone shale zones. The neutron logs, particularly the older logs, tend to stay in the center of the hole and integrate over a time and hole length period. The Neutron gives an average response and thus does not indicate fractures. The more recent sidewall neutron log is pressed against the side of the hole and gives a better indication of fractures, but these logs are rare in the Trenton wells, most of which were drilled a decade or more ago.

The Density Log is also a sidewall tool and is held against the side of the borehole by a strong spring caliper. It is the best of the common tools for indicating fractures. Because the density of the highly indurated shales is only moderately different from the limestone, it does not indicate the tops or the different members. Fortunately, the Density Log also will indicate any intergranular porosity with only a very slight bias caused by the shale interbeds. It is the best device for evaluating Trenton porosity. It is used in those sections where the Neutron Log gives a false reading. Only in the large gas producing fractures is there the normal gas indicating cross-over between the neutron and the density logs.

The usual indication of gas in the formation is indicated by the interplay between the Neutron and the Density Porosity logs. The Neutron Log which is calibrated to read the correct porosity in a water- or oil-saturated formation reads too low a porosity in a gas reservoir, while the density tool, which is also calibrated to read correctly in a water- or oil-saturated formation, gives too high a porosity value when it finds gas. The divergence between the curves shows the real porosity and the gas saturation. Unfortunately, this does not always work in a fractured reservoir.

The Caliper Log indicates hole size and will often show fractures and those caved and rough walled sections that affect the response of the logs. All caliper logs were digitized and displayed as a check against other logs interpretations. They were a major aid in the interpretation.

The Temperature logs also are a major factor in the interpretation of gas production. Trenton wells were mainly drilled with cable tools or air drilled with rotary rigs. Only a very few were drilled with mud. When the borehole is empty or contains only a relatively small amount of water, gas will enter the well and expand. This creates a cooling effect that registers on the temperature log. The log not only gives the location of those zones that produce gas, but also the shape of the curve can be used to estimate the amount of gas being produced. Conversely, hot zones record the influx of formation water. Knowledge of the presence of any fluid in the well is critical to the interpretation. The vast majority of the

Trenton wells were logged with the borehole containing either air or formation water. The formation fluids are brines and normal electrical logs are not effective. Induction logs were run in some recent wells.

The induction logs are displayed as resistivity and conductivity curves. Both curves respond slightly to gas-filled fractures but not in a manner that allows quantitative water saturation calculations. They act as an aid in locating productive fracture zones in the Trenton formation.

POROSITY INTERPRETATION

In wells where both the Neutron and the Density Logs are available and responding correctly to lithology, the calculated porosity curves will indicate the same porosity values in clean, tight formations. They also will show approximately the same porosity under good borehole conditions where the formations contain only water-filled intergranular porosity. The neutron and the density porosities will diverge where gas-filled intergranular porosity is present and where the density curve intersects fracture porosity. Compacted, high-density shales also will cause divergence between the computed porosities. Sonic porosities, although rare in New York State, behave more like the neutron than the density porosities; however the Sonic Log does react more to fracture porosity than does the Neutron. All computed porosities depend on the fluid in the borehole, the shape and size of the borehole and the formation fluids.

New York State well logs were recorded by a variety of logging operators over a considerable period of time using tools with differing responses. For this project, Neutron Log responses to lithology were standardized; then neutron porosities that appear reasonable for tight, dense formations were computed. However, the Neutron Logs give a low porosity reading when natural gas is present, a very common occurrence in the reservoirs of New York State. Consequently, there are very few real checks on the formation parameters used in the neutron porosity calculations. Density Logs measure porosities that are too high in gas-filled zones; yet the computed density should equal that of the neutron porosity in tight formations. Calculations of porosity from the Density Log assume that the original curve displays an accurate presentation of formation density; however such does not appear always to be the case. Most subsurface rocks contain varying amounts of minerals other than carbonates and quartz sands so that the Limestones, Dolostones, or Sandstones that constitute the common reservoir rocks exhibit a range of densities. Consequently, determination of the true density of the Trenton Formation in any one area requires measurements on cores, which are very scarce in New York State. Densities as recorded have had to be accepted for porosity computations. Also, the density tool is a sidewall device and is sensitive to borehole conditions and fractures. Similarly, sonic porosity calculations are very sensitive to borehole conditions.

Interpretation of the Trenton formation is primarily based on the Gamma, Neutron, Density, Temperature and Caliper Logs. Other logs such as the Sonic and Induction Electric were examined, but were too few for any form of continuity. Also, all available stratigraphic logs and some samples were compared with the logs and used in the interpretation. Any descriptions of fluids in the borehole were considered and corrections made where possible.

Comparison of the Neutron and Density Logs with samples and geologs suggest there is more shale in the Trenton than is indicated by the Gamma Log. It appears that much of the calculated neutron porosity appears as a result of the presence of shale and is not indicative of real porosity. Although Bentonitic layers are known and water-sensitive swelling clays have been reported, the Trenton shales apparently have less radioactivity than is usual in common shales. The Neutron Logs that respond to the water content of the shales tend to indicate zones with porosity values that appear to be too high. The same shales appear to be compact, well-indurated and have densities very close to those of the limestone layers. Thus, the Density Logs exhibit little reaction to the shale layers and show virtually no porosity. In this case, the interpretation is weighted towards the density porosity. Additional evidence is provided by the Caliper Log which often suggests minor caving in the shalier areas. The Density Logs do react normally to gas-filled fractures showing strong crossovers and this reaction, in turn, is substantiated by temperature response to gas inflow and sibilation response where the logs have been run.

All information indicates that the Trenton reservoirs are the result of fracture porosity, with little or no intergranular porosity. The best production occurs in those areas where fracturing is most intense such as in those zones where tectonic activity has resulted in folding and faulting. However, minor tectonic movements are all that is necessary to produce effective porosity. Outcrops and logs show extensive fracturing, and a single fracture identification log run in a well within the city of Auburn in Cayuga County indicates a high frequency of fractures. The fractures themselves are most prevalent in the zones with shale interbeds, because the variations in plasticity tend to promote fractures in the brittle limestone beds. The fracture openings make up only a very small percentage of the formation thickness. Summation of potential fractures from Density and Caliper logs suggests averages of less than 1 percent of total Trenton section.

Section 6

HISTORY OF PETROLEUM AND NATURAL GAS IN THE TRENTON FORMATION

Interest in the Trenton Formation as a potential source for petroleum and natural gas began in 1884 after oil and gas were discovered in the Trenton of Ohio. There, the dolomitic upper Trenton proved to be an excellent reservoir and over the years has produced more than 320 million barrels of oil and considerable natural gas. Following an unsuccessful test in the Watertown area, a well was drilled into the Trenton formation just outside the Village of Sandy Creek. This well, in which gas was discovered, was the first in the area and was highly successful. The well was spudded in 1888, but due to drilling difficulties was not completed until the following year. This well was immediately utilized to supply the Village of Sandy Creek and after 8 years of "large but not continuous use" was found to have a shut-in pressure of 60 psig, a drop of only 20 psi. from its original 80 psig. Production varied from 30 to 40 Mcfd with the reservoir recharging when shut-in. Seventeen of 18 follow-up wells drilled in the Sandy Creek area were also producers. The field supplied the villages of Sandy Creek and Lacona until well into the 1940's with a record of only two dry holes and 40 successes.

Following the success at Sandy Creek, and with the knowledge of gas seeps in the area, a group of citizens drilled a gas well within the Pulaski village limits in 1891. This first well found high-pressure gas, blew out, flooded and never was a good producer. Fortunately, follow-up wells were successful, and eventually over 80 wells were drilled in the Pulaski gas field.

A well in the Fulton area was started in 1888 and later deepened to reach the Trenton where gas flow was found. Additional wells were drilled during the 1890's and discovered high-pressure Trenton gas in 1893 just southwest of Fulton. In 1895, gas shows were found in a well drilled near the village of Parish.

In 1897, gas was discovered near Baldwinsville and Warners in Onondaga County and the following year near Memphis, Jordan and Elbridge. The Baldwinsville field was the most successful of the Onondaga plays and supplied gas to the Village of Baldwinsville until 1928. Several wells in the area came in with very high pressures and good volumes; the first Trenton well had a reservoir pressure of over 1600 psig and gas volume of 3 MMcfd. Although many of the wells quickly lost much of their pressure and gas volume, others continued to supply gas for many years to the Village of Baldwinsville until the field was abandoned as a commercial gas field in 1928. Since that time, several wells have been connected to individual houses and farms, and still produce gas. Shut-in pressures on these wells are often several hundred pounds.

During this same period, gas wells were drilled in the Rome and Utica areas. Initial flows and reservoir pressures were high for the shallow section with initial production potentials as high as 7.5 MMcfd. Other Trenton wells were drilled in the western portion of the state and many had gas shows, but they were generally not as successful and did not develop as designated fields. A Trenton well at Clyde in Wayne County, however, was reported to have an initial production of 5 MMcfd. Natural gas was the main product of these wells; although the literature notes instances of light crude oil being found in some of the wells. Evidently, there were some small amounts of condensate or casing head gasoline in a few of the wells; however, there is no record of any substantal production of oil.

The next major drilling period was in the 1920's and 1930's. A small gas field was developed in the Camden area of Oneida County. Eleven more wells were drilled to develop the Rome field. Some of the latter wells, which were completed in the Trenton at depths of 600 to 900 feet, had open flows of 2 to 3 MMcfd. Gas was also developed in the Tug Hill area where five wells were drilled in 1933 and 1934. An additional eight wells were drilled in the Clyde field with large open flows. One well had a reported shut-in pressure of 1900 psig. However, the field was never of commercial importance.

The Camden field supplied the needs of the Village of Camden from the discovery in 1934 until the mid 1940's when low gas pressure and wartime shortages of spare parts, pipe, and drilling supplies caused the shutting down of commercial production. The field was similar to other Trenton producers in that there were high initial reservoir pressures and flow rates. Although pressures dropped quickly and after 10 years of production fell to only a few ounces, several of the wells are still producing gas in quantities sufficient to heat individual homes.

The Theresa and Potsdam sandstones lie at the base of the sedimentary section in Central and Western New York. They exhibit porous and permeable zones up to 400 feet thick that pinch out northward along a zone that is roughly parallel to the southern shore of Lake Ontario. This stratigraphic reservoir triggered a major land acquisition and drilling program in the 1960's by major oil companies. They had a series of basement tests drilled across northern New York in a swath approximately 50 miles wide lying to the south of Lake Ontario. However, the oil companies were looking for oil; they did not want the gas they found in the Trenton and abandoned most of the wells. When the area was found to be gas prone, many of the drilling locations were farmed out and one of the farm-out wells discovered the Blue Tail Rooster field in Cayuga County. The Ripley well, which was the main discovery well, had an initial open flow potential of greater than 10 MMcfd. It produced considerable gas under test. Then, due to legal difficulties, it was shut-in until 1982 when it was, along with two other old wells, finally placed on production.

After the drilling period of the 1960's, the major oil companies lost interest, and there was a relatively quiet period with wells testing the Trenton drilled only sporadically. It was not until the price of gas increased in the late 1970's that more than the occasional well was drilled into the Trenton. In recent years, several wells in Onondaga and Oswego counties have tested the Trenton. Although the modern wells found gas, fields have not been developed, and the Blue Tail Rooster field remains the only active Trenton commercial field.

In all, there have been over 200 wells drilled into the Trenton formation in New York State. Although much of the early information, particularly pre-1900, has been lost, there are records, stratigraphic logs and geophysical logs on over 100 of the more recent wells. Analysis of these records permits a new evaluation of Trenton potential. Unfortunately, there are no detailed records of individual well production; however, from the field history, it is possible to suggest procedures to arrive at production rates that can be optimized for each well as it is produced and its characteristics observed.

It must first be noted that the Trenton reservoirs are very extensive. The majority of the wells that have tested the Trenton have found natural gas. Also, virtually all the wells drilled in the northern half of the State can be considered to have been drilled at random. Only one or two wells drilled in the Southern Tier have been near seismic lines. There is no seismic in the north, and the surface geology is covered and hidden by glacial deposits. The early drillers simply put down wells close to the village that wanted the gas. Even the major oil companies laid out their wells on a widely spaced stratigraphic test basis to ensure evaluation of a large area.

Source rocks are readily available. The Trenton is overlain by black, often organic-rich Utica shales, and the Trenton itself is often black, contains organics and is interbedded with shales. The Trenton overlies the Black River Limestone which in turn overlies Cambrian sandstones which also have porous and permeable sections often containing natural gas. Also, New York State is on the northern and updip edge of the Appalachian basin, directly on the migration route of deep basin petroleum and natural gas.

Analysis of the Density logs and the Temperature logs show the Trenton gas production is from fracture porosity. This interpretation is confirmed by fracture locator logs and borehole televiewer logs run through the Trenton in a well drilled to evaluate geothermal potential in the city of Auburn. Most of the gas production in individual wells is from a relatively few fractures, there being little or no intergranular porosity. Not all of the fractures produce gas and some of the zones that appear highly fractured produce very little gas. Those zones where there are shale interbeds and the limestone is consequently most subject to fracturing, have the most frequent gas indications, but there are no consistent beds where the gas is encountered. Any fractured zone in the Trenton is a potential production zone. Frequency of fracturing does vary and appears to account for the variations in productivity.

Fracture porosity appears to be consistent throughout the area of Trenton production and Trenton shows. As such, the common completion and drilling techniques were not conducive to optimum production. With cable tool rigs, the wells were allowed to blow down before drilling could continue when they hit pockets of gas. Modern wells often are allowed to blow down during production testing. When gas pressure in the formation is allowed to drop, the elastic rock will tend to close off the fractures thus shutting off the gas supply. Over-production has the same effect. This is the reason that many of the early producers felt that Trenton reservoirs were small or would only produce small amounts of gas. However, when the wells were shut-in they would regain their old pressure and could be produced again. In the old jargon this was considered to be "resting the wells." Actually, this phenomenon is indicative of large reservoirs which must carefully be produced to obtain optimum results. Some of the old wells, after a lifespan of 50 or more years, will still show quite high pressure when shut-in.

Additional evidence indicating extensive reservoirs, is that the initial reservoir pressures are commonly above hydrostatic for their depth. Where the reservoir rocks are mature, compact and in equilibrium with their depth of burial, reservoir

The presence of expanding clays in the Trenton Formation indicates that any operator planning a hydrofrac of the pay zones should ensure that inhibitors or a foam frac should be used. A fresh water frac could cause formation damage.

GAS ANALYSIS

Available gas analysis and descriptions of the natural gas produced from the Trenton of New York State are consistent in that they show the gas to be a clean-burning, odorless natural gas. Analyses of gas from the Camden and Baldwinsville fields show the gas to be more than 98.5 percent methane with only traces of carbon dioxide, carbon monoxide, oxygen and nitrogen. There is no indication of sulphur or other noxious gasses. The gas can be utilized directly without treatment. Thermal content averages 1013 Btu per cubic foot.

GAS RESERVES

Gas reserves (standard cubic feet per acre) equal

$$43560 * A * T * (1-SW) * (Ts/Tf) * (Pi-Pa)/PS$$

Where: A = One acre for computation and comparison
T = Total thickness of open fractures = net pay thickness in feet * porosity
Sw = water saturation (approximately 20% in fractured reservoir)
Pi = Original reservoir pressure (psia)
approximately 0.445 psia/ft depth
Pa = Abandonment pressure (psia)
assumed 100 psia for initial open hole completion
Ps = Surface pressure (14.7 psia)
Ts = near surface temperature, degrees Rankin (460 + ^{o}F)
Tf = Formaton temperature, degrees Rankin.

With relatively pure methane, compressibility factors approach 1.0 and are not considered in the calculation.

Estimates from gas detection logs (temperature and silibration) and Density Logs utilizing a comparison with the fracture locator log run in the Auburn well, suggest that suitable fractures may make up between 0.1 percent and 1 percent of the Trenton Formation. An averge estimate would be 0.5 percent of one foot of gas bearing fractures for each 200 feet of Trenton Section.

Considering the central Oswego County area, an estimate of gas potential in a well that intersected average porosity would be:

Depth to Trenton:	Elevation of Trenton top	-600'
	Surface elevation (400')	400
	Subtract algebraically	1000'

Trenton thickness: 600'
Reservoir thickness: 0.005 * 600 = 3'
Total well depth: 1600'
Calculated reservoir pressure to mid point of Trenton without overpressure allowance:

1300 * 0.445 + 14.7 = 593 psia;

Reservoir Temperature:

Average Surface Temperature 50°F = 510° Rankin
Temperature Gradient = 0.0164 F/ft
Reservoir Temperature (1300 * .0164) + 50 = 71°F = 481°R;

Approximate reserves per acre are:

43560 * 3.0 * 0.8 * 510/531 * ((593-100)/14.7) = 3.3 MMcf

Reserves/drilling unit can be computed by multiplying by size in acres of unit.
For a 40 acre unit, reserves are 132 MMcf.
In deeper areas such as Cayuga and Seneca Counties, reserves will increase due to higher pressures increasing the volume of gas (Boyle's Law).
For example, a well in central Cayuga County might find the Trenton at a depth of 2700 ft and have:

43560 * 3.00 * .80 * 510/554 * (1335 - 100)/14.7 = 8.08 MMcf per acre

or:

323 MMcf/40 acre unit.

Also, increased formation pressure in the deeper section will increase producibility of the reservoir and allow higher daily gas volumes with possibly larger drilling units.

OBSERVATIONS ON TRENTON PRODUCTION

The production of gas from fractured reservoirs is different from that of reservoirs with good intergranular porosity. The initial production may be from a large number of fine fractures in the vicinity of the borehole; however, only a relative few of these fractures may be of sufficient extent to bring in gas from outside the local area. Production tests run in the first few days, even if they extend over a considerable period of time may have little to do with the real producibility of the well. The key to producibility is how well the gas can be transmitted to the well from a large area, not just from the zone immediately surrounding the borehole. Local gas can be quickly exhausted so that there can be a rapid drop in pressures and production. However, if the main reservoir is correctly produced, there can be many years of continued production with very little decline. This producibility depends on the recharge rate of the through-going fractures which may not have much to do with the initial production tests. Even locating where the best production zones are will require a period of production.

Fortunately, water zones are rare in the Trenton, and it is possible to do an open hole completion for the entire producing section. It is not a good idea to attempt casing and fracturing until the best zones to frac have been determined, and these can vary from well to well even in offset wells. Acid treatment of the section is not recommended, even an acid frac may not be advisable. Any frac should be aimed at extending the main producing fractures, some of which may be individual fractures, as far as possible. Each well should tap as large an area as possible, because on a volume basis, total porosity is relatively low but the reservoirs are laterally very extensive. With efficient production, the shallow Trenton wells in northern New York can remain in production for many years.

Section 7

TRENTON PROSPECTS

TRENTON PROSPECTS

The Trenton Limestone Formation underlies or outcrops in some 35 New York State counties. Structural control, formation thickness and potential prospects differ for each area. Drilling has been most intensive and productive in the shallow section south and east of Lake Ontario. Tests in the Southern Tier are so sparse that it is not possible to make a detailed analysis and the Trenton Limestone is replaced by the Utica shale to the east so that prospect potential decreases rapidly towards the Leatherstocking area of eastern New York. Because of the large area of good reservoir potential and the variation in economic factors, the description has been written on an area basis with individual counties being considered wherever information warrants.

CAYUGA COUNTY

Cayuga County is the site of the Blue Tail Rooster gas field which is the only commercially producing Trenton gas field in the State at present. This field was discovered in 1966 and appeared sufficiently promising that a pipeline was constructed. However, it was not until 1981 that three of the wells were placed on continuous production. Present production rates are relatively low but this may partly be due to 20 years of neglect of the wells. The most interesting well is the J.L. Ripley No. 1 (031-011-5000) which originally tested more than 12 MMcfd on open flow. Reservoir pressures were well above hydrostatic, and the logs indicate production was mainly from fractures at the base of the Trenton C. Other wells in the area have had good Temperature log responses and may be comparable, but test results are not available. However, a new test drilled in the spring of 1984 was reported to have flowed more than 8 MMcfd with a shut-in reservoir pressure of greater than 1600 psig.

County wells in the Auburn and more southern areas have had gas shows from the Trenton but the records do not indicate gas quantities.

Potential gas production is dependent on through-going fractures. Zones of production can vary from the top to the base with the most frequent zones being at the top to Trenton B and at the base of Trenton A. Pressures are generally above hydrostatic suggesting a thick gas zone. The most productive areas are aligned with the minor tectonic flexures that are conducive to fracturing.

The most prospective area is in the northern half of the county. There are very few wells in the south. Nevertheless, there are hints in the structure map of features in the southernmost part of the county that could prove to be good reservoirs.

The known reservoirs are extensive and appear to pervade the entire 700-foot average thickness of the Trenton. Fractures interconnect and the pressures indicate charging from down dip or deeper formations. The key to long-term gas production is to maintain stable reservoir pressures so that elastic expansion of the rock does not close off the conduits. However, in central Cayuga County, some of the better wells with open flow potential of 10 to 12 MMcfd appear capable of producing up to 200 Mcfd while maintaining a back pressure of over 1000 psig.

ERIE COUNTY

The Trenton elevation ranges from -1700 to -3500 feet from the northern to the southern boundaries of the county. Trenton tests have been fairly well distributed throughout the county, and only one has been reported to have significant Trenton gas shows. A well drilled within the Buffalo city limits in 1924 was reported to have an indicated flow of 700 Mcfd at just over normal hydrostatic pressure. Other wells have not found the open fractures that provide the reservoirs. Consequently, the formation is considered to be tight.

There is gas in the area. However, fracture porosity is not pervasive, and subsurface, preferably seismic, control would be necessary to locate the structures that cause the fractures.

GENESEE COUNTY

The Trenton elevation ranges from -1600 to -2500 feet and the thickness from 400 to 500 feet. The Clarendon-Lindon fault cuts diagonally from north to south across the county and has, as indicated by the logs, created considerable fracturing. The logs do suggest that the Trenton should be prospective; however, there is no mention of

Trenton gas in the reports. There are no temperature logs for gas volume estimates; consequently, the county is difficult to evaluate. The induction logs do suggest possible gas; however, there is considerable caving and hole size effects which bias the interpretation. A possible detriment could be the escape of gas from the reservoirs via the relatively large scale faults that are evident on the present topographic surface and which are known to penetrate the entire sedimentary section from interpretation of seismic lines across the area.

The county does have the requirements for Trenton gas reservoirs but prospects should be determined through interpretation of detailed seismic profiling.

JEFFERSON COUNTY

The Trenton is prospective in the southern portion of the county; however, the shallow thin section suggests reserves only adequate for local farm use. Commercial gas production should not be anticipated in this county.

LEWIS COUNTY

A small Trenton gas field supplied the Village of Lowville in the 1920s and 1930s and a well drilled in 1960 in the southern part of the county had an indicated gas flow of 50 Mcfd on test. The Trenton is prospective throughout the county; however, the formation is near its outcrop and the shallow depth limits the available gas volumes. The best areas would be along the northeast trending faults that extend into the basement and can be seen at the surface in the Adirondacks to the north. Detailed magnetic or gravity mapping can be an aid in the delineation of the prospective trends. Major commercial gas production cannot be expected in this county; however, there are good prospects for local gas supplies suitable for farm and possibly secondary industry use.

LIVINGSTON COUNTY

Elevations of the top of the Trenton range from -2400 to over -5200 feet and thickness to over 750 feet. The logs indicate fracture porosity in both the Trenton A and B units. Unfortunately, there is only one gas show recorded in the published records. The majority of the wells have been drilled since 1960 with air rotary rigs. Large flows of gas would not have gone unnoticed. However, the wells have been concentrated in the northern half of the county, and there still remains much of the area to be explored. The Trenton would probably not be the prime objective in this area, but there have been recorded gas shows from the units below the Trenton. Operators should pay close attention to this formation if their control indicates proximity to tectonic structures that could intensify fracturing. Prospects in this area would need to be based on seismic profiling.

MADISON COUNTY

Trenton elevations in Madison County vary from 1000 feet in the northeast to less than -400 feet in the south. Thickness decreases from over 500 feet in the north west to less than 200 feet in the southeast. Records do not indicate Trenton gas shows in the county; however, known production to the north and probable extension of basement structures into the county could give rise to possible prospects. The northwest corner is the most prospective. The few Trenton tests have not adequately tested the area; and although the Trenton would not be a primary objective, it does appear to have some potential in the northern and western part of the county.

MONROE COUNTY

Elevation of the Trenton formation ranges from -1000 to -2400 feet and thickness from 550 to 650 feet. Logged wells are confined to the northwest corner but all have good Trenton gas shows. Temperature curves suggest 100 Mcfd. The best gas production is from the base of Trenton A, but there are also indications for Trenton B.

Two wells drilled in the Rochester area (1899 and 1934) did not produce any recorded gas nor did a third old well drilled in the southern part of the county. However, there are known gas wells in the counties surrounding Monroe; and with a thick Trenton section, numerous log indicated fractures, and potential gas production in the northwest, the county does have prospects. It is necessary to determine those areas most conducive to intense fracturing that could form large interconnected reservoirs. It would be anticipated that subsidiary fracture zones would be created from the tectonic movements that caused the main Clarendon-Lindon fracture zone just to the west of the county. Fracture zones might be interpreted from outcrops along stream valleys or by shallow high resolution seismic. Random drilling is not recommended in Monroe County. Because of the shallow Trenton section and the scarcity of large systems of open fractures, the southern and western portions of the county are considered to be the most prospective.

NIAGARA COUNTY

Trenton elevations range from -900 to -1700 feet and there is an average Trenton thickness of 450 feet. There are very few Trenton tests, only one of which had an indicated gas flow, although two old wells had reported gas shows. The county has not been adequately explored; however, the Trenton Formation is relatively shallow, and there is little opportunity for large gas deposits unless zones of intense fracturing are located. The eastern and southern portions appear most prospective, but unless detailed subsurface geophysics reveal structural features that would have caused fracture zones, the area may best be considered as potential for local use as farm gas or for use on secondary single industries.

ONEIDA COUNTY

Oneida County has been one of the more prolific Trenton gas areas having both the Rome and the Camden gas fields. The Trenton outcrops in the northeastern part of the county and reaches elevations of -2000 feet at the southern edge. Northeast-southwest trending structures from the Adirondack uplift have produced the required fracture systems, and the thinning and shaling out of the Trenton to the south have left Oneida County along with Oswego County in favorable positions for gas accumulations. Most of the wells in the northern portion of the county have reported gas shows. Wells in the Camden field had initial gas flows of up to 2 MMcfd at considerably over hydrostatic pressures, although the pressures were reported to drop quickly when produced at high volumes.

Oneida County is prospective and has the potential for local, single farm use gas production in the northern area where the Trenton outcrops yet also has the potential for small commercial production in the deeper Trenton areas. The best wells tend to align along the flanks of structures where fractures are open and most numerous; however, nearly all wells produce some gas. Exploration in this area should make use of consider the subsurface structure maps and such geophysical information as the published aeromagnetic and gravity surveys which delineate the basement trends. Production is best regulated by extracting only that volume of gas that maintains reservoir pressures within approximately 200 psig of initial shut-in pressure. Strict pressure control appears to be the key to long-term production.

ONONDAGA COUNTY

Natural gas has been produced from the Trenton Formation of Onondaga County for almost a century. The Baldwinsville gas field and its northern and southern extensions are situated along a structural trend that parallels the Adirondack basement lineaments. These fields were characterized by high gas pressures with large initial flows. The relatively rapid fall off in both pressure and gas flow suggested to the early operators that the reservoirs were very limited. However, this phenomenon is characteristic of fractured reservoirs, even of very large size, and the repeated build up of pressures when the wells were shut in suggests relatively large reservoirs. Some of the wells are still producing on a limited basis.

Trenton tests are sparse in central and eastern Onondaga County; however, there is gas in the west and north and shows to the east. Unfortunately, the lack of tests prevents the mapping of the structures that are likely to control the better reservoirs. The deep structures in this area are masked by shallow Appalachian folds that have little effect on the deeper and more desirable structures. Reservoir controlling structures trend northeast-southwest and should extend as semiparallel sets across the county. Trenton depths and reservoir qualities are sufficient for commercial gas deposits. The county is prospective. It is possible to extend the old fields and to locate new ones. However, optimum new field locations would require seismic profiles to exactly locate the controlling structures.

ONTARIO COUNTY

Trenton elevations range from -2000 feet to less than -4400 feet in the south. Thicknesses are up to 800 feet. There have not been any reported Trenton gas shows in the county. However, there are only three deep tests in the county, and there is gas to the north in Wayne County and shows in the northern portions of adjacent Seneca and Livingston counties. Unfortunately, subsurface control is not sufficient to delineate structural trends that might produce the required porosity.

ORLEANS COUNTY

Trenton elevations range from -900 to -1200 feet and in thickness from 500 to 550 feet. The Clarendon-Lindon fault zone flanks the eastern edge of the county, and a number of test wells have been drilled so that a comprehensive evaluation of the county can be made. Unfortunately, although there have been a number of gas shows, tests have been disappointing with the best open flow potential approximately 20 Mcfd. The logs indicate that there are fractures suggesting gas potential at the base of Trenton A and throughout Trenton B. However, the rather disappointing results of previous tests suggest that only limited local production could be expected.

OSWEGO COUNTY

Oswego County has been the scene of some of the earliest and most continuous Trenton gas production in New York State. The Stoney Creek, Pulaski and Fulton gas fields were historical fields, and some of the wells are still producing on a limited basis. Recent wells have shown that the potential is far from exhausted. Trenton elevations range from +600 feet to less than -1500 feet and Trenton thickness from 550 to 650 feet. Reservoir pressures have generally been above hydrostatic, and the structure maps indicate a series of tectonic features trending southwest from the Adirondack uplift across the county. Examination of old records and newer logs indicates that the vast majority of wells drilled in the county have encountered natural gas. Recorded open flow potentials in the better wells range from 1 Mcfd to 100 Mcfd.

Because of the shallow section, commercial production is expected to be limited to the southern portion of the county. However, the entire county is prospective with the best zones anticipated to lie along the structures emanating from the Adirondacks. Shallow wells are relatively inexpensive and, with careful drilling procedures and production management, could be expected to supply local farm needs for many years.

SENECA COUNTY

The thickest recorded Trenton section, over 800 feet, is in Seneca County. Wells are few and confined to the northern portion of the county, and the drilling records do not indicate Trenton gas. However, the logs suggest that there are gas filled fractures in two of the wells. The most likely horizons appear to be the Trenton B zone and the base of the Trenton A. Structural trends similar to those in Cayuga County to the east, appear to be present in the northern part of Seneca County and could aid reservoir formation. At present, the Trenton would not seem to be a major reservoir in the county; however, operators might be advised to closely examine the Trenton in any Seneca deep test. Some of the early wells appear to have been drilled with heavy muds which would have prevented fracture porosity discoveries.

WAYNE COUNTY

Natural gas was discovered in the Clyde area of Wayne County in 1887 when a well tested over 1 MMcfd on open flow. Later wells in the same area tested from 1 to 5 MMcfd. Unfortunately flow rates declined rapidly, and the field was not considered a commercial success. Other wells in the county have had indicated open flow potential of up to 224 Mcfd.

Trenton elevations in the county range from -1200 feet to over -2400 feet and Trenton thickness is 650 to 750 feet. The county is down dip from the prospective trends that have been successful in Cayuga and Oswego counties. The logs indicate fractures that appear capable of producing gas in both the Trenton A and B zones. The one available temperature log indicates gas at approximately 200 Mcfd from the Trenton B. Wayne County is considered prospective for Trenton production. The best prospects appear to lie along the flanks of northeast southwest trending structures that control the production to the northeast. As in other areas of fracture production pressures should be maintained and production rates closely controlled for optimum field life.

WYOMING COUNTY

Trenton elevations range from -2400 feet to less than -4100 feet at the southern edge. Trenton thickness is from 450 to 550 feet. The Clarendon-Lindon fault zone bisects the county from north to south, and a number of deep tests have been drilled in the vicinity. The operator reports do not indicate Trenton gas; however, several wells were drilled with mud and therefore would not show fracture gas. Many of the well logs do indicate some Trenton fracture porosity which may have gas potential, and one air drilled well in the southern part of the county has a temperature log that shows a good flow of gas from the base of the Trenton.

The Trenton formation in Wyoming County would not be the principal objective considering the information available at present. However, there is potential for natural gas; and where there is geophysical exploration for alternate deep reservoirs, then any resulting wells that penetrate the Trenton should be drilled with air be drilled in a manner that would allow evaluation of the gas potential.

SOUTHERN TIER COUNTIES

The Trenton Formation deepens and thins southward reaching elevations as deep as

-8600 feet. Tests are very sparse and the Trenton of southern New York could be considered as being in a frontier area. There have been gas shows but no major flows. There is not sufficient well control for detailed structural mapping; however, small clusters of wells in Chautauqua and Tompkins counties indicate pronounced northeast-southwest trending structural features that are perpendicular to and predate Appalachian folding. Such features may be numerous and could aid in the formation of Trenton and other deep reservoirs. The Trenton is a major oil producer in Ohio; and with the large gas reservoirs of northern New York, it is conceivable that an oil leg exists in the southern part of the State should suitable reservoirs exist. The southern part of the state is well within the depths and temperatures for maturation and retention of oil and gas.

Exploration in the Southern Tier must be dependent on detailed seismic profiling. Unfortunately, interpretation of the deep section is difficult because of shallow and conflicting Appalachian fold structures.

EASTERN COUNTIES

The Trenton Formation thins, undergoes a facies change, and becomes shaly to the east. The Trenton limestone is not considered prospective east of Otsego County.

NORTHERN COUNTIES

The Trenton Formation, wherever present in northern New York, has some potential for natural gas as in the modest production in the Lowville area of Jefferson County. However, the thin shallow eroded sections do not provide much scope for the development of reservoirs. Local areas where the section is thicker might produce sufficient gas for single farm use.

EXAMPLES OF TRENTON LOGS

Following are 12 examples, one from each of the main prospective counties, of typical logs of the Trenton Formation. The first set of log curves displays the original curves as recorded. All curves are in their original character and track. The amplitudes are unchanged but the depth scales have been standardized for a curve to curve comparison. The second set of porosity curves has been computed from the original data, corrected for shale and displayed along with the calculated shale content. Where the original (available to the project) curves displayed logging operator computed porosities only, these curves have been played out on the porosity display in their original form without additional corrections. Porosity curves include Neutron, Density and Sonic although not all are available for each well.

031-011-05000

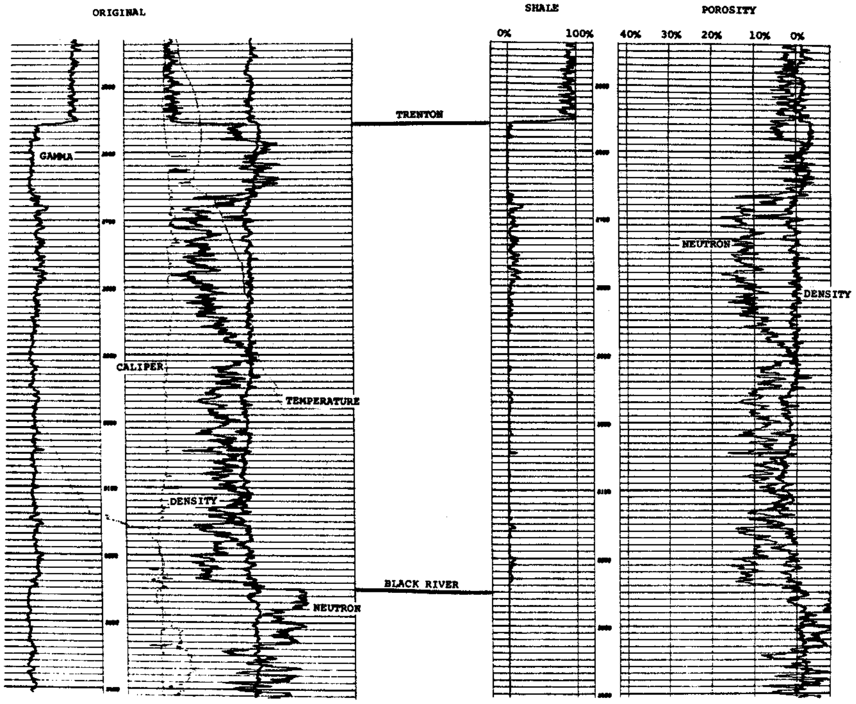

Figure 7-1. Trenton Log, Cayuga County

031-037-13672

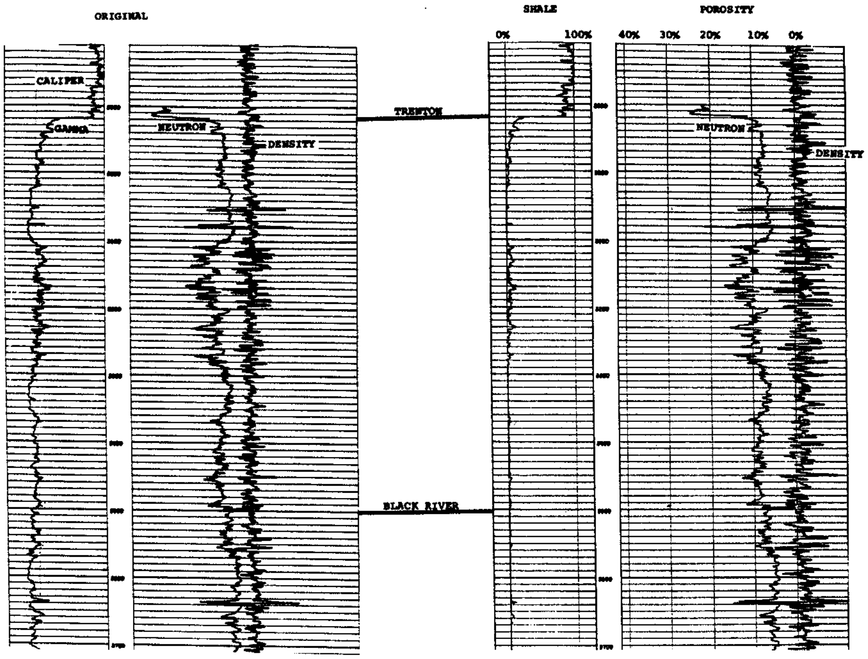

Figure 7-2. Trenton Log, Genesee County

031-051-04630

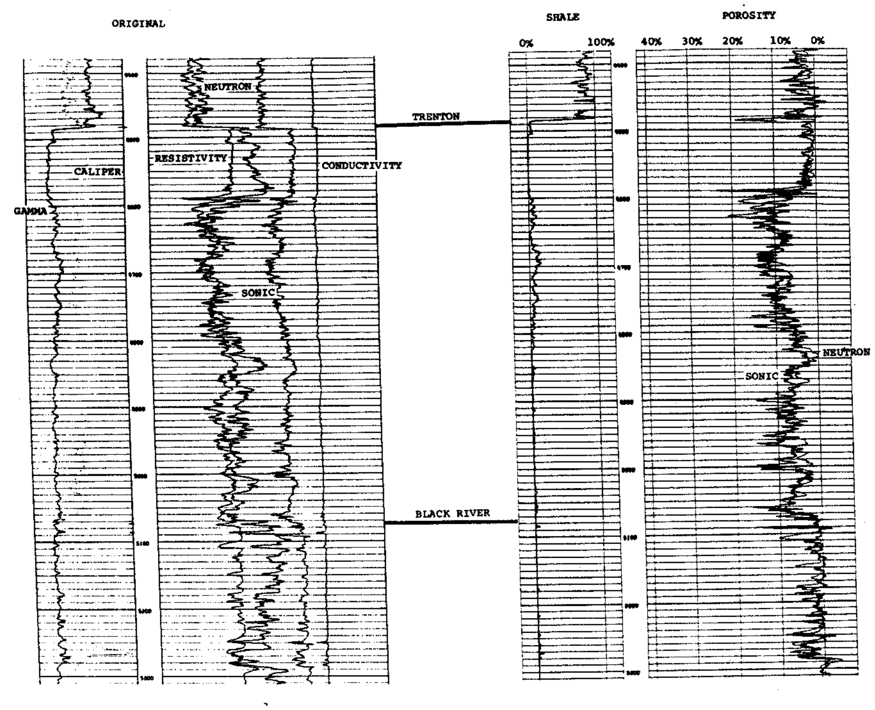

Figure 7-3. Trenton Log, Livingston County

031-055-10921

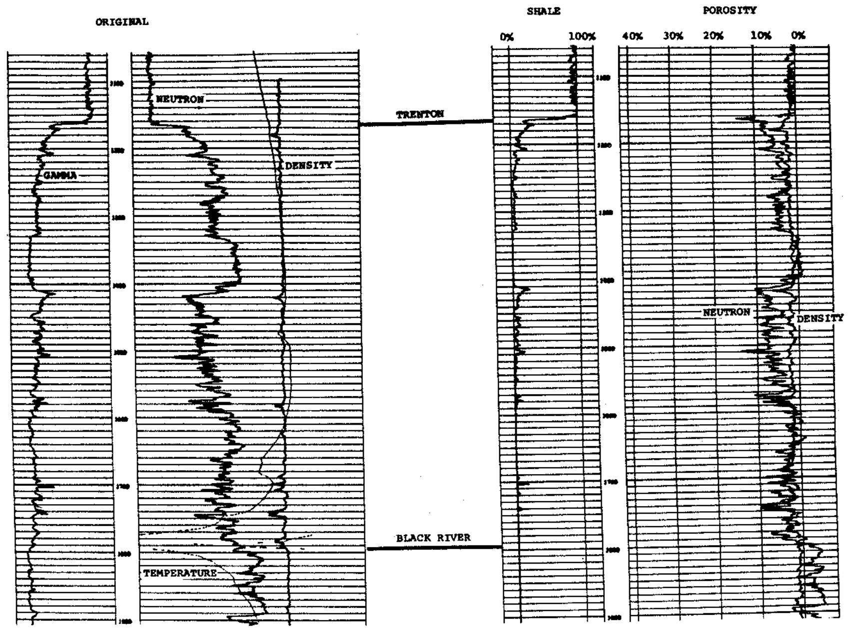

Figure 7-4. Trenton Log, Monroe County

031-063-06667

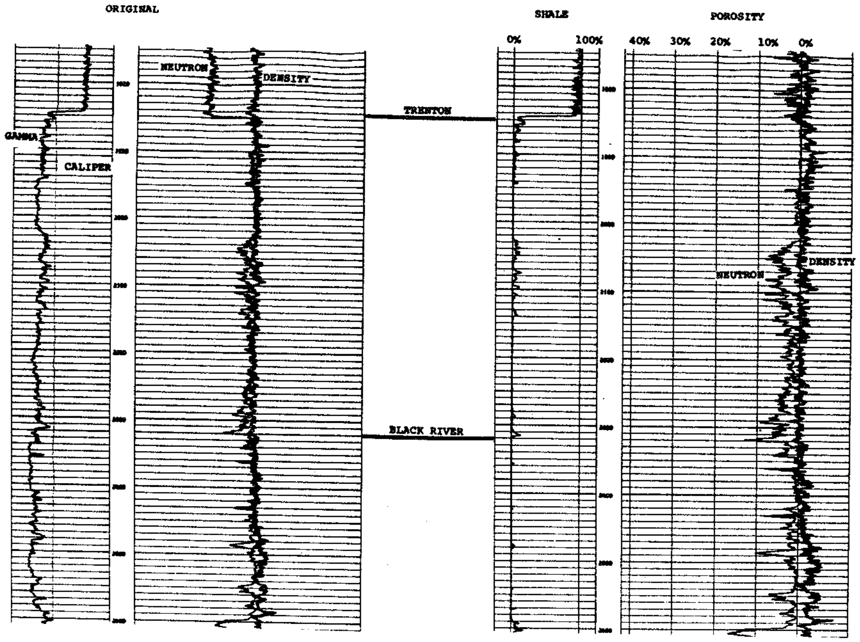

Figure 7-5. Trenton Log, Niagara County

031-067-15584

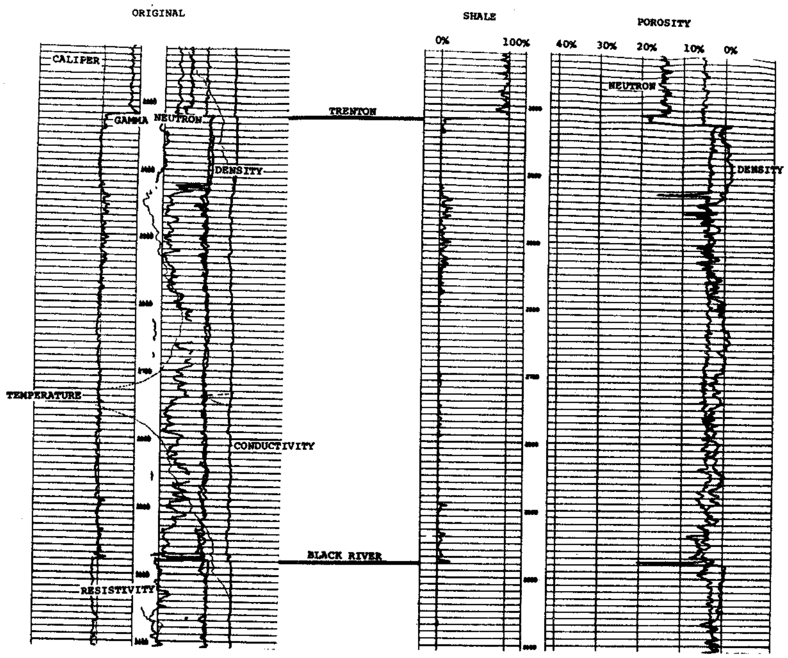

Figure 7-6. Trenton Log, Onondaga County

031-069-06395

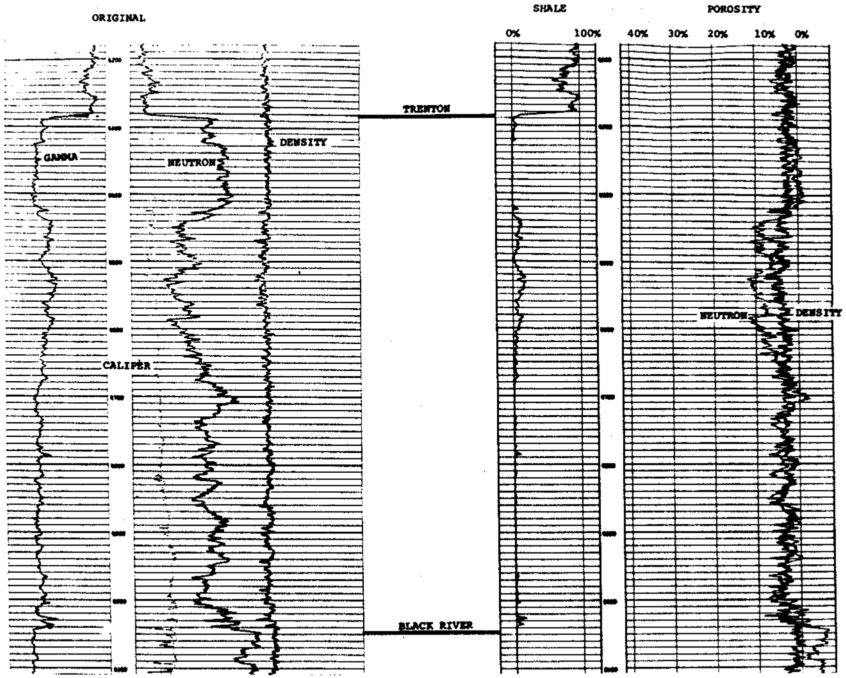

Figure 7-7. Trenton Log, Ontario County

031-073-04912

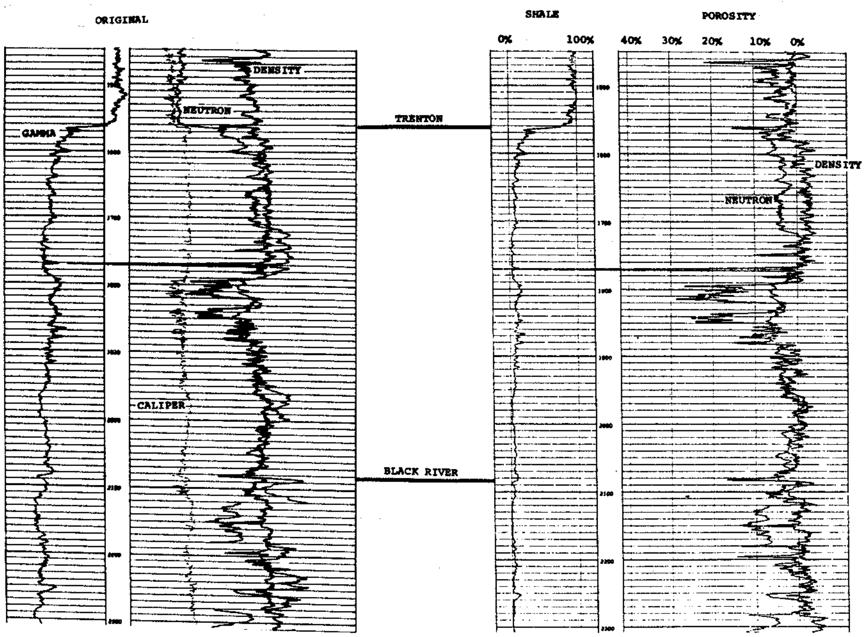

Figure 7-8. Trenton Log, Orleans County

031-075-04520

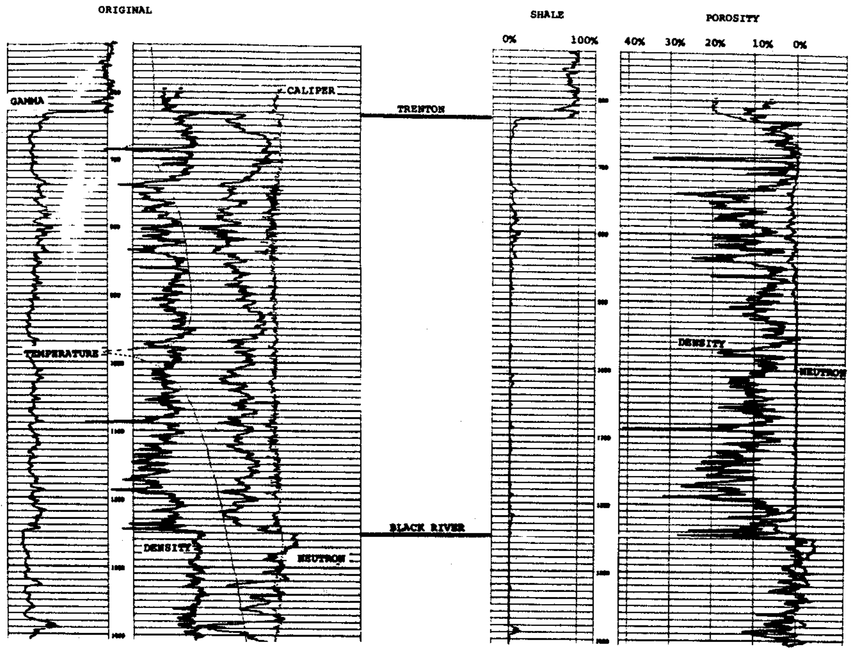

Figure 7-9. Trenton Log, Oswego County

031-099-10893

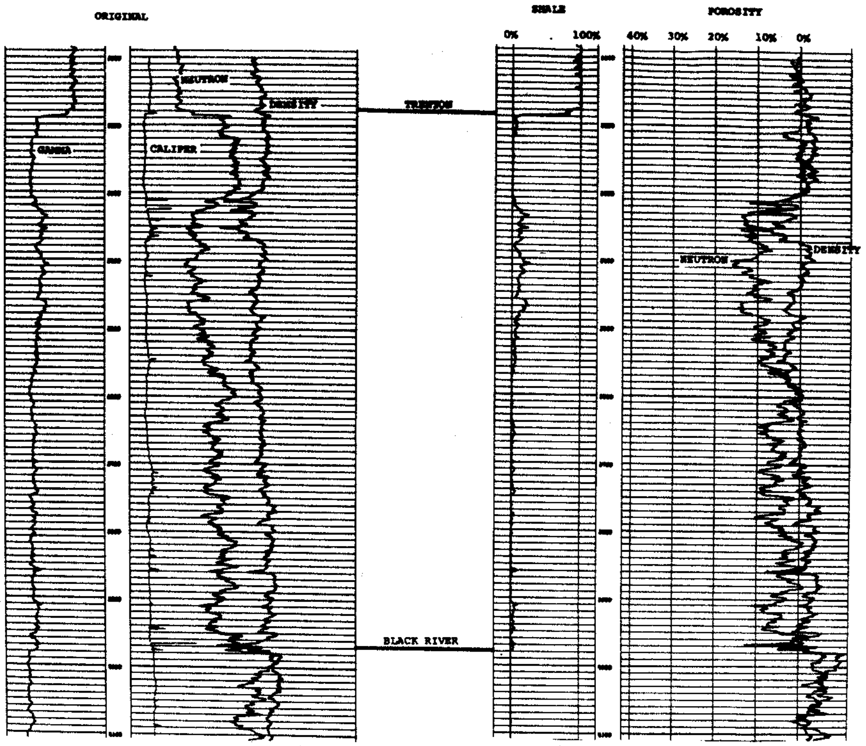

Figure 7-10. Trenton Log, Seneca County

031-117-05041

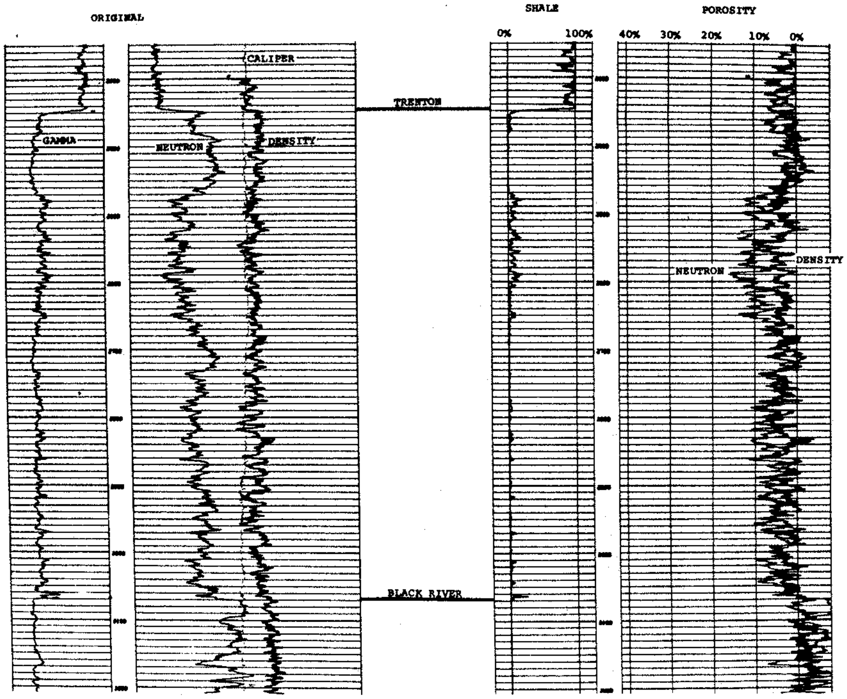

Figure 7-11. Trenton Log, Wayne County

031-121-12178

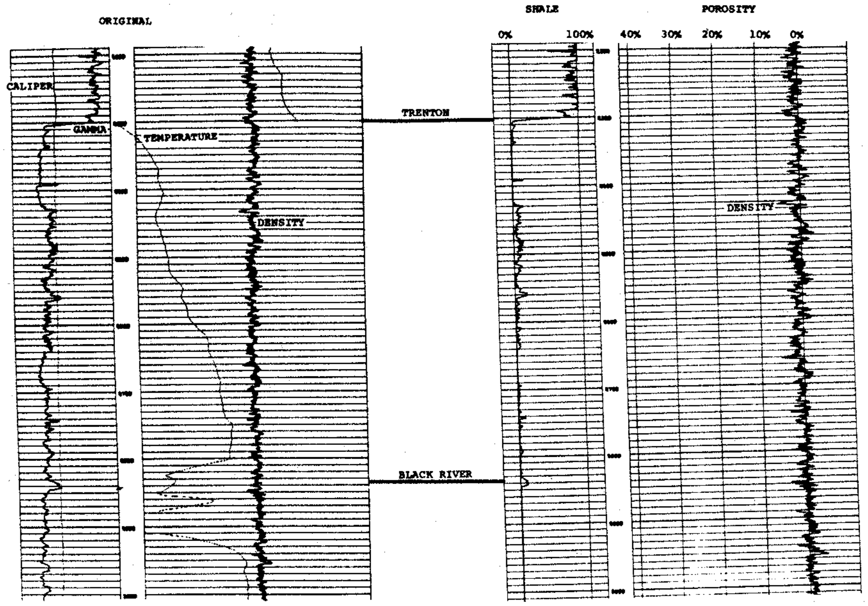

Figure 7-12. Trenton Log, Wyoming County

Section 8

EXPLORATION AND ECONOMICS

EXPLORATION FOR TRENTON NATURAL GAS

Early explorers for natural gas in the Trenton Limestone simply drilled close to the locale where the gas supply was needed. They were usually successful in much of north central New York State as illustrated by the turn of the century field discoveries at Sandy Creek, Pulaski and Baldwinsville. In these areas, the Trenton Limestone is near to the surface and drilling was inexpensive. Moreover, the topographic surface is largely composed of glacial till so that the bedrock features are hidden, severely limiting the mapping of structures from surface exposures. Consequently, for many of the northern areas (especially in the districts where previous discoveries have been frequent) the simplest and most practical exploration method is to drill test wells as close as possible to the place where the gas will be utilized. Drilling costs for shallow Trenton wells are still low, and the drill is the ultimate exploration tool. Also, it is important to have the gas supply close to the user to minimize gathering and transportation pipeline costs.

In those parts of New York State where there are fewer tests and the presence of natural gas is not as certain, the recommended exploration method is to consider the structure contour and isopach maps of the Trenton along with any available geologic and geophysical information in order to locate those areas with the best chance of having the necessary fractures. The greatest degree of tectonic flexing and thus, the most likely location for fracture porosity, occurs both in conjunction with tectonic folds and where minor faulting has occurred. Such zones are most prevalent along the flanks of structures as they are displayed in the structure contour maps and along the margins of aeromagnetic and gravity anomalies that often coincide with the basement-controlled Trenton features. The magnetic and gravity anomalies relate primarily to variations in the mineral content of the Precambrian basement and are not necessarily coincident with the subsurface topographic relief, however, the gradient changes usually represent zones of probable weakness along which tectonic adjustments are likely to occur. Magnetic and gravity maps are available from the New York State Museum and Science Service, Geological Survey and the United States Geological Survey. Examples of gas fields coincident with structural features are the Camden field in Oswego County and the Blue Tail Rooster and Baldwinsville fields of Cayuga and Onondaga counties where the production is aligned along structures that are recognizable in both the structure maps and published geophysical maps.

For more southerly areas, where the Trenton is found at greater depths and where the few tests do not outline the subsurface structure, the most effective exploration method is reflection seismic profiling. Seismic can delineate tectonic structures with great accuracy and can locate gas-filled reservoirs in formations with intergranular porosity. Unfortunately, the cost of seismic is high, $4000 to $5000 per profile mile, and its use tends to be limited to those areas where the reservoirs are likely to be large and very productive. The relatively few Trenton tests in the southern and deeper basin portion of the State where most of the present seismic profiles are located, suggests that the formation would not be a major reservoir in this area. However, there are Trenton gas shows and the Trenton Limestone Formation should not be overlooked as a potential secondary target. Seismic would need to be justified by other potential oil- and gas-bearing reservoirs. The Trenton is a good seismic marker, and the early structural trends that appear in the structure map as northeast-southwest trending folds where data is clustered at the south end of Cayuga Lake and by Lake Erie suggest deep structures suitable for seismic interpretation. Thus, seismic, as keyed to the Trenton reflection, could help to unravel the early structural history and migration patterns of southern New York State.

RECOMMENDED DRILLING PROCEDURES

The most efficient and cost-effective method of drilling Trenton wells is with an air rotary rig. Air drilling, particularly with a hammer bit is fast, does little formation damage and provides the best chance of locating all gas-producing zones. Certainly, the Trenton section of the well should be drilled with air. Drilling fluids, particularly mud, can prevent the entry of gas into the borehole and may seal potential gas-producing fractures. Fracture porosity is rarely evident on the standard logs, and producing zones must be located through detection of escaping gas. The gas-producing fractures can occur anywhere in the Trenton section.

Because of the variability of the gas production within the Trenton section and the difficulty of detecting the best long-term production zones, it is recommended that the test hole be drilled to the top of the Trenton, then casing set and cemented. The entire Trenton section should be drilled with air, then tested and completed "open hole" without additional treatment.

The history of stimulation efforts, including fracting and acidizing, suggests that there will be little increase in production and in some cases there has been a drastic drop in production. At least in the initial production stages, where reservoir pressures are relatively high, artificial stimulation is not recommended. It is recommended that production rates be regulated so that reservoir pressures are maintained as close as practical to original pressures.

Higher than normal gas pressures are often encountered in Trenton reservoirs, and it is therefore recommended that the driller have a good blowout preventer and that a gate valve be installed below the blowout preventer. Logs run should include a Temperature or a Sibilation Log along with the standard Gamma Ray, Neutron, Density, and Caliper Logs.

If it is possible to control the well, it should not be blown down during production testing. Large pressure losses can adversely affect future production. All drilling and testing procedures must be conducted in compliance with the New York State Department of Environmental Conservation rules and regulations.

DRILLING COSTS

The cost of drilling a well to test and produce Trenton gas can vary according to prices negotiated with the drilling contractor and type of casing and equipment used. Approximate costs for two Trenton wells, one drilled to 1600 feet and the other to 3300 feet are as follows.

	1600'TD well		3300'TD well	
Survey and permits		$1,500		$1,500
Site preparation and dig slush pit		$2,500		$2,500
Drill and set 100' 13 3/8" conductor pipe		$3,500		$3,500
Drill and set 400' 9 5/8" surface casing		$8,400		$8,400
Drill and set 7" casing to top of Trenton	1000'	$17,000	2700'	$54,200
Drill 600' Trenton open hole		$7,200		$7,200

Cement services	$2,500	$3,000
Logging	$2,500	$3,000
Well head equipment	$3,000	$3,000
Total	$48,100	$86,300
Gathering System 1320' plastic conductor pipe	$7,900	$7,900
Total system costs	$56,000	$94,200

Dry holes would not need the well head equipment but would entail approximately $1500 in plugging costs.

Also, drill stand-by time and problems encountered during drilling can increase drilling costs.

Early stimulation is not recommended.

Economic Evaluation

An economic scenario for wells in Oswego and Cayuga counties considers similar wells having initial production rates in the practical range from 20 to 100 Mcfd. The present price for New York State gas delivered to pipelines is approximately $3.20 Mcf. However, the cost of gas delivered to a customer is approximately $6.00 Mcf and is escalating at approximately 6 percent per annum. These prices are considered to be the low and high for the scenario. Present worth is computed at an average discount rate of 16 percent. Royalty is 12.5 percent gross production and maintenance is estimated at $2,000/year. The scenario is for a 10-year life with an estimated 10 percent decline rate in production. Figure 8-1 shows the decline curves for four initial productions of (A) 100, (B) 50, and (C) 20 Mcfd. Economic factors are displayed in Table 8-1, 8-2, 8-3.

Oswego Well	Cayuga Well
1,600' TD	3,300' TD
Cost $56,000	Cost $94,200
Reserves: 132 MMcf/40 acre unit	Reserves: 323 MMcf/40 acre unit

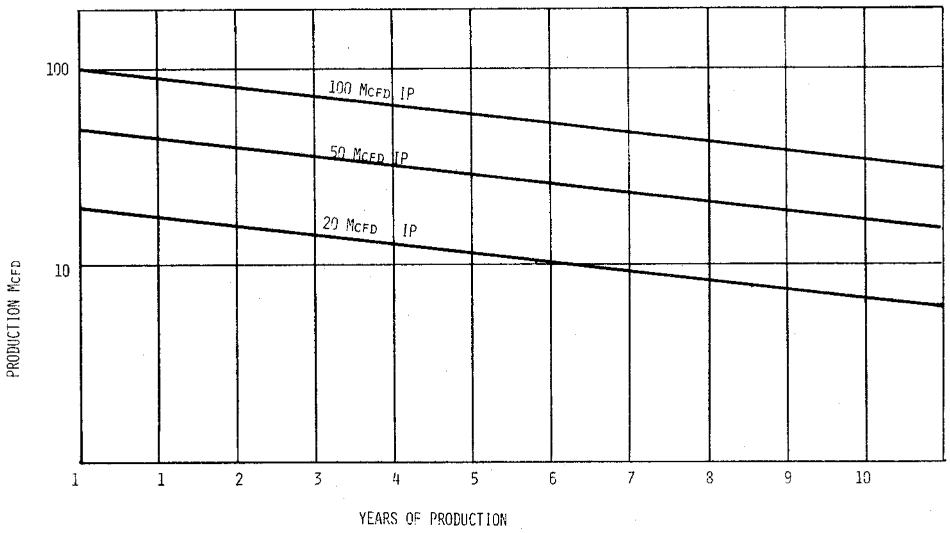

Figure 8-1. Trenton Decline Curves

10-year production Payout at $3,20/Mcf		Payout at $3,20/Mcf	
A	0.5 year	A	0.84 year
B	1.01 year	B	1.77 year
C	2.77 year	C	5.32 year

Return on investment over 10 years at $3.20/Mcf without royalty, maintenance included:

A	12.50:1	A	7.45:1
B	6.04:1	B	3.59:1
C	2.34:1	C	1.39:1

Profitability for immediate sale based on gas at $3.20 Mcf and a discount rate of 15%. Royalty not included. Maintenance costs included over 10-year life.

A	7.40:1	A	4.40:1
B	3.70:1	B	2.20:1
C	1.19:1	C	0.71:1

Net income compared to investment for a 10-year life with gas at $3.20 Mcf and allowing for maintenance and one-eighth royalties.

A	10.92:1	A	6.49:1
B	5.46:1	B	3.24:1
C	1.88:1	C	1.12:1

Table 8-1

ECONOMIC FACTORS FOR INITIAL PRODUCTION OF 100 Mcfd.

Initial Production 100 Mcfd

Year	Production Mcf	Cumulative Mcf	Value @ $3.20 Mcf	Cumulative	Present Worth	Cumulative	Royalty	Maintenance Expenses	Income	Cumulative	Commercial Cost	Cumulative
1	34,643	34,643	$110,857	$110,857	$103,430	$103,430	$13,857	$2,000	$95,000	$95,000	$207,858	$207,858
2	31,178	65,821	$99,771	$210,628	$80,914	$184,344	$12,471	$2,000	$85,300	$180,300	$198,292	$406,150
3	28,060	93,881	$89,794	$300,422	$63,304	$247,649	$11,224	$2,000	$76,570	$256,870	$189,169	$595,319
4	25,254	119,135	$80,815	$381,237	$49,539	$297,187	$10,101	$2,000	$68,714	$325,584	$180,467	$775,786
5	22,725	141,860	$72,722	$453,959	$38,760	$335,947	$9,090	$2,000	$61,632	$387,216	$172,138	$947,924
6	20,456	162,316	$65,461	$519,420	$30,373	$366,320	$8,182	$2,000	$55,279	$442,492	$164,951	$1,112,875
7	18,412	180,728	$58,920	$578,340	$23,744	$390,064	$7,365	$2,000	$49,555	$492,047	$156,706	$1,269,581
8	16,576	197,304	$53,045	$631,385	$18,618	$408,682	$6,630	$2,000	$44,415	$536,462	$149,515	$1,419,096
9	14,896	212,200	$47,668	$679,053	$14,538	$423,220	$5,958	$2,000	$39,710	$576,172	$142,451	$1,561,547
10	13,431	225,631	$42,979	$722,032	$11,389	$434,609	$5,372	$2,000	$35,577	$611,749	$136,056	$1,697,603

Table 8-2

ECONOMIC FACTORS FOR INITIAL PRODUCTION OF 50 Mcfd

Initial Production 50 Mcfd

Year	Production Mcf	Cumulative Mcf	Value @ $3.20 Mcf	Cumulative	Present Worth	Cumulative	Royalty	Maintenance Expenses	Income	Cumulative	Commercial Cost	Cumulative
1	17,321	17,321	$55,427	$55,427	$51,713	$51,713	$6,928	$2,000	$46,501	$46,501	$103,927	$103,927
2	15,589	32,910	$49,884	$105,311	$40,455	$92,169	$6,235	$2,000	$41,649	$88,150	$99,146	$203,073
3	14,630	46,940	$44,908	$150,219	$31,660	$123,829	$5,613	$2,000	$37,295	$125,445	$94,584	$297,657
4	12,627	70,928	$40,406	$190,625	$24,768	$148,598	$5,050	$2,000	$33,356	$158,801	$90,233	$387,890
5	11,362	81,157	$34,086	$224,711	$18,167	$166,766	$4,260	$2,000	$27,826	$186,627	$86,069	$473,959
6	10,228	90,363	$32,729	$257,440	$15,186	$181,952	$4,091	$2,000	$26,639	$213,266	$82,028	$555,987
7	9,206	98,651	$29,459	$286,899	$11,871	$193,824	$3,682	$2,000	$23,777	$237,043	$78,353	$634,340
8	8,288	106,099	$26,521	$313,420	$9,308	$203,133	$3,315	$2,000	$21,206	$258,249	$74,257	$709,097
9	7,448	112,814	$23,833	$337,253	$7,269	$210,402	$2,979	$2,000	$18,854	$277,103	$71,225	$780,322
10	6,715	11,878	$21,488	$358,741	$5,694	$216,096	$2,686	$2,000	$16,802	$293,905	$68,028	$848,350

Table 8-3

ECONOMIC FACTORS FOR INITIAL PRODUCTION OF 20 Mcfd

Initial Production 20 Mcfd

Year	Production Mcf	Cumulative Mcf	Value @ $320 Mcf	Cumulative	Present Worth	Cumulative	Royalty	Maintenance Expenses	Income	Cumulative	Commercial Cost	Cumulative
1	6,928	6,928	$22,170	$22,170	$20,684	$20,684	$2,771	$2,000	$17,399	$17,399	$41,571	$41,571
2	6,235	13,163	$19,953	$42,123	$16,181	$36,865	$2,494	$2,000	$15,459	$32,858	$39,658	$81,229
3	5,612	18,775	$17,963	$60,086	$13,222	$50,087	$2,245	$2,000	$13,718	$46,576	$37,833	$119,062
4	5,050	23,825	$16,162	$76,248	$9,907	$59,994	$2,020	$2,000	$12,142	$58,717	$36,093	$155,155
5	4,545	28,370	$13,634	$89,882	$7,266	$67,260	$1,704	$2,000	$9,930	$68,640	$34,427	$189,582
6	4,091	34,461	$13,091	$102,973	$6,074	$73,334	$1,636	$2,000	$9,455	$78,103	$32,811	$222,393
7	3,682	36,143	$11,783	$114,756	$4,748	$78,082	$1,472	$2,000	$8,311	$86,414	$31,341	$253,734
8	3,315	39,458	$10,608	$125,364	$3,723	$81,805	$1,326	$2,000	$7,282	$93,696	$29,903	$283,637
9	2,979	42,114	$9,533	$134,897	$2,907	$84,712	$1,191	$2,000	$6,342	$100,038	$28,490	$312,127
10	2,686	441,569	$8,595	$151,251	$2,277	$86,989	$1,074	$2,000	$5,521	$105,559	$27,211	$339,338

Savings over commercial purchase for a wholly owned well during a 10-year life.

A	29.95:1	A	17.80:1
B	14.97:1	B	8.90:1
C	5.70:1	C	3.39:1

Trenton gas can be economically viable at today's prices to the producer. Only one of the production scenarios is sub-marginal, and this is for low-production in the deeper well. However, present day producer prices are very low; they will escalate. A realistic scenario is that set out for a potential producer whose alternative is a dependency on commercial distributors of natural gas. All the scenarios are profitable with up to a 30:1 return on the initial investment as savings over the calculated 10-year span.

Section 9

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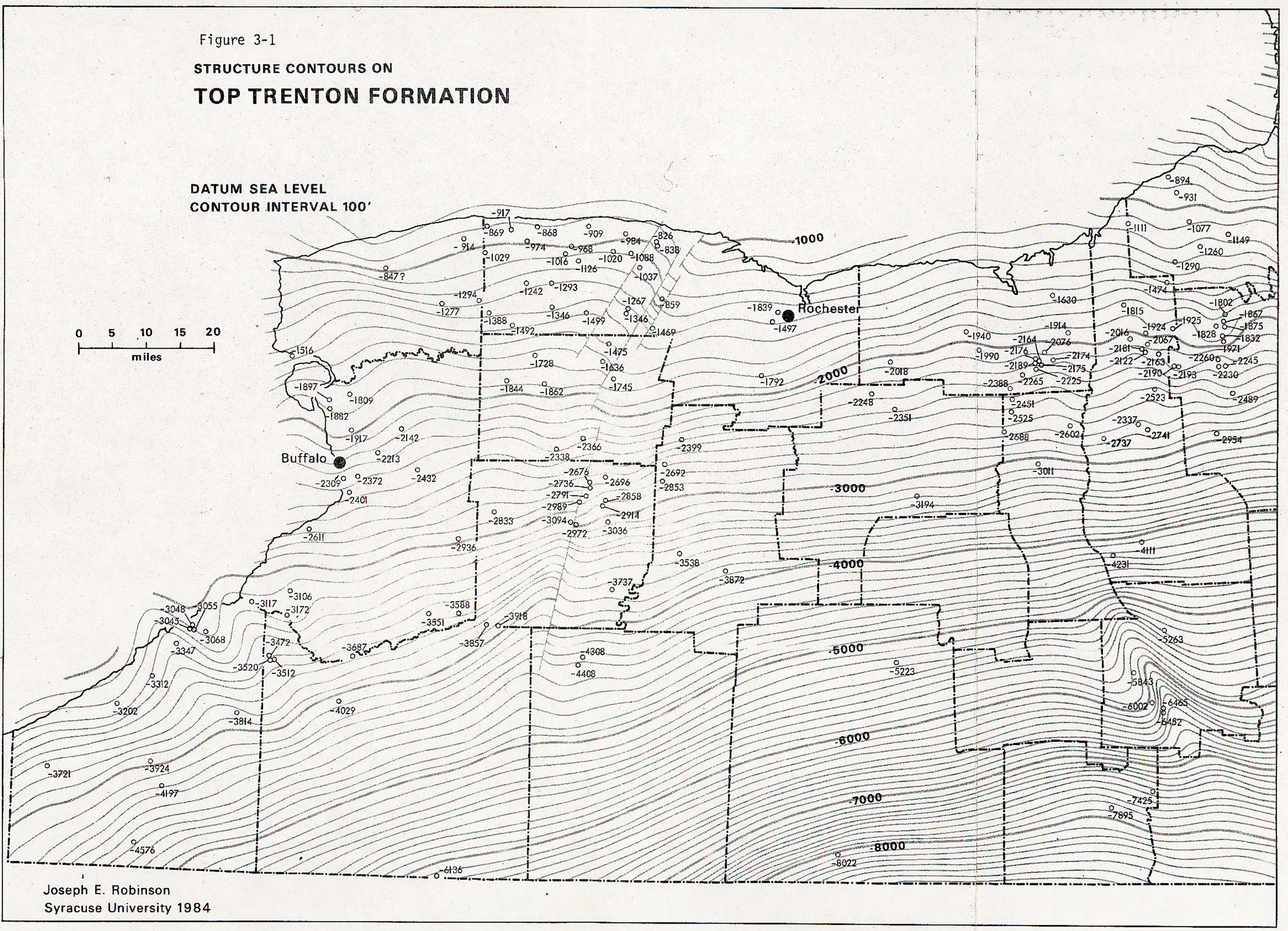
Figure 3-1

STRUCTURE CONTOURS ON

TOP TRENTON FORMATION



Joseph E. Robinson
Syracuse University 1984

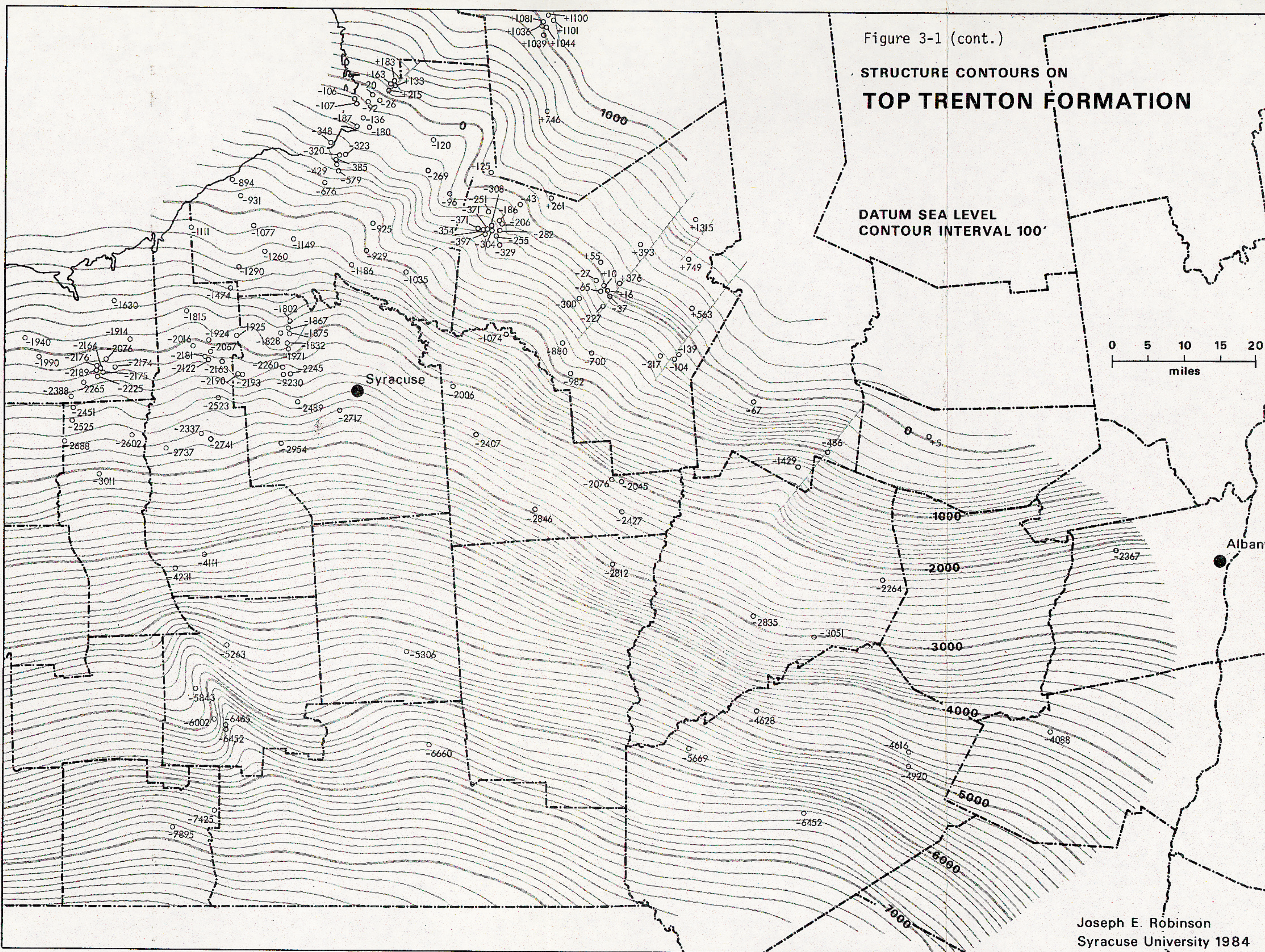


Figure 3-1 (cont.)

STRUCTURE CONTOURS ON

TOP TRENTON FORMATION

DATUM SEA LEVEL
CONTOUR INTERVAL 100′

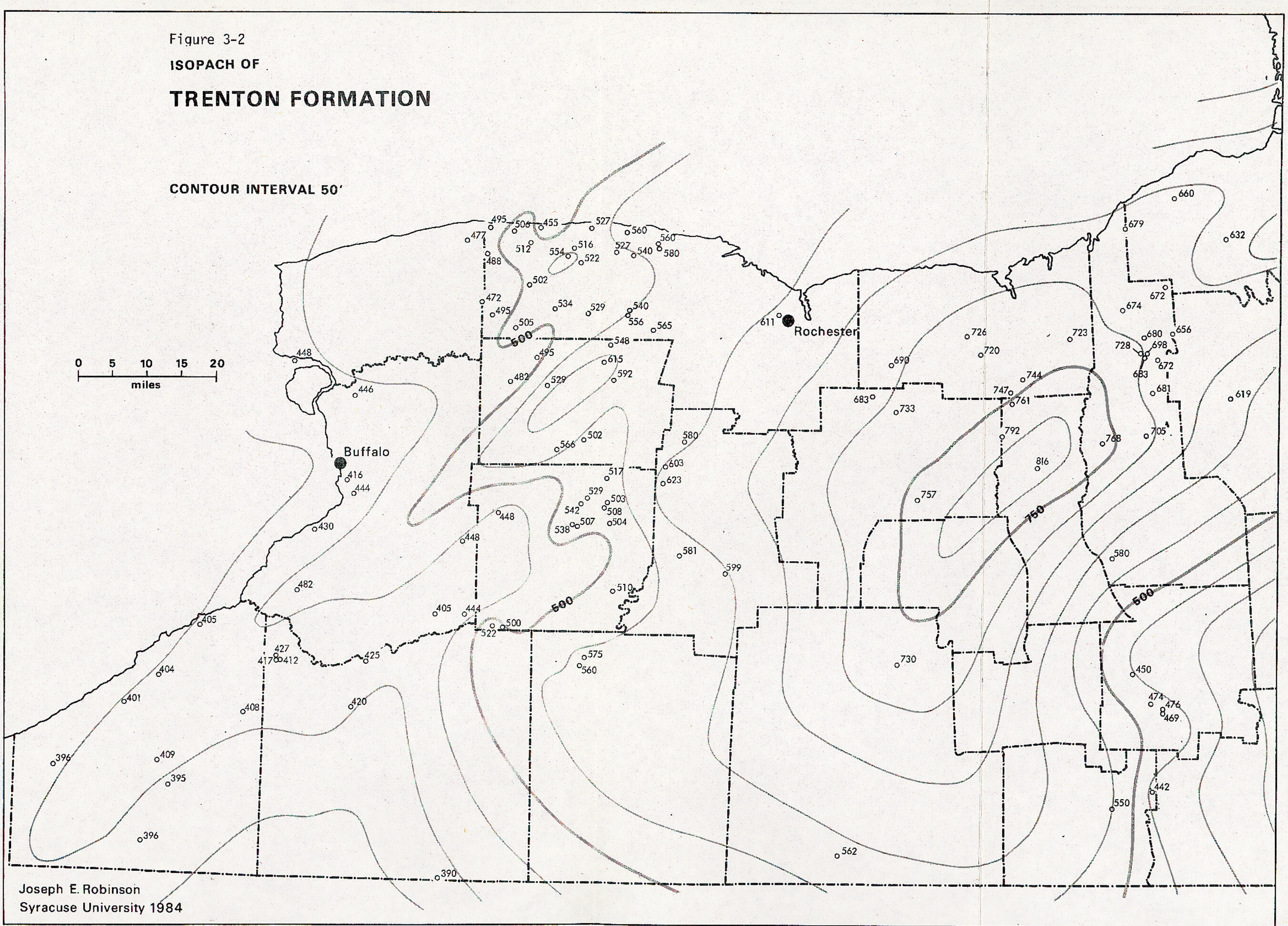
Joseph E. Robinson
Syracuse University 1984

Figure 3-2

ISOPACH OF

TRENTON FORMATION

CONTOUR INTERVAL 50′



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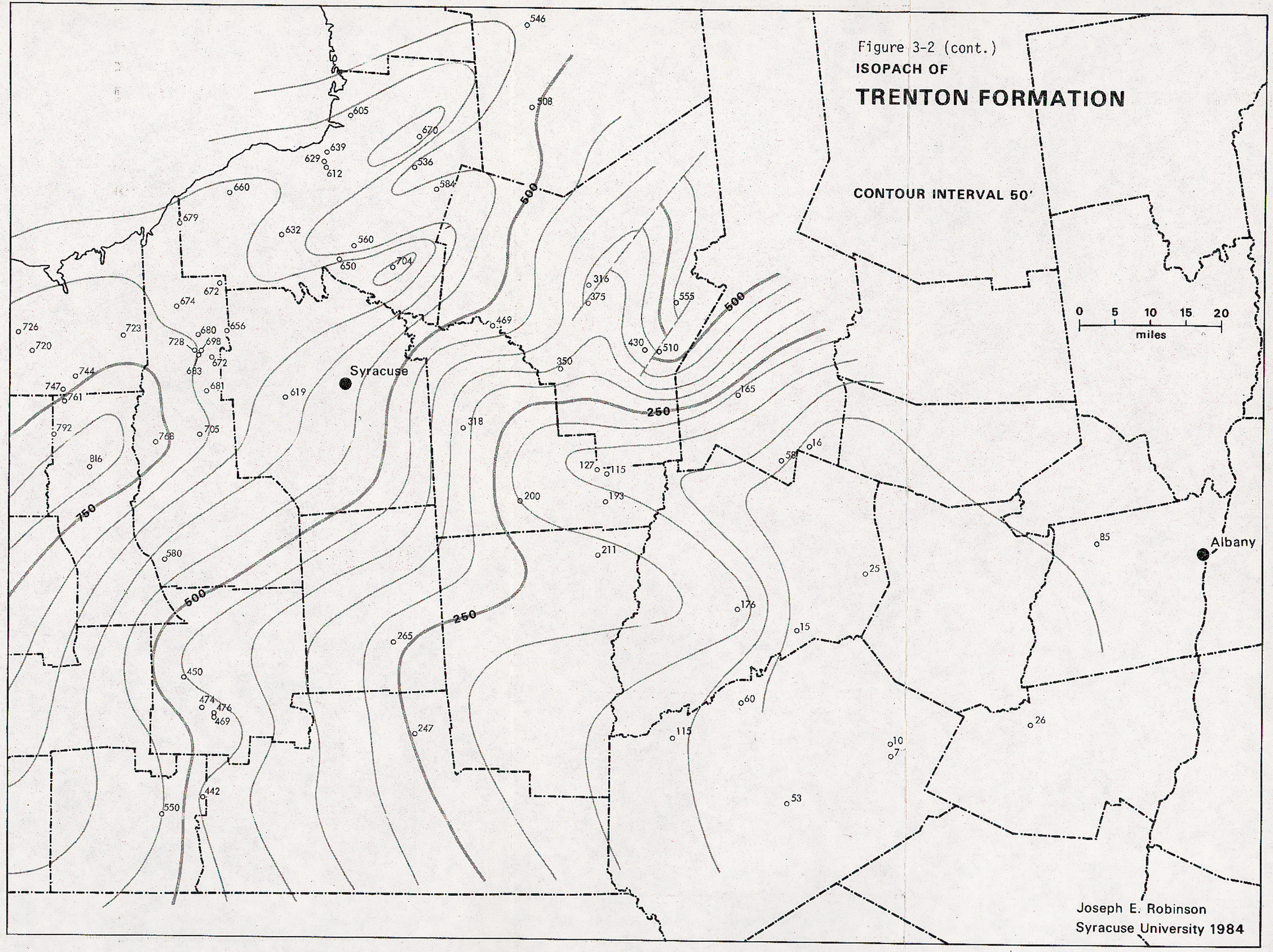
Figure 3-2 (cont.)

ISOPACH OF

TRENTON FORMATION

CONTOUR INTERVAL 50'

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Figure 3-3

TRENTON WELL LOCATIONS

AMERICAN PETROLEUM INSTITUTE WELL CODE

API WELL CODE	State	County	Well no.
	031 –	009 –	1000

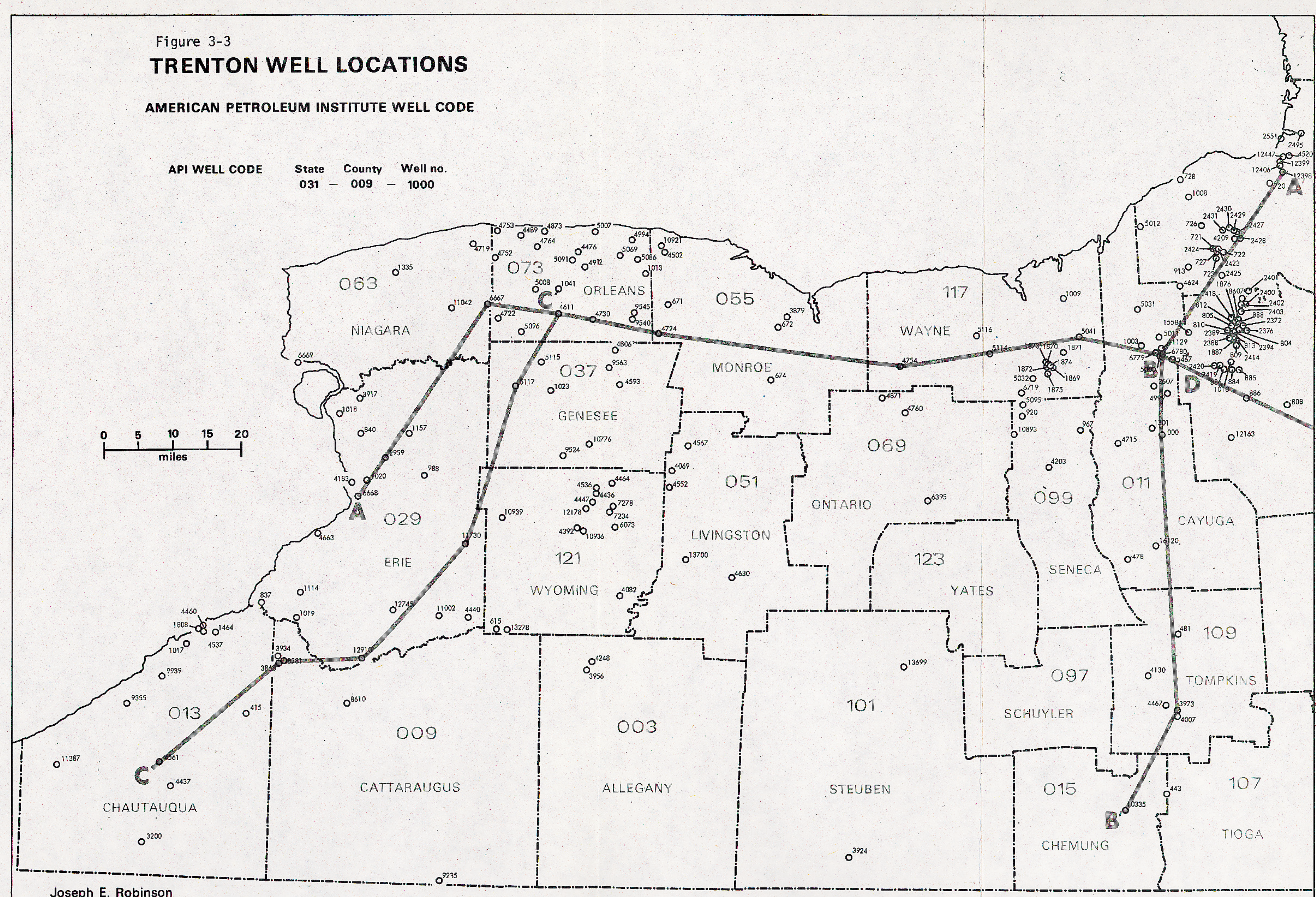

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Figure 3-3 (cont.)

TRENTON WELL LOCATIONS

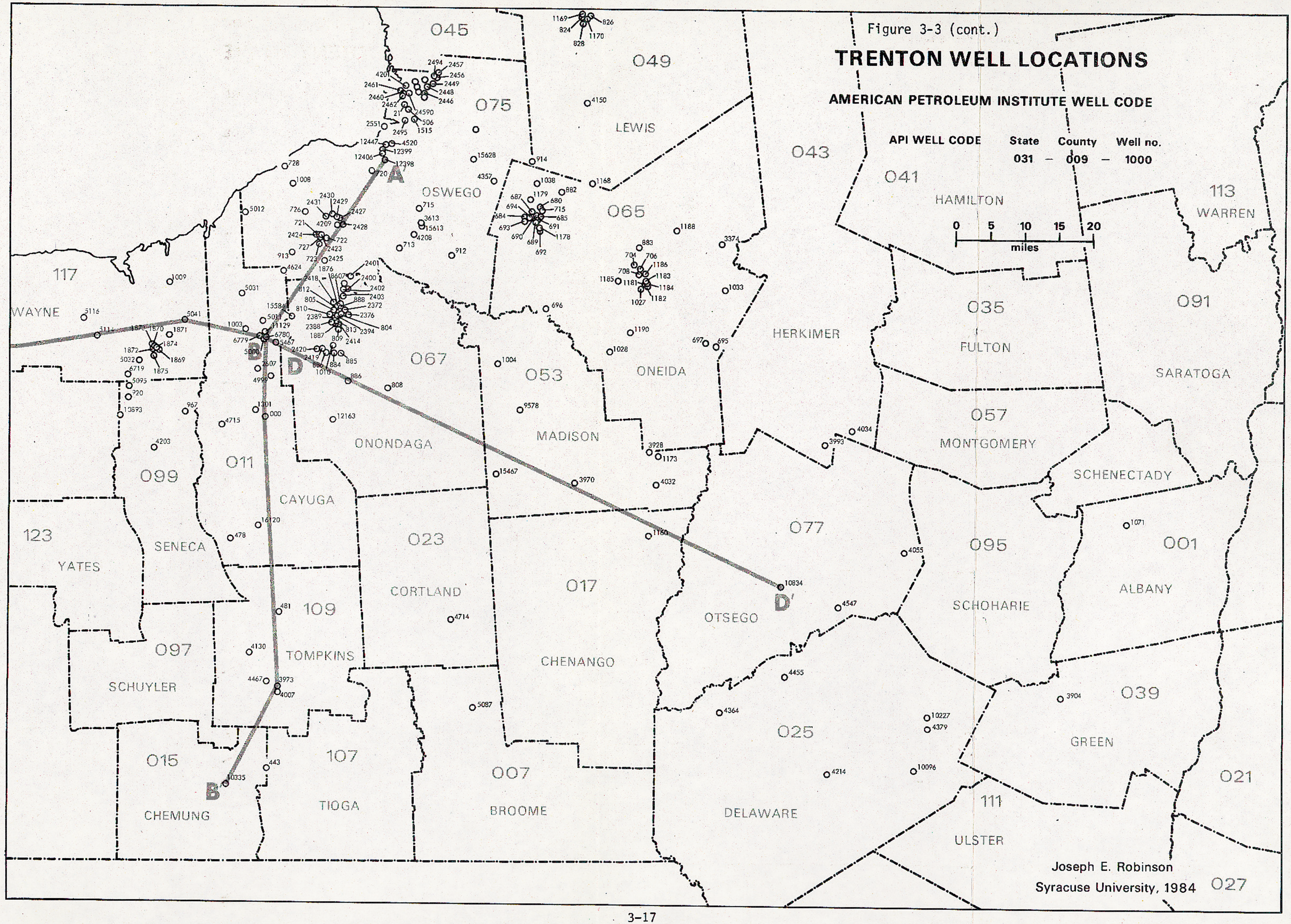

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Figure 3-4

TRENTON CROSS SECTION A-A'

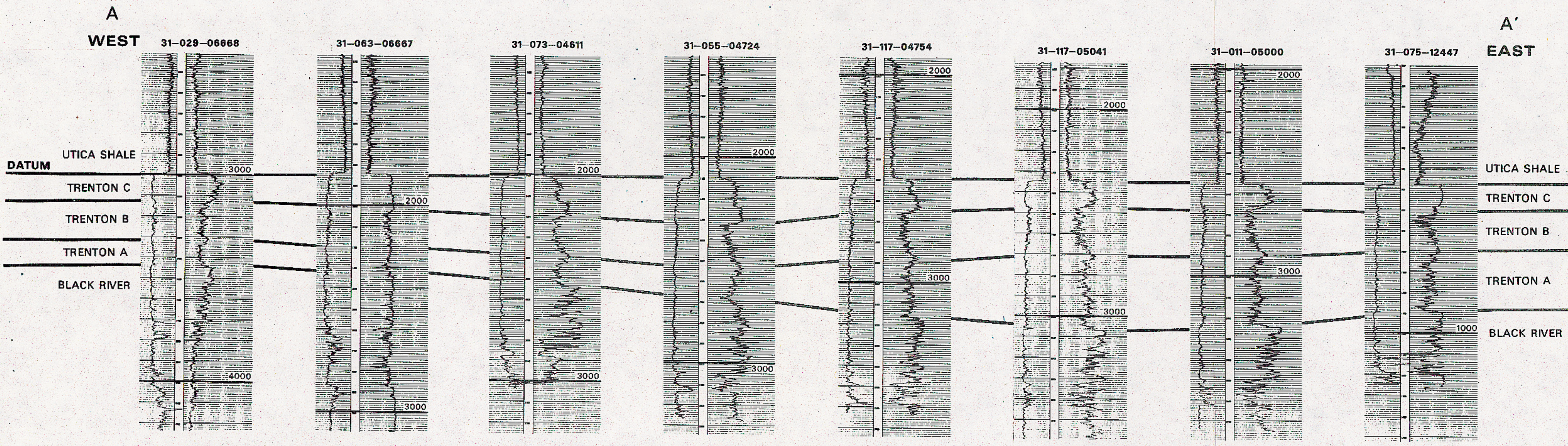

Figure 3-5

TRENTON CROSS SECTION B-B'

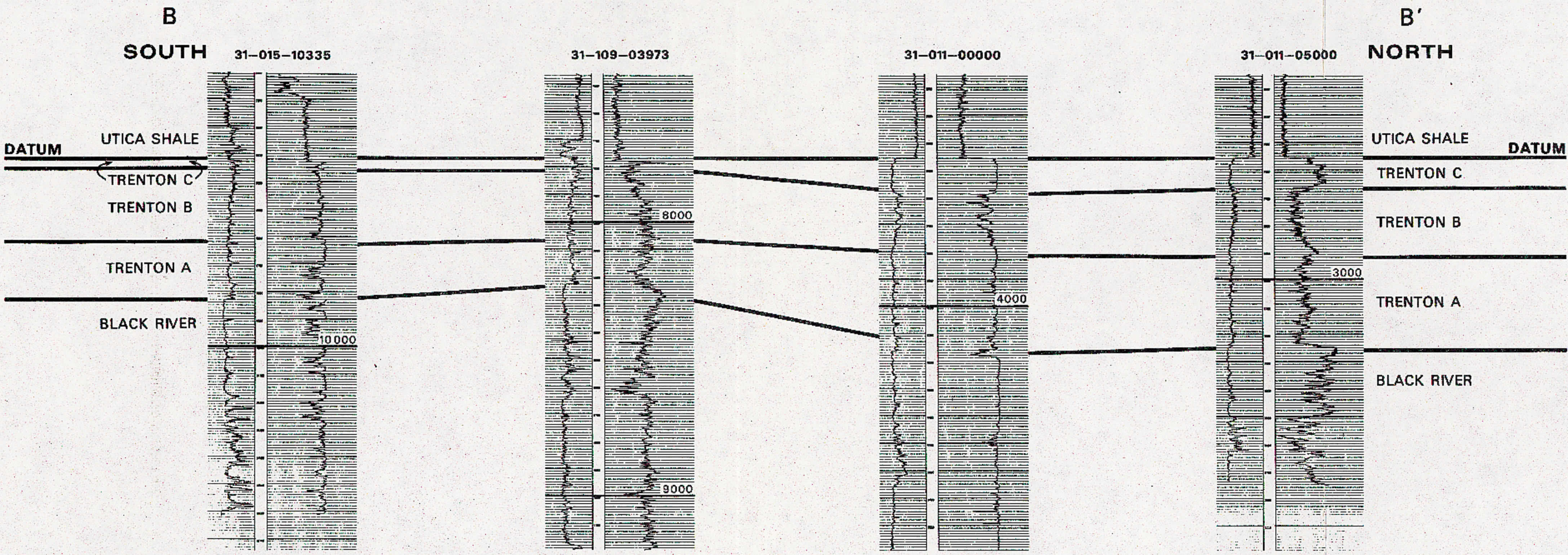

Figure 3-6

TRENTON CROSS SECTION C-C′

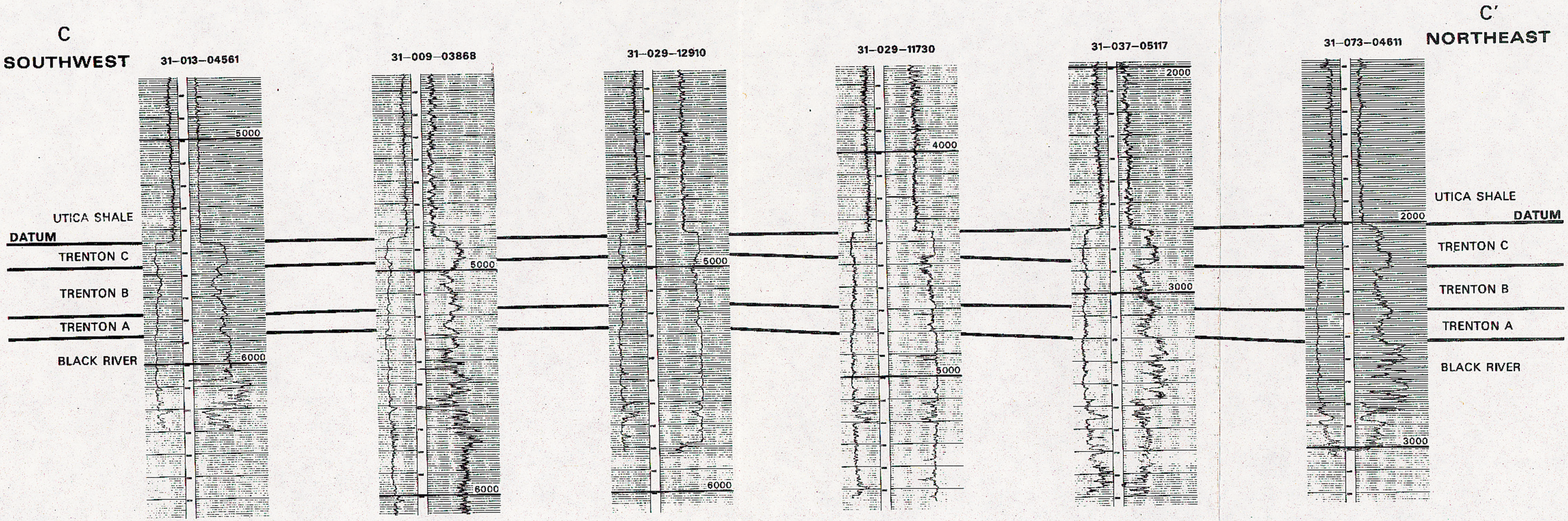

Figure 3-7

TRENTON CROSS SECTION D-D′