Principal Oil and Gas Plays in the Appalachian Basin (Province 131)

Middle Eocene Intrusive Igneous Rocks of the Central Appalachian Valley and Ridge Province—Setting, Chemistry, and Implications for Crustal Structure

U.S. GEOLOGICAL SURVEY BULLETIN 1839–I, J

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I. Principal Oil and Gas Plays in the Appalachian Basin (Province 131)

By WALLACE de WITT, Jr.

J. Middle Eocene Intrusive Igneous Rocks of the Central Appalachian Valley and Ridge Province—Setting, Chemistry, and Implications for Crustal Structure

By C. SCOTT SOUTHWORTH, KAREN J. GRAY, and JOHN F. SUTTER

U.S. GEOLOGICAL SURVEY BULLETIN 1839–I, J

EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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Chapter I

Principal Oil and Gas Plays in the Appalachian Basin (Province 131)

By WALLACE de WITT, Jr.

A discussion of the six remaining principal oil and gas plays in reference to the stratigraphic and structural framework of the Appalachian basin, and a general description of oil and gas productivity of individual plays

U.S. GEOLOGICAL SURVEY BULLETIN 1839

EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

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Principal Oil and Gas Plays in the Appalachian Basin (Province 131)

By Wallace de Witt, Jr.

Abstract

The Appalachian basin is an elongate, asymmetric foreland basin that is about 230,000 square miles in area. It is more than 1,000 miles long and as much as 350 miles wide. More than 550,000 cubic miles of Paleozoic rock ranging in age from Early Cambrian to Early Permian fill the basin. The basin lies south and east of the cratonic platform and west of a series of orogenic highlands that were major sources for much of the basin-filling siliciclastic sediment. Large tectonic fan-delta complexes, which contain abundant coarse-grained siliciclastic reservoir rocks of shallow neritic to fluvial depositional environments, are concentrated mainly on the eastern side of the basin. Carbonate rocks are more abundant in the western part of the Appalachian basin. Finer grained turbiditic siltstone and sandstone are associated as prodelta reservoirs for gas and oil. Karstic carbonate reservoir rocks are associated with unconformities in the major carbonate strata. Reefs are of lesser importance as reservoirs. Extensive marine shale source rocks rich in organic detritus blanketed large segments of the basin during parts of the Ordovician and Devonian Periods. Coals and canneloid shales in the Mississippian and Pennsylvanian terrestrial rocks may have been source beds for oil and gas reservoired in late Paleozoic rocks. Thermal maturation increased in intensity eastward across the basin with increasing depth of burial of specific strata. Oil and associated gas occur mainly in the western part of the basin. Nonassociated dry gas occurs in the central and eastern parts of the basin, where maturation temperatures are too high for the existence of oil. Thick sequences of shale, mudrock, or massive carbonate rock appear to be the better reservoir-sealing strata in the basin.

As defined for the national assessment of undiscovered recoverable oil and gas resources, a play is a group of rocks and its contained hydrocarbons having the same general stratigraphy, structure and tectonic history, source rocks, degree of thermal maturation, and types of reservoir rocks, traps, and seals. Because of the great areal extent and thick stratigraphic sequence of the Appalachian basin, plays tend to be less well delineated in this basin than plays in some smaller basins with thinner stratigraphic sequences.

In descending stratigraphic order, the major oil and gas plays in the Appalachian basin are the Upper Devonian sandstone play, the Lower Devonian Oriskany play, the Lower Silurian sandstone play, the Ordovician carbonate shelf play, the Upper Cambrian and Lower Ordovician Knox carbonate shelf play, and the Rome trough play.

INTRODUCTION

During much of the Paleozoic Era, the Appalachian basin was an elongate active foreland basin west of a series of orogenic source areas that were generated by continental collision between the North American continental plate and several other continental plates or associated island arcs. During the Cambrian and Early Ordovician, the eastern margin of the North American plate was passive, and Early and Middle Cambrian extensional tectonics associated with the opening of an ancestral Atlantic Ocean were dominant. Sediments from cratonic sources accumulated in nearshore shallow-water environments in rift and postrift sequences. In the Middle Ordovician and continuing to the close of the Paleozoic Era, the continental margin was active, and most of the clastic detritus filling the foreland basin was derived from eastern orogenic source areas.

Basin Size

The Appalachian basin of the petroleum industry, Province 131 (Dolton and others, 1981; U.S. Geological Survey and Minerals Management Service, 1988), and as used in this report (fig. 1) includes all or parts of 10 States

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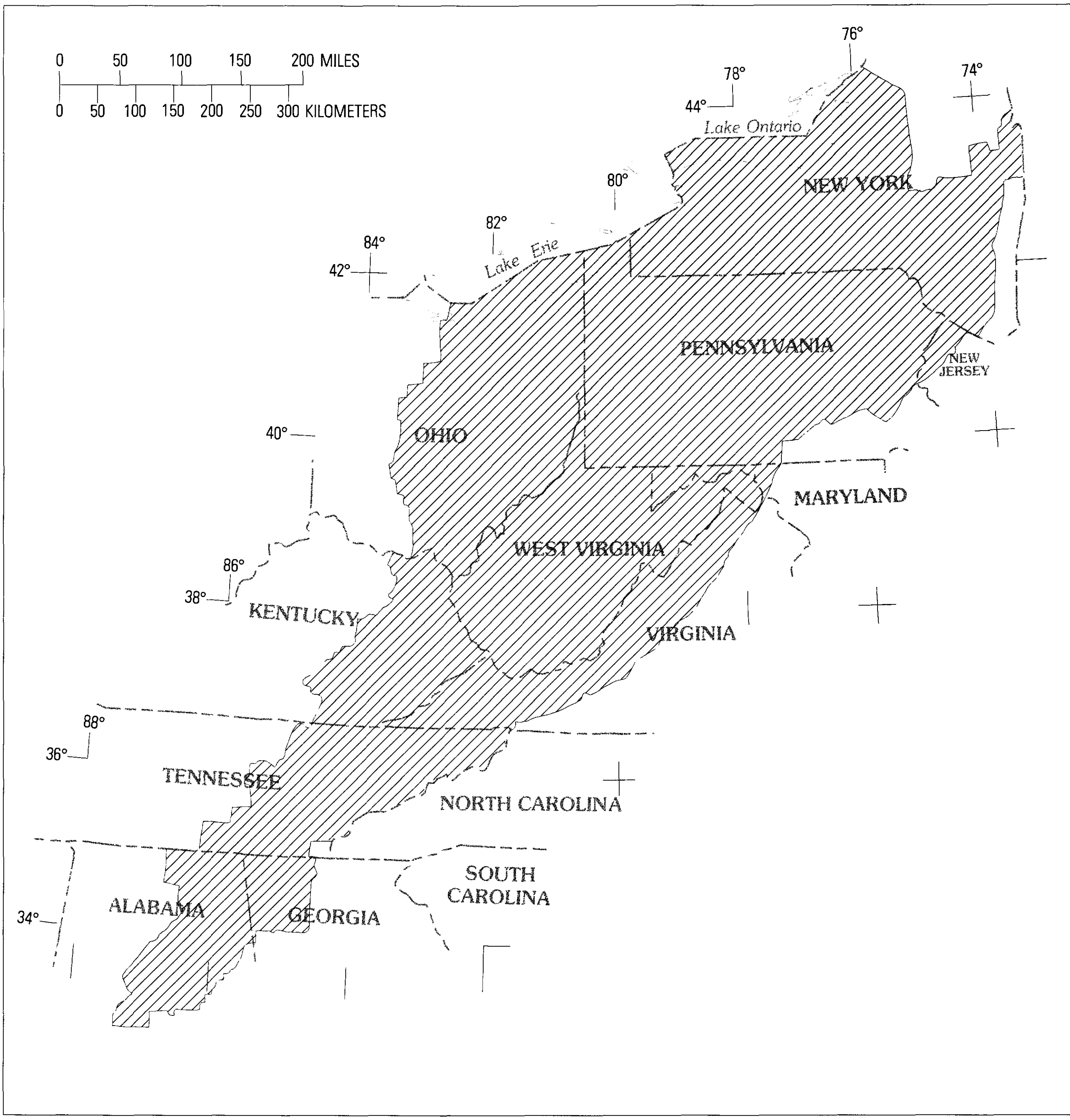

Figure 1. The surface extent of the Appalachian basin.

and the United States' segments of Lakes Erie and Ontario. The basin includes about 230,000 mi^2 of the Eastern United States from the Canadian border south to central Alabama. In its present thrust-faulted configuration, the asymmetric Appalachian basin is 75 to 350 mi wide and more than 1,000 mi long. Its most extensive subdivision, the Appalachian Plateaus segment, covers about 135,000 mi^2 (fig. 2) from Lakes Erie and Ontario south to central Alabama, where the Plateaus segment melds with the Black Warrior basin to the west and southwest. The Appalachian Plateaus segment of the basin includes much of the Appalachian Mountains as well as small parts of the Great Lakes plains or the Eastern Interior lowlands. It lies along the eastern flank of the Cincinnati arch and is bordered on the east by the Allegheny Front, a conspicuous east-facing escarpment that extends from New York to Alabama. The Valley and

Ridge segment of the basin abuts the Appalachian Plateaus segment on the east. It covers an area of about 45,000 mi^2 from eastern New York to central Alabama, where Mesozoic and Tertiary coastal plain rocks cover the south-plunging Paleozoic rocks of the Valley and Ridge. Overthrusted metamorphic and igneous rocks of the Blue Ridge and Piedmont border the Valley and Ridge on the east.

The Appalachian basin is filled by more than 550,000 mi^3 of Paleozoic sedimentary rock ranging in age from latest Precambrian to Early Permian (fig. 3); source beds and reservoir rocks are widespread (fig. 4, table 1). Gas and oil have been found and exploited in some parts of the basin in rocks from all periods of the Paleozoic except the Permian.

Structure

The Appalachian basin is asymmetric in cross section (fig. 5). Cambrian rocks on the west flank of the basin dip gently eastward from about 2,000 to 5,000 ft below sea level along the flank of the Cincinnati arch to more than 50,000 ft below sea level in the eastern buried segment beneath the Blue Ridge (fig. 6). In contrast to the generally gently dipping rocks exposed on the Appalachian Plateaus, Paleozoic strata of the Valley and Ridge segment of the basin have been greatly thrust faulted, folded, and telescoped by orogenic events that occurred mainly during the Alleghany orogeny, at the close of the Paleozoic Era. During this orogeny, metamorphic rocks of the Blue Ridge and Piedmont were thrust more than 150 mi westward over a wedge of Paleozoic Valley and Ridge sedimentary rocks as much as 20,000 ft thick (Harris and others, 1981). As a result of thrusting, the easternmost segment of the Appalachian basin is hidden beneath the Blue Ridge and contiguous Piedmont province. The extent of the eastern buried or hidden segment of the basin is known only from a few deep reflection seismic profiles and a scattering of fensters in the Blue Ridge of eastern Tennessee and adjacent North Carolina. It is not well defined. Harris and others (1981) suggested that the eastern segment may be as large in area as the Valley and Ridge segment. If so, the Appalachian basin, including its eastern buried segment, would underlie more than 230,000 mi^2 of the Eastern United States.

Thrust faulting and associated folds produced by duplication of parts of the stratigraphic sequence are not restricted to the Valley and Ridge and the eastern buried segments of the Appalachian basin. Thrusts extend westward in a major thrust-fault system under the eastern and central parts of the Appalachian Plateaus. Décollements follow several zones of shale or evaporitic rocks in the Cambrian to Devonian sequence. Anticlines commonly formed where thrust faults ramped steeply across sequences of resistant, more brittle beds between décollement levels or where thrusts splayed into thick sequences of middle to upper Paleozoic clastic strata. The area of the Appalachian basin underlain by thrust faults is termed the Eastern Overthrust belt by the petroleum industry as an analog of its western counterpart in the western cordillera. The western boundary of the Eastern Overthrust belt is the western limit of Alleghanian thrusting. Because bordering thrust faults do not crop out, the western boundary of the Eastern Overthrust belt is totally in the subsurface. At places such as the Burning Springs anticline of northern West Virginia or along the Bass Islands trend of Chautauqua County in western New York, the western boundary of the overthrust belt is sharply defined. Elsewhere, the terminal faults are not easily located, and the west edge of the belt is not as clearly delineated.

The Eastern Overthrust belt is an important element in the Appalachian basin because of the belt's structural traps and associated zones of fracture porosity. Many oil and gas fields in the central and eastern parts of the Appalachian Plateaus occur because zones of fracture porosity form the reservoirs. Gas fields in the Oriskany Sandstone from central New York to eastern West Virginia are good examples of anticlinal fault traps in which fractures are the dominant type of porosity in the sandstone. Secondary porosity developed extensively within the Eastern Overthrust belt because fracture porosity is dominant in the eastern part of the Appalachian Plateaus segment and the adjacent Valley and Ridge segment of the basin, particularly in the "cleaner" siliciclastic reservoir rocks. In contrast, original intergranular porosity, commonly modified by interstratal solution of chemically unstable minerals to develop some secondary porosity, is dominant in stratigraphic traps in the relatively undeformed rocks in the western part of the Appalachian Plateaus.

Source Beds

Two sequences of dark-gray, dark-brown, and black marine shale, rich in organic matter, have been documented as major source beds of oil and gas in the Appalachian basin. The younger sequence, which ranges in age from Middle Devonian to Early Mississippian, is extensive beneath the Appalachian Plateaus from New York to Alabama. The Devonian shale source-bed sequence includes many black shales from the Lower Devonian Mandata Formation to the Lower Mississippian Sunbury Shale (Roen and de Witt, 1984). Adjacent to its pinchout in southern Tennessee (Conant and Swanson, 1961, p. 21–42), the Devonian source-bed sequence consists of one or two beds of black shale in about 30 ft of the Upper Devonian Chattanooga Shale. The black shale thickens to the north and northeast where it interfingers and merges into an eastward-thickening sequence of lighter gray, coarser grained siliciclastic rocks in West Virginia, Pennsylvania,

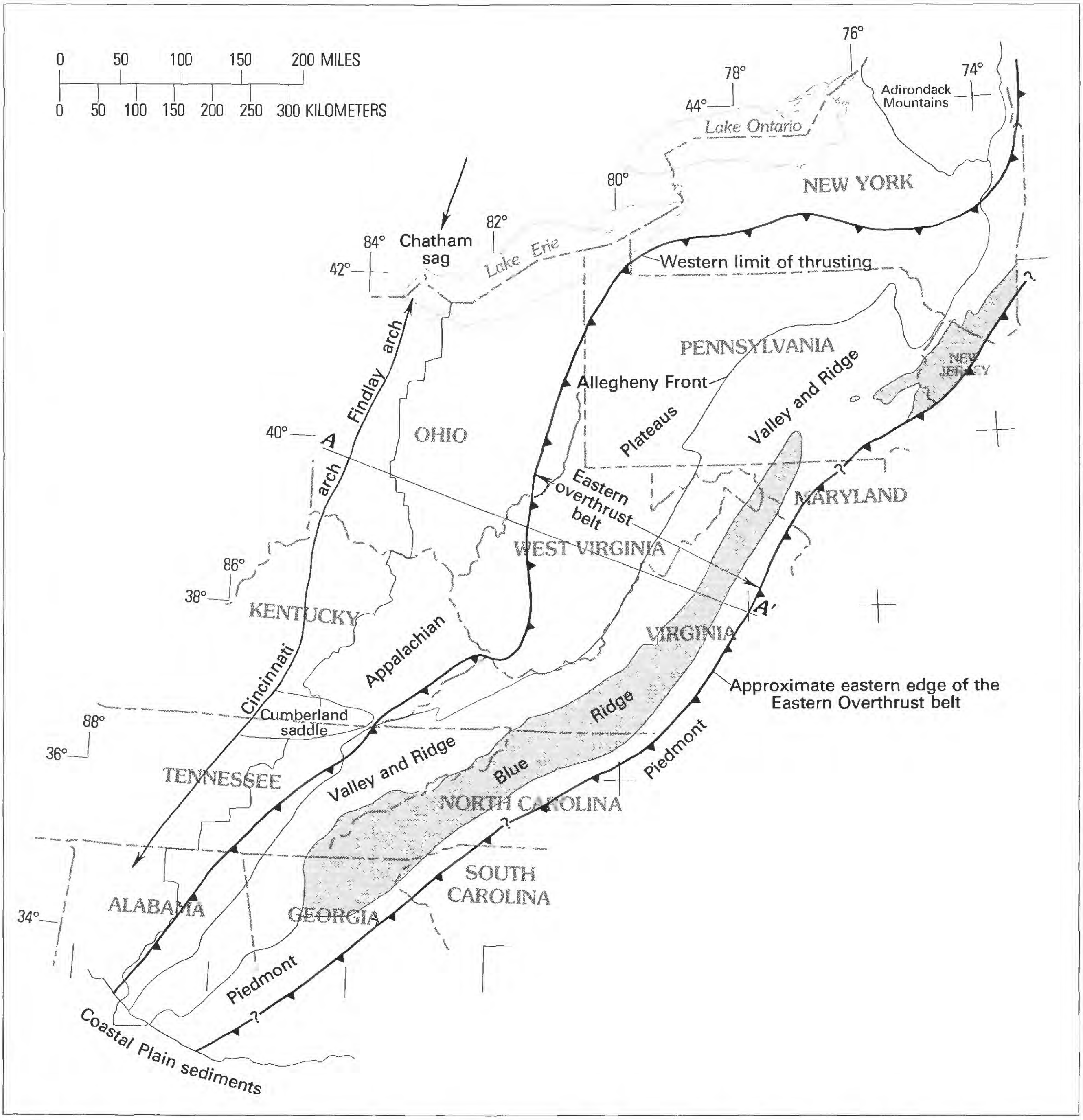

Figure 2*A*. Locations of some structural features mentioned in the text. *A–A'*, approximate line of section shown in figure 5.

and central New York. In New York, the black Devonian source-bed sequence includes at least five extensive discrete black shales intercalated in several thousand feet of gray or greenish-gray mudrock, shale, siltstone, and sandstone. The more porous rocks in the gray siliciclastic sequence in New York, Pennsylvania, and West Virginia are reservoirs for the oil and gas derived from adjacent black Devonian source rocks.

The older source-bed sequence, which is Middle to early Late Ordovician in age, consists largely of brownish-black to black marine shale with small amounts of gray shale, siltstone, or intercalated nodular argillaceous lime-

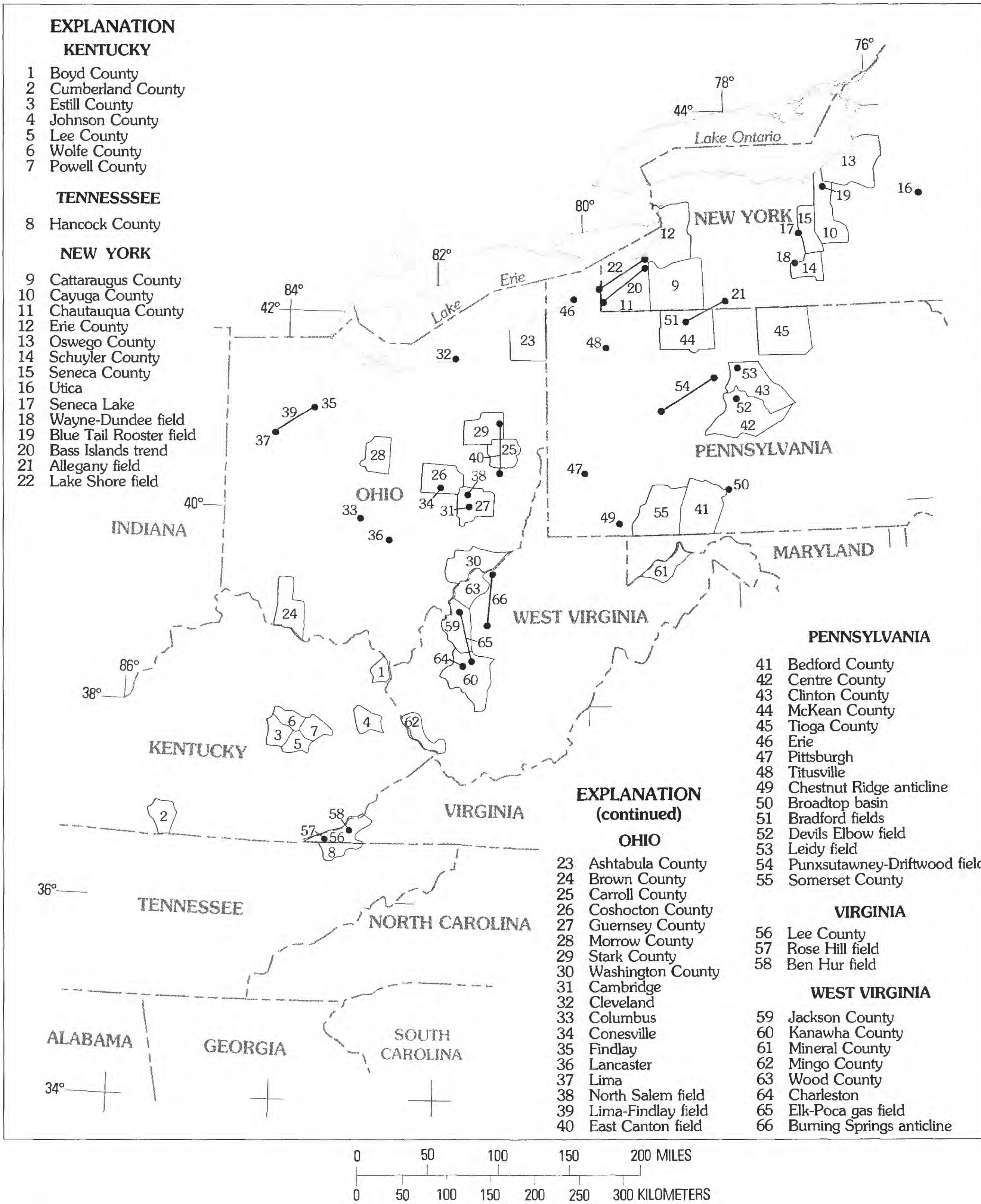

Figure 2*B*. Locations of places mentioned in the text.

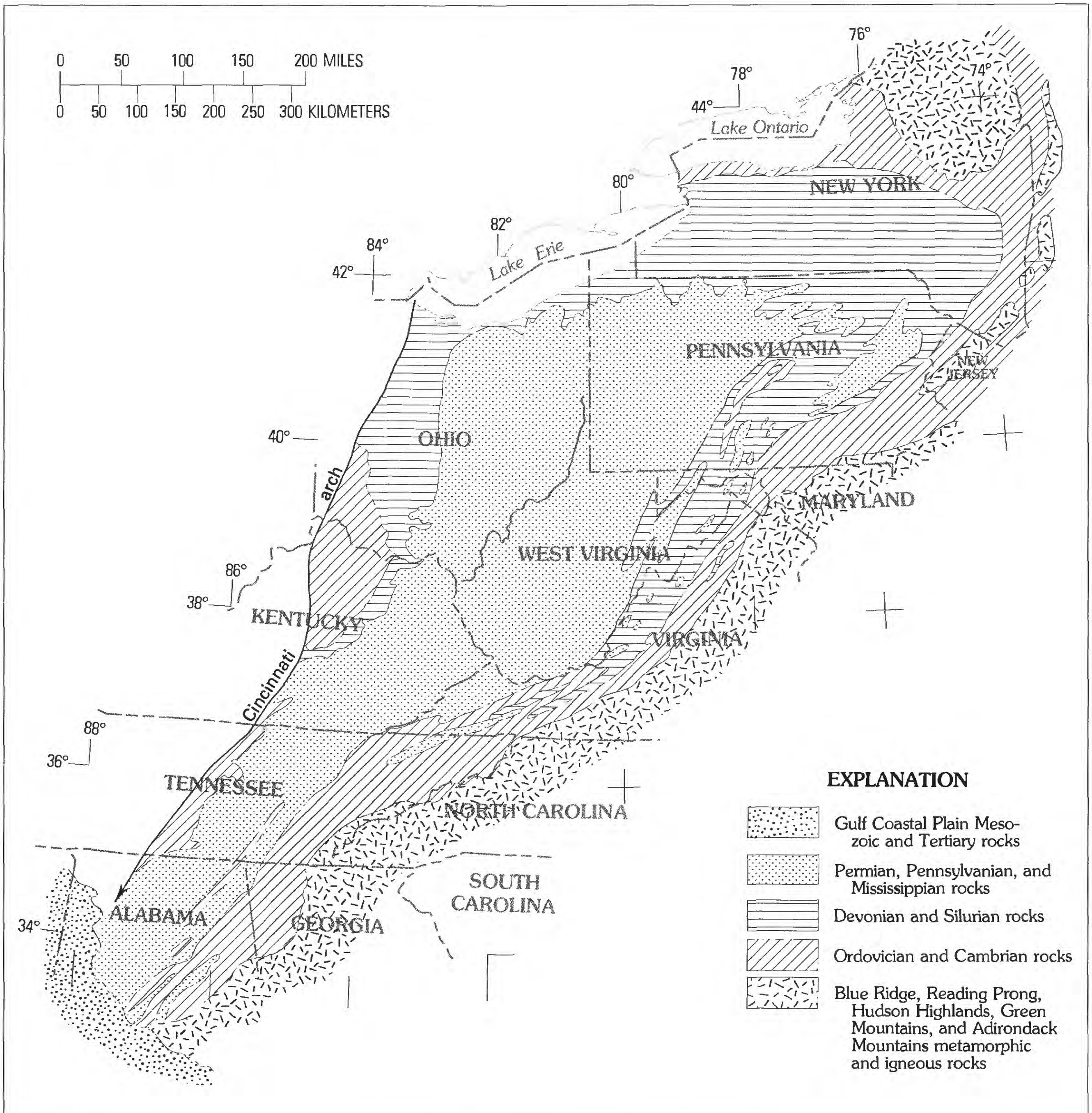

Figure 3. Generalized geology of the Appalachian basin.

stone. The sequence is best developed in the northern part of the basin and in the Valley and Ridge segment from New York to Alabama. The sequence has been termed the "Utica facies" for exposures near Utica in east-central New York (Wallace and Roen, 1988). The facies includes the Athens Shale in Alabama, the Blockhouse Shale in Tennessee, the Paperville Shale in southwestern Virginia, the Antes Shale in Pennsylvania, the Utica Shale in northern Ohio, and the Point Pleasant Formation in southwestern Ohio. Utica source beds range in thickness from a feather edge to as much as 600 ft in the Appalachian Plateaus and thicken eastward into the black slate of the Martinsburg Formation in the Valley and Ridge of eastern Pennsylvania. The "Utica facies" is present across the northern part of the basin and in the adjacent part of the Michigan basin. Cole and others (1987) have analyzed the characteristics of the "Utica

Era	System	Series	Source beds Reservoir rocks	Principal oil and gas plays
PALEOZOIC (part)	Permian (part)	Lower		
	Pennsylvanian	undivided	s r′ ✷ s r′ ● s r′ ☼	Virtually exhausted
	Mississippian	Upper	s r′ ☼ r′ ✷	
		Lower	R′ ✷ S R′ ✷	
	Devonian	Upper	S R ● ✷ ☼ Rf ☼	Upper Devonian sandstone
		Middle	s r ☼	
		Lower	R, Rf ☼	Lower Devonian Oriskany
	Silurian	Upper	r ✷ r ✷	
		Lower	R, Rf ✷ ☼	Lower Silurian sandstone
	Ordovician	Upper	r ☼ S r ☼	Ordovician carbonate shelf
		Middle	s R ● ✷ ☼ Rf ● S r ✷	
		Lower	r ● R ✷ ☼	Upper Cambrian and Lower Ordovician Knox carbonate shelf
	Cambrian	Upper	R ✷ r ☼	
		Middle	r ✷ ☼ s	Rome trough
		Lower	r?	?

EXPLANATION

- S Major source bed
- s Minor source bed
- R Major reservoir
- Rf Major fracture-porosity reservoir
- r Minor reservoir
- ′ Virtually depleted reservoir
- ☼ Mainly gas
- ✷ Oil and gas
- ● Mainly oil

Figure 4. Age and position of source beds, reservoir rocks, and principal oil and gas plays in the Appalachian basin.

Table 1. The relative stratigraphic position of rock units mentioned in the text

[Other Paleozoic units and erosional hiatuses are not shown on this chart]

Era	System	Series	Principal oil and gas plays	New York	Pennsylvania	Maryland	West Virginia
PALEOZOIC (PART)	Mississippian	Upper			Mauch Chunk Formation (part)	Mauch Chunk Formation (part)	Pennington Group Ravencliff Member of the Hinton Formation
	Mississippian	Lower			Big Injun sand Squaw sand Sunbury Shale Berea Sandstone		Keener sand Big Injun sand Squaw sand Weir sand Sunbury Shale Berea Sandstone
	Devonian	Upper	Upper Devonian sandstone play	* Dunkirk / Bradford zone sandstones Rhinestreet Middlesex Geneseo	Venango zone sandstones Dunkirk / Bradford zone sandstones Rhinestreet Middlesex Burket Geneseo	Bradford zone sandstones Burket	Cleveland / Venango zone sandstones Huron Dunkirk / Bradford zone sandstones Rhinestreet Middlesex Burket Geneseo
	Devonian	Middle		Geneseo Marcellus Shale	Geneseo Marcellus Shale	Marcellus Shale	Geneseo Marcellus Shale
	Devonian	Middle		Onondaga Limestone	Onondaga Limestone, Huntersville Chert, Needmore Shale	Huntersville Chert, Needmore Shale	Onondaga Limestone, Huntersville Chert, Needmore Shale
	Devonian	Lower	Oriskany play	Oriskany Sandstone	Oriskany Sandstone Mandata Formation	Oriskany Sandstone Mandata Formation	Oriskany Sandstone Mandata Formation
	Silurian	Upper					
	Silurian	Middle		Rochester Shale	Rochester Shale Keefer Sandstone	Rochester Shale	Keefer Sandstone
	Silurian	Lower	Lower Silurian sandstone play	Medina Sand Whirlpool Sandstone	Medina Sand Tuscarora Sandstone Whirlpool Sandstone	Tuscarora Sandstone	Clinton sand / Tuscarora Sandstone
	Ordovician	Upper	Ordovician carbonate shelf play	Utica Shale	Antes Shale	Antes Shale	Antes Shale
	Ordovician	Middle		Utica Shale Trenton Group Black River Group	Trenton Group Black River Group		Trenton Group
	Ordovician	Middle		Beekmantown Group	Beekmantown Group	Beekmantown Group	Beekmantown Group
	Ordovician	Lower	Knox carbonate shelf play	Beekmantown Group	Beekmantown Group	Beekmantown Group	Beekmantown Group
	Cambrian	Upper		Beekmantown Group "Theresa"	Gatesburg Formation	Gatesburg Formation	Gatesburg Formation / Copper Ridge Dolomite
	Cambrian	Middle	Rome trough play		Pleasant Hill Limestone		Conasauga Group Rome Formation
	Cambrian	Lower			Waynesboro Formation basal sand ?		Rome Formation basal sand ?

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TABLE 1

Virginia	Ohio	Kentucky	Tennessee	Alabama
Pennington Group Ravencliff Member of the Hinton Formation		Pennington Group	Pennington Formation	Pennington Formation
Weir sand Sunbury Shale Chattanooga Shale Berea Sandstone	Keener sand Big Injun sand Squaw sand Weir sand Sunbury Shale Berea Sandstone	Big Injun sand Weir sand Fort Payne Formation Sunbury Shale Chattanooga Shale Berea Sandstone	Fort Payne Formation Chattanooga Shale	Fort Payne Formation Chattanooga Shale
Cleveland Huron Rhinestreet Millboro Shale Chattanooga Shale	Cleveland Venango zone sandstones Huron Rhinestreet Middlesex Geneseo	Cleveland Chattanooga Shale Huron Rhinestreet	Cleveland Chattanooga Shale Huron Rhinestreet	Chattanooga Shale
Marcellus Shale Millboro Shale	Geneseo Marcellus Shale	Marcellus Shale	Marcellus Shale	
Onondaga Limestone Huntersville Chert Needmore Shale	Columbus Limestone	Corniferous lime		
Oriskany Sandstone	Oriskany Sandstone	Oriskany Sandstone Corniferous lime		
		Corniferous lime		
Rochester Shale Keefer Sandstone		Corniferous lime Big Six sand		
Tuscarora Quartzite Clinch Sandstone	Clinton sand Cabot Head Formation Medina sand	Clinch Sandstone	Clinch Sandstone	
	Utica Shale Point Pleasant Formation			
Paperville Shale Beekmantown Group	Trenton Limestone Black River Limestone Wells Creek Formation	upper Sunnybrook sand Wells Creek Dolomite	Blockhouse Shale	Athens Shale
Beekmantown Group	Beekmantown Group Rose Run Sandstone		Knox Group	
Gatesburg Formation Copper Ridge Dolomite	Copper Ridge Dolomite Trempealeau Formation	Rose Run Sandstone Copper Ridge Dolomite	Knox Group Copper Ridge Dolomite	Copper Ridge Dolomite
		Conasauga Group Rome Formation basel sand ?		

*Devonian gas-shale source-bed sequence
Cleveland = Cleveland Member of the Ohio Shale
Huron = Huron Member of the Ohio Shale
Dunkirk = Dunkirk Shale Member of the Perrysburg Formation
Rhinestreet = Rhinestreet Shale Member of the West Falls Formation
Middlesex = Middlesex Shale Member of the Sonyea Formation
Burket = Burket Shale Member of the Harrell Formation
Geneseo = Geneseo Shale Member of the Genesee Formation

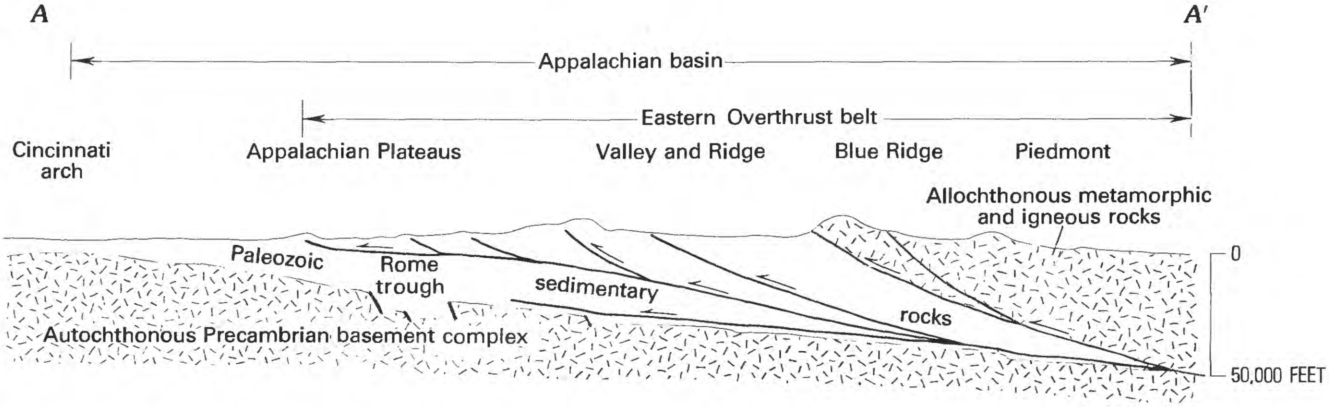

Figure 5. The Paleozoic sedimentary rock sequence from the Cincinnati arch eastward to the west flank of the Blue Ridge and extending eastward in the subsurface beneath the Blue Ridge and adjacent Piedmont. Approximate line of section *A–A′* shown on figure 2*A*. No horizontal scale.

facies" as a source bed in Ohio. Other marine shales that may have some potential as source beds include the Middle and Upper Cambrian Conasauga Group, the Middle Ordovician Wells Creek Formation, the Lower Silurian Cabot Head Shale, the Middle Silurian Rochester Shale, and the Lower Devonian Mandata Shale.

Possible source beds in Mississippian and Pennsylvanian rocks include the many coal beds and associated canneloid shales in the Appalachian Plateaus, the Lower Mississippian coals of Virginia's Valley coal fields, and the anthracite of the eastern Pennsylvania anthracite fields. The abundance of natural gas in many coal beds of the Appalachians attests to the ability of the coals to generate methane gas in quantity.

Thermal Maturation

General eastward thickening of the basin's Paleozoic sequence is the result of nearly continuous deposition in the central and eastern parts of the basin. Westward thinning of major siliciclastic delta sequences and several episodes of nondeposition and subaerial erosion in the western part of the basin thin the Paleozoic sequence along the flank of the Cincinnati arch. Consequently, the degree of thermal maturation of source rocks, which is dependent largely upon thickness of sediment, depth of burial, and existing thermal gradient, increases from west to east across the basin (fig. 7). Epstein and others (1977) noted that levels of thermal maturation in the basin determined from analysis of conodont color alteration data were controlled mainly by depth of burial and showed little effect of tectonism in much of the Appalachian basin. The conodont color alteration index (CAI) isograds depicted by Epstein and others (1977) intersect and cross the main structural trends. This pattern of intersection indicates that the maturation pattern was established in the basin generally before the Alleghanian thrusting. Oil and associated gas occur in fields and pools in the relatively low level of thermal maturation in the western part of the basin, whereas only nonassociated dry gas occurs in the more mature rocks of the Valley and Ridge of Pennsylvania and adjacent States. Although data are generally lacking, maturation levels in the buried eastern segment of the basin appear to be sufficiently low to contain nonassociated dry gas in eastern Tennessee and possibly in contiguous North Carolina and Virginia. However, farther to the east, where the Paleozoic sedimentary rocks underlie the eastern side of the Blue Ridge and inner Piedmont, source beds are overmature, and dry gas is probably not present in commercially producible volumes.

Oil and Gas Migration

Data delineating the time of oil and gas migration are very scant for the Appalachian basin. Cole and others (1987) suggested that an increased thermal gradient associated with the Alleghany orogeny at the close of the Paleozoic Era was responsible for generation of oil and gas in the Ordovician rocks of eastern Ohio and contiguous Pennsylvania. Because of their shallower depth of burial, Devonian black shale and younger source rocks passed into and through the oil-generation zone (window) farther to the east in Pennsylvania and central West Virginia. Thrusting during the Alleghany orogeny developed structural traps with extensive zones of fracture porosity at the propitious interval for recently generated hydrocarbons to migrate into these newly formed structural traps.

Migration of hydrocarbons from more deeply buried source beds (for example, from shale in the Conasauga Group in the Rome trough) may have occurred earlier, prior to the Alleghany orogeny, when the shale reached oil-generation temperature beneath the thick sedimentary fill in

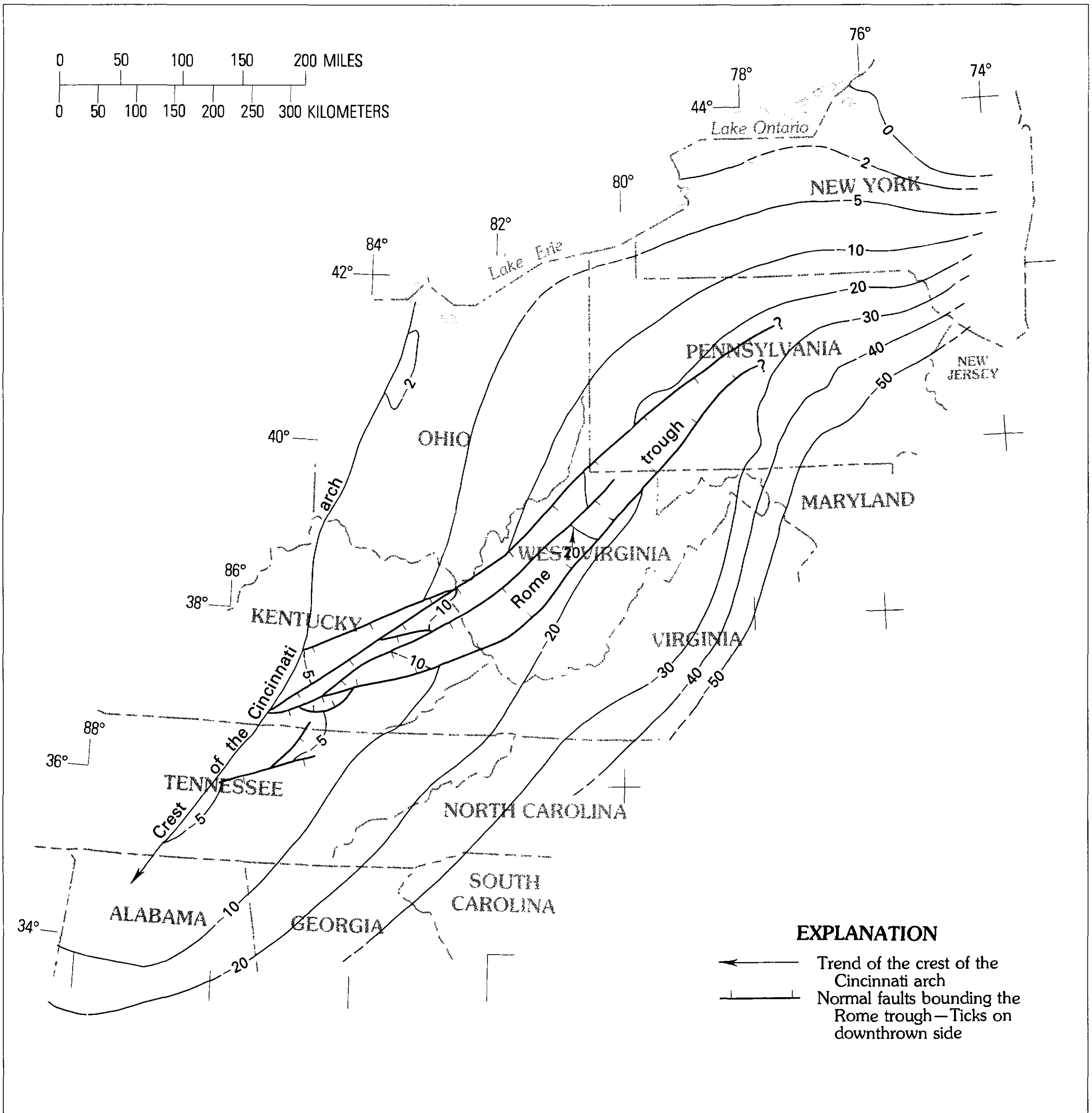

Figure 6. The structure on the top of the autochthonous Precambrian basement complex under the Appalachian basin. Datum is mean sea level. Contour interval 10,000 ft (with 2,000- and 5,000-ft intervals shown locally). Rome trough faults shown by ticks on the downthrown side. Modified from Harris (1975).

the trough. Also, the thinned crust beneath that extensional feature might have produced a greater thermal gradient, which would have accelerated maturation. These are speculative concepts because data are lacking for the deeper rocks in much of the basin. The scant data available for times of hydrocarbon generation and migration in the Appalachian basin clearly indicate the need for more detailed research on these subjects.

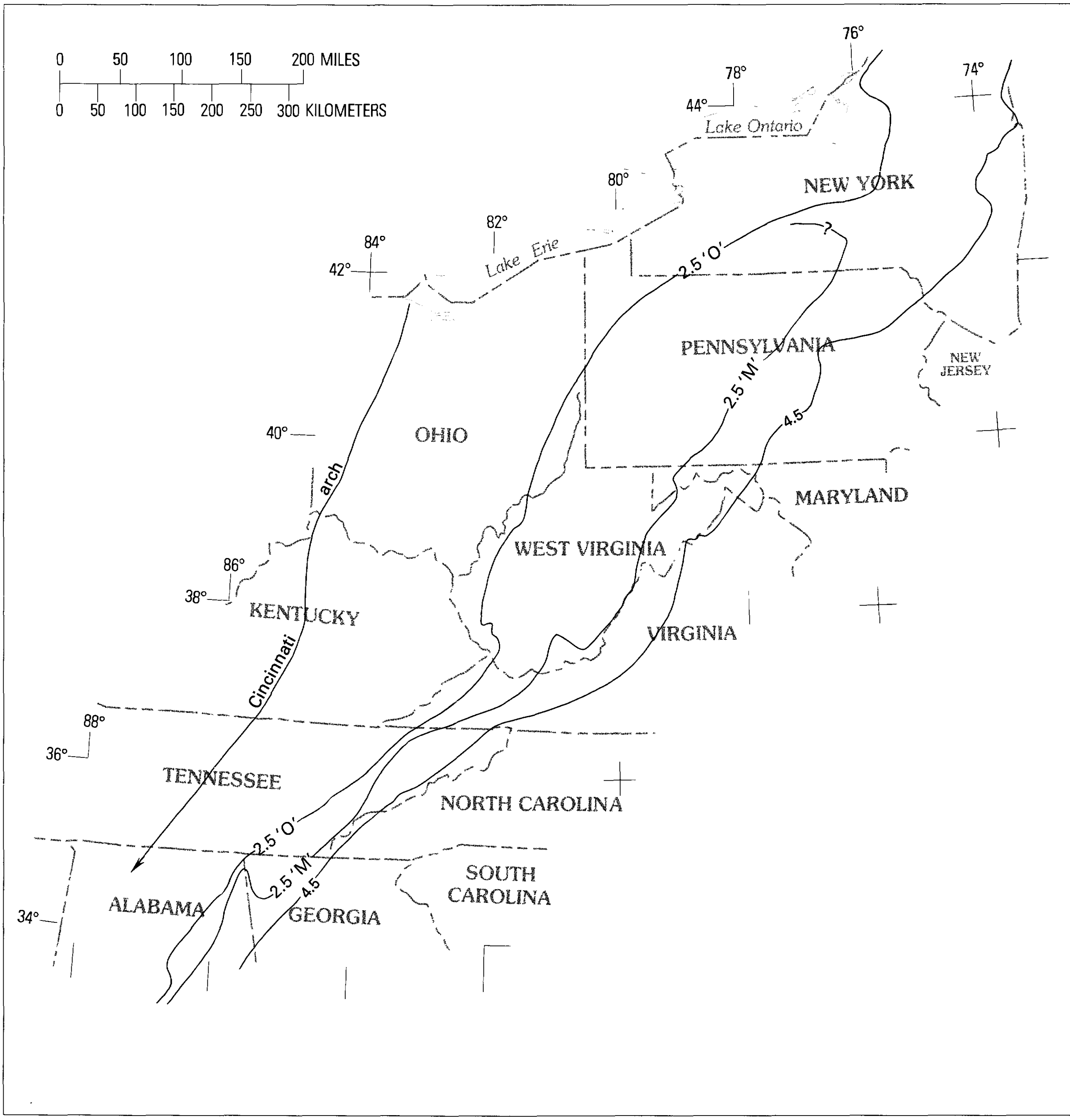

Figure 7. Conodont color alteration index isograds in the Appalachian basin. Isograds 2.5 'O' and 2.5 'M' mark the eastern limits of oil occurrence in the Ordovician amd Mississippian rocks, respectively. Isograd 4.5 marks the eastern limit for the recovery of nonassociated dry gas in the basin. Modified from Harris and others (1978).

Depositional History

A general discussion of the burial history of Paleozoic rocks in the Appalachian basin requires consideration of the basin's large size and the fact that the southern part may have been undergoing subaerial erosion concurrently with subsidence and the accumulation of thousands of feet of deltaic sediments in the northern part. Such differences in deposition and erosion occurred in the basin during the Late Devonian.

An episode of extensional tectonics in the Late Proterozoic opened a rift basin early during the creation of the proto-Atlantic Ocean, Iapetus. Early Cambrian seas flooded the rift and expanded westward onto the edge of the

North American craton. A sheet of sandy sediment accumulated along the edge of the transgressing sea as detritus was swept eastward and southward from the craton. The Rome trough (fig. 6), whose rift phase occurred in the Middle Cambrian, contains Cambrian rocks from the time of rifting and postdating the rifting (Ryder, 1989). As much as 8,000 ft of siliciclastic mud, silt, sand, and some intercalated carbonate sediment accumulated in the trough in parts of West Virginia and Pennsylvania. Dark shale and associated argillaceous limestone rich in organic matter are most probably the source beds for oil and gas found in the western part of the trough in Kentucky and for dry gas in contiguous West Virginia. Because of the great depth of burial of both source beds and reservoir rocks to the northeast, much of the Rome trough's 23,000 mi^3 of fill remains to be explored and evaluated.

During the Late Cambrian and the Early Ordovician, a broad shelf of shallow-marine carbonate sediment blanketed a large part of the basin except for its eastern deeper water segment. About 7,500 ft of shallow-water to supratidal sediment accumulated in the central part of the basin. A brief episode of uplift and erosion near the close of the Early Ordovician exposed the shelf strata and developed local zones of karstic porosity in the carbonate rocks, or concentrated residual quartzose sandstones along the unconformable surface leached into the carbonate strata. At a later date, oil and gas migrated into the porous sandstones or the residual karstic hills mainly in central and eastern Ohio or in the Cumberland saddle (fig 2.) of southern Kentucky and adjacent north-central Tennessee. Potential source beds include some of the Middle Ordovician shales that cap and seal the porous carbonate reservoir rock.

Along the Findlay segment of the Cincinnati arch in northwestern Ohio, the Trenton and Black River Limestones of Middle Ordovician age were extensively dolomitized to form the reservoir rock of the giant Lima-Findlay oil and gas field. Although not strictly a part of the Appalachian basin, local porous zones of dolomitized limestone project from the Lima-Findlay area downdip into central Ohio, where some oil and gas has been found in the Trenton Limestone.

During the Middle Ordovician, the eastern margin of the North American continent shifted from passive to active. A foreland trough formed in the eastern and central part of the basin apparently as a result of compressional tectonics associated with active plate collision to the east. Siliciclastic sediment from eastern orogenic source areas accumulated east of the basin's carbonate shelf. During the Middle and Late Ordovician and Early Silurian, an extensive wedge of deltaic clastic sediment from eastern sources prograded westward across the foreland trough and spread onto the adjacent cratonic platform. A basal blanket of black mud covered much of the eastern half of the basin from New York to Alabama. This black mud, the "Utica facies" (Wallace and Roen, 1988) also spread westward across the northern part of the basin and into the Michigan basin by way of the Chatham sag north of the Findlay arch. The "Utica facies," which is the older of the two principal source-rock sequences in the Appalachian basin, is as much as 600 ft thick. It supplied gas to the Trenton Limestone in northeastern New York and oil and gas to the Trenton and older limestones in the Valley and Ridge of southwest Virginia and to the Ordovician carbonate reservoir rocks in the nearby Cumberland saddle of southern Kentucky and contiguous Tennessee. Cole and others (1987) suggested that the source of oil from the Late Cambrian Trempealeau Formation, a Copper Ridge Dolomite equivalent, in central Ohio may have been the black "Utica facies" to the east, where it lay deeper in the basin.

Widespread, dominantly marine transgressive Lower Silurian sandstones in the northern part of the basin are reservoirs for oil and associated gas in Ohio and locally in Kentucky and Pennsylvania. They contain nonassociated dry gas in New York, Pennsylvania, and West Virginia. The sandstones are the upper part of the thick and extensive siliciclastic deposits of the Queenston delta that filled the northern part of the foreland trough during the Late Ordovician. The basal Silurian sandstones change from marine to terrestrial, thicken, and become coarser grained eastward. They thicken from a feather edge in central Ohio to more than 700 ft in the Valley and Ridge in northern Virginia.

Continued transgression of the shallow epicontinental sea flooded all but the eastern part of the foreland trough during the Middle Silurian. The Bloomsburg delta, a small mass of red siliciclastic sediment built above sea level in eastern Pennsylvania, and some of its flanking sandstones spread southward into Virginia and adjacent West Virginia. A marine carbonate shelf with small fringing reefs occupied the western segment of the basin. Local exposure of the carbonate strata produced small zones of karstic, enhanced porosity near the top of the carbonate sequence. During the Late Silurian, restricted circulation of the shallow sea within the basin produced a superhaline environment, and evaporitic sediment accumulated widely from New York to central West Virginia and westward to the Michigan basin by way of northern Ohio and the Chatham sag (fig. 2). A scattering of oil and gas pools has been found in the carbonate platform rocks, mainly in Ohio. However, counterparts of the coeval, prolific oil- and gas-filled reefs of the Michigan basin have not been found in the Appalachian basin, although the Silurian carbonate sequence has been penetrated by many thousands of wells from Lake Erie south to the Ohio River.

During the Early Devonian, much of the central part of the basin was covered by a shallow sea that had a prograding shoreline on the east and a low coastal plain on the west. Carbonate muds accumulated along the shore of the western coastal plain, and carbonate sands were deposited on higher energy depositional sites to the east. On the eastern side of the sea, carbonate sediments intertongued with siliciclastic detritus from adjacent source areas. The abundantly fossiliferous Oriskany Sandstone was spread as a marine shallow-water, high-energy blanket of quartz sand from eastern New York to eastern Ohio and southwest to south-central Virginia in both the Valley and Ridge and the Appalachian Plateaus. It ranges in thickness from a feather edge in Ohio to more than 300 ft in central Maryland (Oliver and others, 1971). The Oriskany is one of the principal gas sands of the Appalachian basin. It produced gas and a little associated oil from stratigraphic traps in Ohio and western West Virginia, whereas it produced dry gas in abundance from zones of fracture porosity associated with structural traps downdip in the basin in the Eastern Overthrust belt from central New York to east-central West Virginia in both the Appalachian Plateaus and the Valley and Ridge.

Probably as a result of increasing orogenesis at the onset of the Acadian orogeny, the sea deepened in the foreland trough in the Middle Devonian. The vast Catskill delta, a tectonic delta complex (Friedman and Johnson, 1966) composed of siliciclastic detritus from eastern orogenic sources, prograded westward into the foreland trough. West of the growing delta, an anoxic environment in the deepening sea preserved much of the terrestrial organic detritus swept into the sea from eastern sources as well as much of the locally abundant marine organic matter. Beds of black mud charged with large amounts of organic matter blanketed the central and western parts of the basin at different times during the Middle and Late Devonian and Early Mississippian. Upon lithification, these muds formed the younger of the two principal source-bed sequences for hydrocarbons in the Appalachian basin. These black shales are generally called the Devonian shale sequence or the Devonian gas-shale sequence. Extensive Devonian black shales were not confined to the Appalachian basin. At times the black sediment spread through the Chatham sag across the crest of the submerged Cincinnati arch or through the Cumberland saddle into the Michigan or the Illinois basin.

The Devonian and Mississippian black shale sequence is the main source for oil and gas in middle and late Paleozoic reservoir strata in the basin. The black shales are nonconventional reservoirs. Where extensively fractured, as along the Rome trough, the shales are both source beds and reservoir rocks. Because their contained organic matter adsorbs much of the indigenously generated gas, the Devonian and Mississippian black shales are estimated to contain a large, nonconventional gas resource of about 840 trillion cubic feet (Charpentier and others, 1982), most of which is unrecoverable by existing extraction techniques.

Middle to Late Devonian erosion cut deeply into the rocks in the western part of the basin and formed a series of karstic porous zones in Ordovician, Silurian, and Devonian carbonate rocks beneath a Devonian unconformity from Ohio south to Tennessee. During the early part of the present century in eastern Kentucky, prolific oil fields were discovered in the Corniferous lime (drillers' term), a local designation for the Middle Silurian to Lower Devonian carbonate rock sequence.

During the Middle and Late Devonian, the vast Catskill tectonic delta-fan complex prograded into and filled much of the northern half of the foreland trough with a sequence of siliciclastic sediment that ranged from coarse conglomeratic sands in the east to fine-grained mud and clay in the west. In places, as much as 12,000 ft of quartzose clastic sediment accumulated in the eastern part of the basin. To the west, prodelta turbiditic silts, shallow marine sheet sands, bars, and beach sands were deposited by the prograding Catskill delta. Many of the beds of silt or sand became reservoir rocks for oil and gas generated in the adjacent and interfingering black shale sequences. The Upper Devonian sandstones of the Venango and Bradford sequences of western Pennsylvania and adjacent New York and West Virginia are the principal oil reservoirs in the basin. More than half the oil recovered in the Appalachians has been produced from the Upper Devonian sandstones, particularly from the giant Bradford field astride the Pennsylvania–New York State line.

From the Late Devonian into the Early Permian, the Appalachian foreland basin was largely filled by siliciclastic detritus, largely from eastern orogenic source areas, with the exception of a period of flooding and accumulation of shallow-water carbonate sediment during the Late Mississippian. The carbonate sediment was deposited in the southern and western part of the basin and interfingered to the northeast and east into red beds of the terrestrial Mauch Chunk delta. At times some clastic detritus was eroded from the cratonic shield to the north and northwest of the Appalachian foreland trough and was swept southward into the northwestern part of the trough. Although locally important as reservoir rock, the amount of siliciclastic sediment from cratonic sources is trifling in comparison to the vast amount of clastic material derived from eastern orogenic source areas.

In the western part of the basin, several deltaic shallow-marine sandstones of Early Mississippian age have been and are reservoirs for oil and gas whose source was the black shales of the Devonian and Lower Mississippian shale-gas sequence. The Berea Sandstone, having sediment source areas both on the craton and in the orogenic highlands to the east (Pepper and others, 1954), is the most extensive of these siliciclastic reservoir rocks. The younger Keener, Big Injun, Squaw, and Weir sequence produced large volumes of oil and gas in parts of eastern Kentucky, southern Ohio, and northern West Virginia during the past century. During the Early Mississippian, much of the eastern part of the foreland trough was filled with coarse-grained terrestrial deltaic deposits. Coal beds are present locally in the sequence in the Valley and Ridge of Maryland, Pennsylvania, Virginia, and West Virginia. Marine sandstones extending westward into the basin from the

Early Mississippian deltas produced much nonassociated dry gas in western Pennsylvania and contiguous West Virginia. Farther to the west, oil and associated gas accumulated in the porous shallow-water sandstones. Although these petroliferous reservoir sandstones have long been in a mature stage of exploration and have been drilled extensively, they contained important oil and gas fields during the past century, when the petroleum industry developed in the Appalachian basin.

Although the southwestern segment of the Appalachian basin was inundated in the Early Mississippian, the last major flooding of the Appalachian foreland trough by the Paleozoic epicontinental sea occurred mainly in the early part of the Late Mississippian. A broad northeastward-thinning wedge of shallow-marine to locally supratidal carbonate sediments blanketed the western and southern parts of the basin. Evaporitic sediments, including halite, accumulated in partly isolated subbasins. The carbonate strata thin and intertongue with red siliciclastic rocks of the Mauch Chunk delta in the northeastern and eastern segment of the basin. The Mississippian carbonate strata are more than 3,500 ft thick in the Greendale syncline in the Valley and Ridge of southwest Virginia and thin to a feather edge in the Broadtop basin in south-central Pennsylvania. Dolomitized zones with enhanced porosity and permeability, especially in the lower part of the Mississippian carbonate sequence, produced both oil and gas in parts of West Virginia, eastern Kentucky, and adjacent Tennessee. Other reservoirs in the carbonate sequence include vugular porosity in biostromes or small bioherms (Milici and others, 1979).

During the Late Mississippian, great volumes of terrestrial siliciclastic sediment from eastern orogenic source areas prograded into and filled the northern and central parts of the foreland basin. The Mauch Chunk deltaic sequence of red beds is more than 6,000 ft thick in eastern Pennsylvania (Wood and others, 1969, p. 65–70). The continental rocks of the delta grade laterally into and intertongue with sequences of marine rocks to the southwest along the central part of the basin in the Pennington Formation. The formation contains a mixture of siliciclastic and carbonate rocks, many of which were deposited in shallow-marine to coastal-swamp environments. Local coal beds and coaly shale as well as dark-gray to black marine shale or mudrock may have been source beds for some of the oil and gas trapped in the more porous rocks of the Pennington Formation. Several quartzose channel, bar, and beach sandstones in the Pennington form stratigraphic traps for both oil and gas, mainly in the central and west-central parts of the basin. Of the channel-filling sandstones, the Ravencliff Member of the Hinton Formation of West Virginia is probably the most extensive gas reservoir in the Upper Mississippian rocks of the basin.

To the south in Alabama, much of the middle and upper part of the Mississippian sequence is dominated by shale and mudrock. Dolomite, limestone, and sandstone are interbedded in the sequence, although the finer grained siliciclastic rocks make up much of the sequence. Some of these shaly rocks may have been source beds for gas and oil trapped in porous strata to the west in the Black Warrior basin.

Coal-bearing sequences of dominantly siliciclastic deltaic rock derived largely from eastern orogenic source areas filled the Appalachian foreland basin during the Pennsylvanian and Early Permian. Locally, in eastern Pennsylvania and southwestern Virginia, these strata are more than 5,000 ft thick, and in central Alabama they are about 9,500 ft thick (Wanless, 1975). In general, the coal-bearing rocks thin to the west, and several relatively thin sequences of marine limestone, mudrock, and chert from the midcontinent extend eastward into the basin's Pennsylvanian rocks, particularly in Ohio. Most of the carbonate rocks in the Appalachian basin are, however, lacustrine limestones. Coals in the basin range from high-volatile bituminous to anthracite. Bituminous coals underlie the Appalachian Plateaus in the western and central parts of the basin, whereas anthracite occurs in the folded and faulted Valley and Ridge rocks in eastern Pennsylvania. Black canneloid and carbonaceous shales are locally abundant in these upper Paleozoic rocks. Both the coals and black shales were probably source beds for gas and oil in stratigraphic traps in the coarser grained sandstones and conglomerates of the Pennsylvanian strata. Some hydrocarbons in Pennsylvanian reservoirs may have been derived from the Devonian and Lower Mississippian black shale sequence. Data are lacking, so the genesis of oils trapped in the Pennsylvanian rocks cannot be resolved at present.

Locally, channel-filling, beach, and bar sandstones of Pennsylvanian age have produced oil or gas or both in eastern Kentucky, southeastern Ohio, southwestern Pennsylvania, and West Virginia. Although by present standards the volume of oil and gas from the Appalachian basin's Pennsylvanian rocks is relatively small, it was economically important during the nascent stages of the petroleum industry, from 1860 to 1890, and was responsible for much drilling and exploration in the vicinity of the Burning Springs anticline of north-central West Virginia and adjacent southeastern Ohio during and just after the Civil War. Consistent with the general pattern of increasing thermal maturation eastward across the Appalachian basin, oil and associated gas commonly occur in the western part of the basin, whereas nonassociated dry gas is present farther to the east.

DEFINITION OF THE PRINCIPAL PLAYS

The procedure for assessing the undiscovered recoverable oil and gas resources in the Appalachian basin requires subdividing the basin's rocks into a series of individual oil and gas plays. An assessment was made for each play after the geometry of the plays was delineated and their geologic attributes were defined and documented. The total analysis of all plays yields the required evaluation of the basin's undiscovered recoverable resources of gas and oil.

A play is a sequence of rocks and its contained hydrocarbons having the same general stratigraphy, structure and tectonic history, source rocks, general degree of thermal maturation, and types of reservoir rocks, traps, and seals. A play is a discrete entity both geologically and geographically. It differs in some of its characteristics from adjacent plays. With sufficient data available, plays of small geographic extent may be rigorously defined and their resources estimated to a high degree of accuracy. Conversely, a play of large geographic extent, for example, a play involving a basin of several hundred thousand square miles in area, will be less well defined, particularly if data are relatively scant in a large segment of the play's extent. The principal plays of the Appalachian basin are categorized as being extensive.

In this report, some plays are named for the principal reservoir rock or stratigraphic unit. However, a play will contain other units—source beds, reservoirs, or seals—that may be of different age than the play's named unit. In the Appalachian basin, the principal plays consist of generally extensive, well-known stratigraphic units or sequences of units whose geometries are clearly defined. Most Appalachian basin plays contain coarse-grained siliciclastic reservoir rocks that underlie all or parts of several States and range from areas of extensive drilling and exploration in the Appalachian Plateaus to the little-drilled area of the Valley and Ridge. Facies relations within the siliciclastic reservoirs are moderately well documented from drill cuttings, core samples, and electric logs. Areas of low permeability and low porosity produced by diagenesis are reasonably well known. Regional and local structural features in the mainly unfaulted western segment of the basin have been mapped on many different stratigraphic units, whereas to the east in the overthrusted areas many deeply buried features may be defined only from seismic profiles. Consequently, it is necessary to select plays, the boundaries of which are clearly defined lithologically and are readily identifiable in seismic sections, in order to establish their subsurface extent in the Eastern Overthrust belt. To evaluate plays containing karstic carbonate and siliciclastic sandstone reservoir strata associated with unconformities of regional or local extent requires the knowledge of their stratigraphic position, lithology, thickness, volume of rock removed during known erosional intervals, and the paleotopography of existing unconformities. Many of these data are available from outcrop studies on the basin's periphery and to a considerably smaller extent from sample studies, cores, and the analysis of suites of wire-line geophysical logs. Karstic carbonate oil and gas reservoirs are found mainly in the western segment of the basin, where extensive unconformities formed in rocks along and adjacent to the Cincinnati arch.

The principal plays defined in the present assessment of the Appalachian basin's undiscovered recoverable oil and gas resources are, in descending stratigraphic order, the Upper Devonian sandstone play, the Lower Devonian Oriskany play, the Lower Silurian sandstone play, the Ordovician carbonate shelf play, the Upper Cambrian and Lower Ordovician Knox carbonate shelf play, and the Rome trough play.

DETAILS OF THE PRINCIPAL PLAYS

Upper Devonian Sandstone Play

The Upper Devonian sandstone play underlies about 33,000 mi^2 of Maryland, New York, Ohio, Pennsylvania, and West Virginia (fig. 8). The play consists of a 15,000-mi^2 western area (Area 1, fig. 8) generally producing oil and associated gas, and an eastern 13,000-mi^2 area (Area 2, fig. 8) containing nonassociated dry gas. The play consists of a 600- to 4,000-ft eastward-thickening sequence of deep-water to shallow-marine to terrestrial delta-plain rocks—shale, mudrock, siltstone, sandstone, and conglomerate—within the vast Catskill tectonic fan-delta complex (Friedman, 1988), which occupied much of the northern part of the Appalachian foreland basin during the Late Devonian. Sources of siliciclastic sediment lay to the east in orogenic highlands elevated during continental-plate collision in the Acadian orogeny. Clastic detritus was transported westward along the paleoslope into the subsiding foreland trough. Rates of sedimentation exceeded subsidence, and the Catskill delta prograded west across the trough so that its mud and silt blanketed the eastern edge of the cratonic platform in Ohio. The Upper Devonian sandstone play lies within the marine clastic sequence in the Catskill delta.

Reservoir Rocks

In the Upper Devonian sandstone play, reservoir rocks range from very tight, low-permeability, low-porosity, distal- to proximal-turbidite siltstones in the lower part to highly porous, high-permeability, pebbly, beach or offshore-bar sandstones in the upper part. The siliciclastic rocks generally increase in grain size upward so that in west-central Pennsylvania gas-bearing silty turbidites of the Bradford zone in the lower part of the play are overlain by oil-productive sandstones in the Venango zone in the upper part of the play. Similarly, the beach and nearshore bar sands grade westward into equivalent-age tight, largely nonproductive siltstones in eastern Ohio. Although the Upper Devonian sandstone play may be several thousand

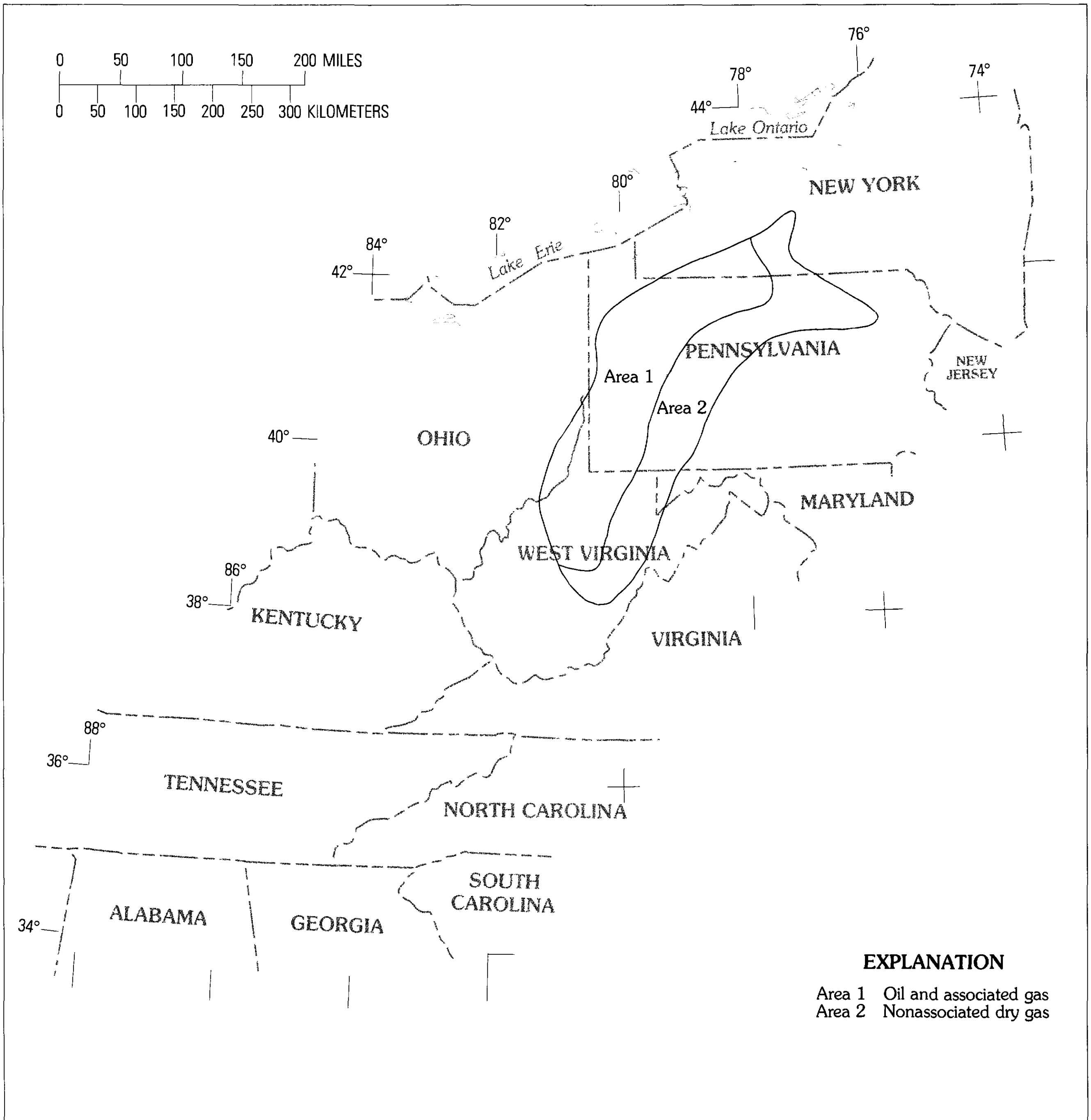

Figure 8. The upper Devonian sandstone play. The play consists of a 15,000-mi^2 western area (Area 1) and a 13,000-mi^2 eastern area (Area 2).

feet thick, only about 10 to 15 percent of the play at a given locality is reservoir rock; much of the sequence is composed of siltstone, silty mudrock, or shale. Porosity ranges from about 25 percent in the coarse-grained pebbly beach and bar sandstones to less than 4 percent in the fine-grained distal turbiditic siltstones. Permeability ranges from several darcies locally in conglomeratic sandstones (Dickey, 1941) to less than 10 μD in unfractured siltstone. In the finer textured reservoir rock, fracture porosity is an important factor for gas productivity, particularly to the east in the segment of the play within the buried western part of the Eastern Overthrust belt.

Traps and Seals

In the western part of the play, traps are mainly stratigraphic in the form of permeability barriers or are stratigraphic traps modified by small-amplitude anticlines or domes. Some original porosity may be preserved in the coarser grained pebbly sandstone; however, much of the porosity is secondarily developed during diagenesis by dissolution of chemically unstable mineral grains and by modification of clay coatings and cements in the original pores. Some of the coarser grained oil sands contain saltwater, which underlies oil in low-amplitude folds.

Source Beds

Source beds for oil and gas in the Upper Devonian sandstone play are the dark-gray, dark-brown, and black Middle and Upper Devonian and Lower Mississippian shales that underlie, are intercalated in, or overlie the coarse-grained rocks of the play. Because of greater depth of burial to the east, maturation levels in the source rocks range from immature (conodont alteration index 1.5) in central Ohio to mature (CAI 2 to 2.2) in eastern Ohio, western Pennsylvania, and contiguous West Virginia to overmature (CAI 4.5 to 5) in the Valley and Ridge of eastern Pennsylvania, eastern Tennessee, and central Virginia (Harris and others, 1978). Some data indicate that the source shales contain an admixture of marine kerogens, type II, and terrestrial kerogens, type III. The increase in the amount of terrestrial kerogens to the east, and also the increase in the degree of thermal maturation, indicates that the source rocks are progressively more gas prone eastward across the play. Some oil is present in the source beds in the central part of the basin from northwestern Pennsylvania south to southeastern Kentucky. The shales produce oil locally from fracture porosity in southeastern Ohio and adjacent West Virginia. Newberry (1860) suggested that the black Devonian shales were the source for oils in Pennsylvania's Upper Devonian oil sand reservoirs. Claypool's (G.E. Claypool, written commun., 1978) geochemical analyses of the black shales and oil from the Bradford oil sands confirmed Newberry's suggestion.

Timing and Migration

Data on the time of generation and migration of oil in the Upper Devonian sandstone play are scant. Cole and others (1987) suggested that maximum maturation and attendant migration took place at the close of the Paleozoic during the Alleghany orogeny, when the maximum burial depth of strata in the basin was coupled with a pulse of increased temperature accompanying the orogeny. Oliver (1986) suggested that hot brines squeezed from thick sequences of shale beneath the Appalachian megathrust fault system during the orogeny may have been part of the migration mechanism for displacing hydrocarbons from source beds to cooler reservoir rock. Hearn and Sutter (1985) presented evidence that during the Pennsylvanian and Permian, brines reacting with siliciclastic detritus in some carbonate rocks of the Valley and Ridge formed potassic feldspars at relatively low temperatures. These data suggest that warm to hot fluids migrated into the rocks of the Appalachian basin at about the time suggested by Oliver (1986) and Cole and others (1987).

Depth of Occurrence

In the shallow, western, oil-producing part of the play, oil and gas occur at depths of 450 to 1,000 ft in western New York, from 1,600 to 2,500 ft in southeastern Ohio, from 695 to 3,900 ft in western Pennsylvania, and from 2,600 to 3,900 ft in central West Virginia. In the eastern, nonassociated dry-gas segment of the play, the upper reservoirs of dry gas underlie the deepest oil-bearing sands of the oil play. Reservoirs of nonassociated dry gas have been found to depths of 5,000 ft under the eastern part of the Appalachian Plateaus in central Pennsylvania and to more than 6,500 ft under the eastern part of the plateaus of northeastern West Virginia.

Exploration Status

The western, oil-productive segment of the Upper Devonian sandstone play has been largely explored and exploited. Drilling began in the play in 1859 with Drake's well at Titusville, Pa., and spread to the south in the 1860's. The area of the play was considerably extended into New York by the discovery of the Bradford and Allegany fields in the 1870's. At several times, parts of the play were redrilled when deeper sands were found to contain oil. Exploration spread southward into northern West Virginia, where many local oil-bearing sandstones were found in this part of the play. Most of the major oil pools had been discovered and delineated by 1910. More than half of the 3 billion barrels of oil and gas liquids produced in the Appalachian basin have come from the Upper Devonian sandstone play. The introduction of secondary recovery methods, principally by waterflooding, recovered a large volume of oil that was unobtainable by primary recovery techniques, particularly in the sands of the giant Bradford field. In the oil-productive part of the play, the number of wells in a single pool ranges from one to several hundred. In the early drilling campaigns, drilling density was commonly excessively high, as several wells were drilled on a 1-acre lease. Consequently, reservoir pressure was soon dissipated, and much of the original oil was not recovered. Deeper drilling for nonassociated gas in the western part of the play began in the 1880's as the market for gas to fuel steel and glass manufacturing developed in the Pittsburgh area, and pipelines were laid to exploit newly discovered gas pools and fields at considerable distances from these major markets. After exploiting the gas sands in the less deeply buried western segment of the Upper Devonian sandstone play, drilling for gas spread slowly to the east and southeast into the more deeply buried low-permeability reservoir rocks in the nonassociated dry-gas segment of the play. At present, drilling is concentrated mainly in the eastern segment of the basin under the eastern and central parts of the Appalachian Plateaus from north-central Pennsylvania southwest to east-central West Virginia. Many low-permeability siltstone or fine-grained turbiditic sandstone reservoir rocks are stacked in this part of the play. Hydraulic fracturing stimulation techniques in areas of fracture porosity have developed gas production in parts of the play that were heretofore believed to be dry. These newly developed stimulation techniques have extended the potentially productive part of the dry-gas play almost to the western edge of the Valley and Ridge in northeastern West Virginia and in central Pennsylvania. Pool size data are very sparse for nonassociated-gas pools and fields of this play. Production ranges from single well pools with cumulative production of several million cubic feet of gas to multiwell fields producing from as many as eight zones and having a cumulative production exceeding 1 billion cubic feet of dry gas. At present, the eastern limit of the play appears to be the Allegheny Front at the west edge of the Valley and Ridge. The few wells drilled to the Lower Devonian Oriskany Sandstone or to older stratigraphic units in the Valley and Ridge did not encounter commercially exploitable volumes of gas in the Upper Devonian sandstones. Much of the Valley and Ridge contiguous with the play area is in a terrestrial red-bed sequence that has maturation levels equivalent to CAI 4 to 4.5, which precludes the presence of oil and suggests only a small possibility for nonassociated gas in commercially exploitable amounts.

Lower Devonian Oriskany Play

The Lower Devonian Oriskany play underlies about 88,000 mi^2 of the northern part of the basin in a triangular area from eastern New York to northern Ohio and south to eastern Kentucky. It includes much of the northern half of the Appalachian Plateaus and parts of the adjacent Valley and Ridge of Pennsylvania, Maryland, Virginia, and West Virginia (fig. 9). The play is dominantly a siliciclastic sandstone reservoir play except in parts of West Virginia, Maryland, and Pennsylvania where beds of fractured chert in the overlying Huntersville Chert have been included in evaluating fracture porosity zones of the Oriskany play. The Oriskany is an abundantly fossiliferous, siliciclastic, marine, sheet sandstone that is more than 350 ft thick near its depositional center in western Maryland and adjacent West Virginia. The sandstone thins to a feather edge to the north, west, and southwest. Within the sheet of sandstone are areas of considerable areal extent in which the Oriskany was either not deposited or was scoured away before younger rocks were deposited. The southern edges of the areas of the Oriskany are permeability barriers that locally trapped gas during its migration northwestward up the regional dip. The very fossiliferous Oriskany Sandstone has been tightly cemented by secondary calcite at many places. Locally, the sandstone has been cemented by silica.

The Oriskany play is subdivided into two segments. The western and smaller segment (Area 1, fig. 9) is gas dominated with some associated oil at a few widely spaced localities in New York, Ohio, and West Virginia. The eastern and larger segment (Areas 2 and 3, fig. 9) contains nonassociated dry gas.

Reservoir Rocks

In the western segment of the Oriskany play, gas and oil accumulated in a highly porous, extremely permeable open-textured quartz sandstone reservoir. Although much of the sandstone is relatively fine grained, even at the edges of the Oriskany Sandstone, some coarse-grained sand, granules, and small pebbles are present. Permeability barriers, such as decrease of grain size and abundance of secondary calcite cement, commonly limit the size of reservoirs. Saline water is generally present downdip from gas or oil. Porosities in the reservoirs range from less than 10 percent to as much as 25 percent. Because many of the Oriskany reservoirs in the western segment of the play were drilled by cable tools and few, if any, cores were cut in the more productive zones, high permeabilities in this segment of the play are indicated only by scant data. Lockett (1937) noted that wells 1 mi apart quickly registered a change in reservoir pressure if one of the two were shut in or was produced at full capacity with no back pressure to restrict the gas flow. Such quick response to pressure change in the reservoir indicates a very permeable reservoir.

To the east and deeper into the basin, the initial intergranular porosity has been largely obliterated by diagenesis and secondary cementation of the reservoir rock. Solution of chemically unstable minerals in the framework may have locally enhanced porosity, but the general effect decreased both porosity and permeability. However, within the Eastern Overthrust belt, secondary porosity increased as a result of the development of zones of fracture porosity associated with imbricate and splay faults rising from a zone of décollement in the upper part of the subjacent Silurian sequence. Fracture porosity is commonly localized along anticlinal folds produced by thrust duplication of parts of the stratigraphic section. Some intergranular porosity is necessary for continuing production from Oriskany wells, even where the sandstone has been fractured (Sanders, 1982).

Traps and Seals

Stratigraphic traps formed from a decrease of permeability and porosity dominate the western segment of the

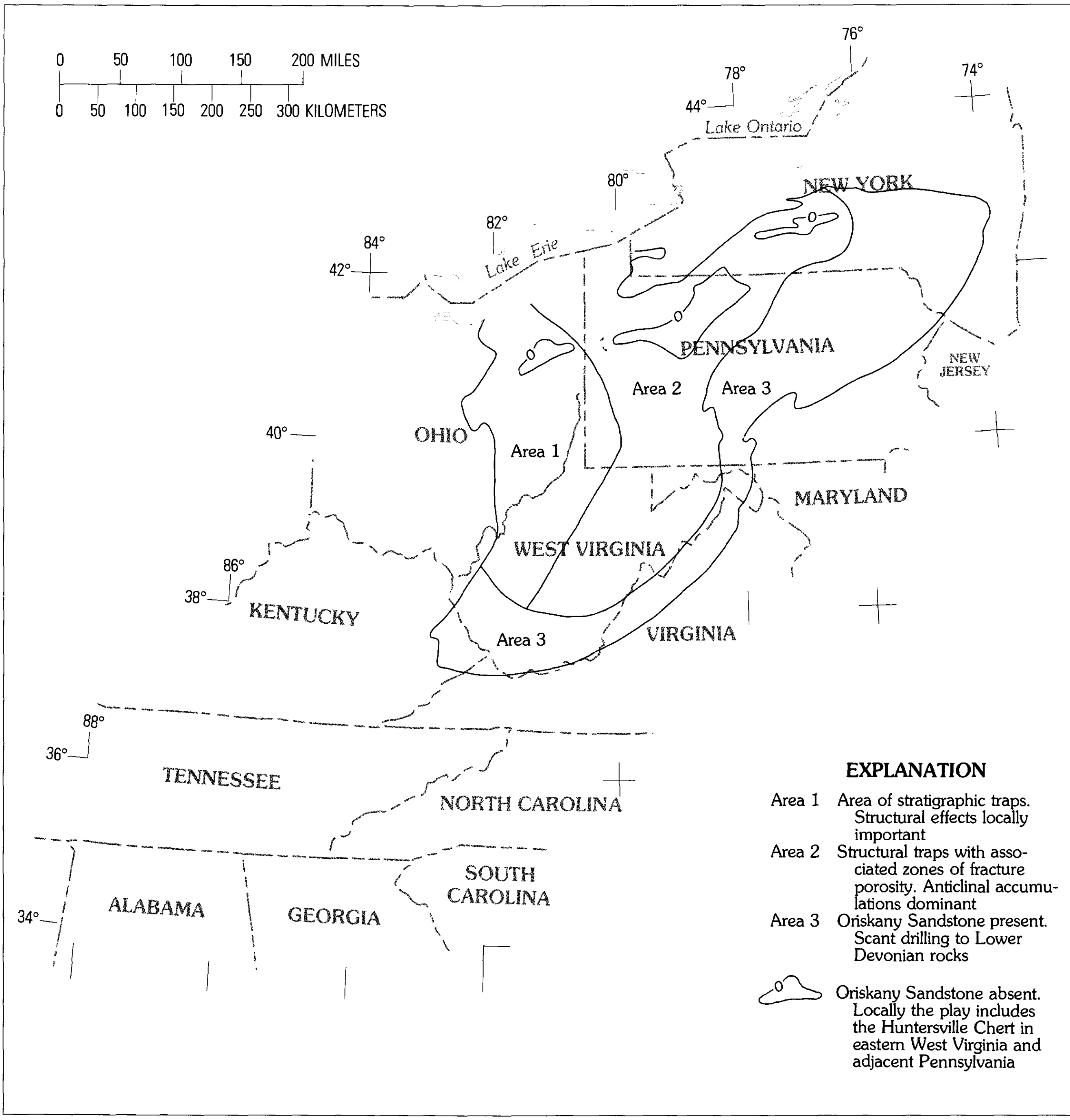

Figure 9. The Lower Devonian Oriskany play. Area 1 is gas dominated with some associated oil. Areas 2 and 3 contain nonassociated dry gas.

Oriskany play. Locally, small-scale folds and faults may slightly modify traps. In this segment of the play, saltwater lies downdip to the east of oil or gas, and the sandstone is tight and dry updip to the west or northwest. The giant Elk-Poca field near Charleston in central West Virginia, which has produced almost a trillion cubic feet of gas, is a typical stratigraphic trap that has a well-defined gas-water contact on its eastern side.

To the east, in the dry-gas segment of the Oriskany play, stratigraphic traps become less important as intergranular porosity decreases, and structural traps with associated fracture porosity dominate in the Eastern Overthrust belt. All of the eastern dry-gas part of the play lies within the overthrust belt. Seismic data and drilling show that structural features in the Oriskany beneath major anticlines in the eastern half of the Appalachian Plateaus and in the Valley and Ridge are complex because of numerous fault blocks (Gwinn, 1964). Some blocks may contain saltwater, whereas adjacent blocks are dry. Small, pop-block anticlinal fault traps are not uncommon in the bottom of larger synclines. Such small structural traps are not apparent in the surface geology and must be located by detailed reflection seismic profiles.

In the western segment of the Oriskany play, the Columbus Limestone or equivalent Onondaga Limestone generally overlies the Oriskany and forms a tight seal to Oriskany reservoirs. In West Virginia, the Huntersville Chert, a sequence of brittle bedded chert with some intercalated limestone or shale, which is a siliciclastic facies of the Onondaga, overlies the Oriskany Sandstone. Where the chert is extensively fractured, it may contain gas that is in equilibrium with gas in the underlying Oriskany. A sequence of Devonian shale, mudrock, and siltstone several thousand feet thick overlies the Huntersville and effectively seals the Oriskany and Huntersville reservoirs.

To the east, in the dry-gas segment of the Oriskany play, the Huntersville Chert is present above the Oriskany under much of the Appalachian Plateaus in West Virginia and adjacent southern Pennsylvania. Eastward into the Valley and Ridge, the Huntersville grades laterally into the Needmore Shale, which, with the younger Devonian shales, is an adequate seal for the Oriskany reservoirs in that part of the play.

Source Beds

The Middle Devonian to Lower Mississippian shale sequence contains at least eight regionally extensive dark-brown to black shales, which contain as much as 10 percent organic matter by weight. They appear to have been source beds for much of the oil and gas trapped in Upper Silurian to Pennsylvanian rocks of the basin, including strata of the Oriskany play. The Marcellus Shale, which closely overlies the Oriskany Sandstone and Huntersville Chert sequence, is the logical source bed for these reservoirs. However, younger Devonian black shales—the Geneseo Shale Member of the Genesee Formation, the Burket Shale Member of the Harrell Formation, the Middlesex Shale Member of the Sonyea Formation, the Rhinestreet Shale Member of the West Falls Formation, the Dunkirk Shale Member of the Perrysburg Formation, and the Huron Member of the Ohio Shale—may also have been source beds for some gas in the Oriskany Sandstone.

Timing and Migration

Sparse data suggest that gas migrated into the Oriskany Sandstone reservoirs during or just after the Alleghany orogeny during the closing phases of Paleozoic tectonism. The existence of several different sites of residual hydrocarbons within quartz grains or pores in the Oriskany Sandstone of eastern West Virginia, as noted by Bruner and Heald (1989), indicates that discrete pulses of migrating hydrocarbons had passed through the Oriskany in the Eastern Overthrust segment of the nonassociated dry-gas part of the play. Formation of extensive zones of fracture porosity in the otherwise well-cemented Oriskany during the Alleghany orogeny at about the peak of gas generation and migration would have assured the widespread occurrence of Oriskany gas pools associated with large and small anticlines within the area of the Eastern Overthrust belt in the central Appalachians.

Depth of Occurrence

In the western segment of the play, which contains oil and gas, gas occurs in the Oriskany Sandstone at a drilling depth of 1,600 ft in Ashtabula County in northeastern Ohio, about 1,950 ft near Conesville in southern Coshocton County in central Ohio, and about 4,600 ft in the Elk-Poca field near Charleston, W. Va. In the eastern segment of the play, which contains dry gas, many fields occupy the crests of anticlines, and drilling depths range from about 1,800 ft at the Wayne-Dundee field in Schuyler County, N.Y., to more than 8,500 ft along the Allegheny Front in northeastern Mineral County, W. Va. To the east in the Valley and Ridge, the top of the Oriskany Sandstone in synclines may exceed 10,000 ft in drilling depth, whereas the Oriskany may crop out on the sides of adjacent anticlines.

Exploration Status

The western oil and gas segment of the Oriskany play has been thoroughly explored, particularly in Ohio, where the Oriskany Sandstone has been penetrated by thousands of wells drilled to the basal Silurian Clinton sands. In contrast, considerable areas in the eastern dry-gas segment of the play remain largely unexplored, although most of the large anticlines under the northern part of the Appalachian Plateaus have been explored and their contained Oriskany pools and fields converted to gas storage.

Drilling for hydrocarbons in the Oriskany Sandstone began about 1899 in northeastern Ohio, where the sand was originally called the Jefferson gas rock or the Austinberg gas sand in Ashtabula County. Both oil and gas were found. In the early 1920's, drilling for Oriskany gas began in east-central Ohio near Cambridge in Guernsey County, where several large stratigraphic trap fields were quickly delineated. Drilling spread southward near the edge of the sheet of Oriskany Sandstone. By 1930, the first wells were drilled in the giant Elk-Poca field near Charleston, W. Va. Many wells in stratigraphic traps in the western segment of the Oriskany play had initial open flows in the 1-MMCF (million cubic feet) to 10-MMCF range. Pools ranged from a single well to the 160,000-acre Elk-Poca field (Cardwell and Avary, 1982), which produced more than 960 BCF (billion cubic feet) of gas before being converted largely to gas storage. A scattering of relatively small oil fields was found in the Oriskany, mainly in Ohio. The largest of the oil fields, the North Salem field in Guernsey County, which lies downdip from two small gas fields, was discovered in 1926. Some of the wells produced for more than 20 years. In general, oil is a rarity in the Oriskany play.

Drilling also began in the eastern dry-gas segment of the play in the Eastern Overthrust belt in 1930 with the discovery of the Wayne-Dundee field in Schuyler County in central New York and the Tioga field on the Sabinsville anticline in Tioga County in north-central Pennsylvania. Drilling spread quickly along the larger anticlines in the part of the Appalachian Plateaus where Oriskany wells had initial open flows in the 1 to 60 MMCF range. By the early 1950's, many Oriskany gas fields had been found in anticlinal traps from southern New York to northeastern West Virginia. As drilling sought deeper Oriskany pools eastward in the basin, the effective economic drilling depth by cable tools was reached, and in the late 1950's rotary drilling rigs were introduced to explore Oriskany Sandstone targets unreachable by cable tool rigs. From that time, most drilling for Oriskany gas in the dry-gas segment of the play has been by rotary methods. The use of wire-line electric well logging equipment and refinements in Common Depth Point (CDP) reflection seismic profiles enabled geologists and geophysicists to enhance their subsurface maps and to resolve many of the small-scale structural complexities in anticlinal Oriskany fault traps.

Analysis of detailed seismic profiles and deep exploratory drilling in the eastern part of the Appalachian Plateaus and in the adjacent Valley and Ridge led to revision of many ideas in Appalachian tectonics and the development of the concept of a basinwide megathrust system in which the gas-productive Oriskany anticlines are only a small part of a complex of décollements, imbricates, duplexes, and splay faults. By the late 1970's, most of the more obvious anticlines in the Appalachian Plateaus had been explored, and some Oriskany pools had been defined in the Valley and Ridge of southern Pennsylvania and adjacent Maryland and West Virginia. At present, exploration for Oriskany gas continues in the eastern part of the Appalachian Plateaus and in the adjacent part of the Valley and Ridge from northeastern Pennsylvania to west-central Virginia.

In the Appalachian Plateaus, field sizes range in ultimate production from about 5 to 960 BCF in West Virginia (Cardwell and Avary, 1982) to large, complex fields such as the Leidy field in Clinton County, Pa., with a cumulative production of more than 160 BCF and the Punxsutawney-Driftwood field with a cumulative production greater than 383 BCF (Harper, 1984). Fields in the Valley and Ridge tend to be smaller in ultimate yield and are usually in the 5- to 30-BCF range. Along the eastern side of the dry-gas play, thermal maturation of the Oriskany and associated rocks is in the range of CAI 4.0 to 4.5, which approaches the limit for commercially exploitable volumes of gas in the Oriskany play. However, an area of more than 32,000 mi^2 in the eastern part of the Oriskany play where drilling depths are in the 8,000- to 12,000-ft range and anticlinal structures are complex remains little explored. The size and extent of zones of fracture porosity within structures will control the volume of gas available to a specific well. The area can be classed as a high-risk drilling area.

Lower Silurian Sandstone Play

The Lower Silurian sandstone play underlies about 117,500 mi^2 in the northern half of the Appalachian Plateaus and the adjacent Valley and Ridge (fig. 10). The play is bordered on the north and east by outcrops of several Lower Silurian sandstones except where Lake Erie intervenes. The western boundary of the play is defined in the subsurface at the depositional termination of several Lower or lower Middle Silurian sandstones in Ohio and Kentucky. The southern boundary is arbitrarily chosen at the feather edge of the Clinch Sandstone in Tennessee.

The Lower Silurian sandstone play includes several of the more quartzose marine sandstones in the vast Late Ordovician and Early Silurian Queenston delta. These sandstones include the sandstones of the Medina Group of western New York and northwestern Pennsylvania; the Tuscarora Sandstone of Pennsylvania, Maryland, northern Virginia, and contiguous West Virginia; the Clinton sands of Ohio and western West Virginia; the Middle Silurian Keefer Sandstone and equivalent Big Six sand, mainly in eastern Kentucky; and the Clinch Sandstone of southern Virginia, southeastern Kentucky, and northeastern Tennessee.

The Lower Silurian sandstone play may be subdivided into four general segments. A western shallow-oil and associated-gas segment occupies much of east-central Ohio (Area 1, fig. 10), whereas an eastern deeper nonassociated dry-gas segment extends from New York south to eastern Tennessee (Areas 2 and 3, fig. 10). The dry-gas segment may be subdivided into a western section under the Appalachian Plateaus in which gas has been produced from Lower Silurian reservoirs (Area 2), a speculative eastern section, mainly in the Valley and Ridge (Area 3, fig. 10), in which gas has not been found to date in commercially exploitable quantity except in the vicinity of the Devils Elbow field in Centre County, Pa., and the area of Keefer-Big Six sand of northwestern West Virginia and adjacent Kentucky (Area 4, fig. 10).

Reservoir Rocks

Reservoir rocks of the Lower Silurian sandstone play are dominantly quartzose sandstones and siltstones, which accumulated in a variety of shallow-marine to delta-plain environments associated with the large Queenston tectonic fan-delta complex in the northern half of the Appalachian

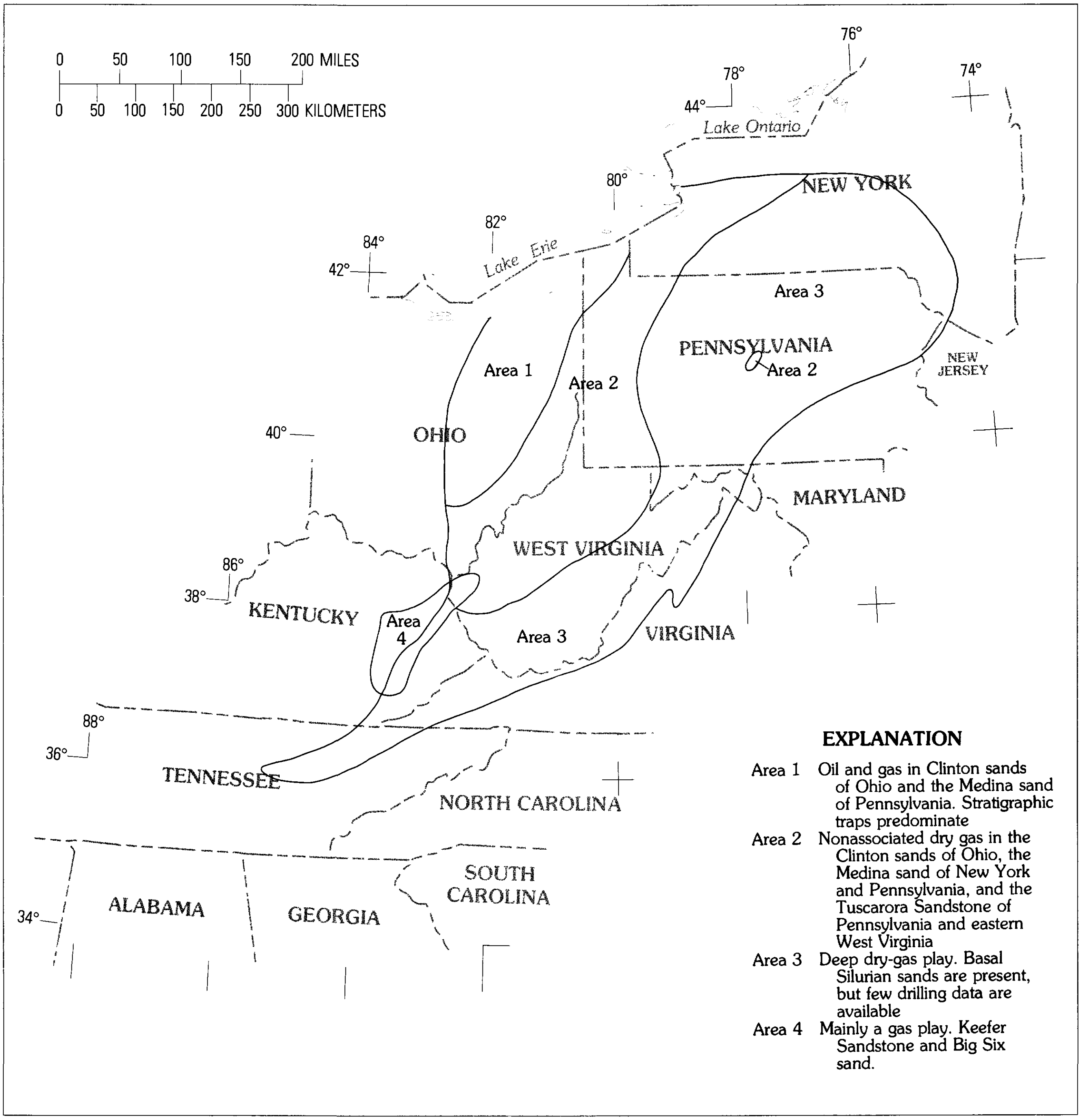

Figure 10. The Lower Silurian sandstone play. This play consists of two main segments. Area 1 is a western shallow-oil and associated gas segment. The second main segment comprises Areas 2 and 3, which are a deeper, nonassociated dry-gas segment. Area 4 is a separate unit of sands slightly younger than those of Area 1.

basin. Sheet sands, offshore bars, and beach sands, marine and terrestrial channel-filling sands, and crevasse-splay and point-bar sands are found within the play. Marine reservoir rocks predominate in the west, whereas fluvial reservoirs typical of delta-plain accumulation predominate to the east. In the western segment, the grain size of reservoir siliciclastics, which has been only moderately altered by diagenesis, ranges from fine sand to medium silt. Porosity ranges from 10 to 25 percent, and permeability is commonly greater than 1 mD. Near Charleston, W. Va., the gas-productive part of the Tuscarora Sandstone has porosity ranging from 3 to 12 percent, horizontal permeability from less than 0.10 to 750 mD, and vertical permeability from less than 0.10 to 240 mD (Bruner and Heald, 1982). To the east, in the dry-gas segment of the play, grain size increases, and locally some coarse sand and granules are present. Diagenesis and cementation have modified much of the original porosity and developed considerable secondary porosity by solution of chemically unstable mineral grains (Laughrey and Harper, 1986). The reservoir rocks in the dry-gas segment of the play are much tighter, with porosity ranging from less than 2 to 12 percent and permeability in the range of 0.2 to 0.01 mD. Although the basal Silurian sandstone reservoirs are generally considered dry-gas sands, nonproducible saline water commonly fills a large percent of the pore space in the finer grained sandstone and siltstone.

Traps and Seals

Most of the traps in the western and central parts (Areas 1 and 2, fig. 10) of the Lower Silurian sandstone play are stratigraphic barriers to permeability or stratigraphic traps with slight structural modification. The pinchout of effective porosity and permeability associated with depositional changes along channels, bars, and beaches is the most common type of trap. In the eastern part of the play, which includes the Eastern Overthrust belt, thrusting and folding involve the basal Silurian rocks. Structural traps with zones of closely spaced fracture porosity become dominant. Both regional joint systems and tectonically induced fractures are traps. The regional joints are commonly open and are more important in trapping gas than the fractures are (Wescott, 1982).

Throughout the play area, the Lower Silurian sandstones are overlain by a sequence of soft, silty clay shale and mudrock with small amounts of interbedded sandstone, siltstone, and limestone. Commonly the shale appears to be an adequate seal in most of the play. At many localities in the western part of the play, several sheets of marine sandstone are separated by beds of silty shale. Although many of the sandstones may produce gas or oil or both, scant production data suggest that natural vertical communication does not exist between adjacent reservoirs. In most of the western, oil and associated-gas segment of the play, hundreds of feet of massive dolomite and dolomitic limestone overlie the basal Silurian siliciclastic rocks and form a regionally extensive seal for this part of the play from Lake Erie south to eastern Kentucky and adjacent West Virginia.

Source Beds

Data on source rocks for hydrocarbons reservoired in the Lower Silurian sandstone play are scant and somewhat conflicting. The several sandstones in the western part of the play grade westward and intertongue with a sequence of gray and greenish-gray marine shale, the Cabot Head Shale of Ontario (Knight, 1982). The Lower Silurian sandstones are overlain by grayish-red to very dark gray marine shale in the Valley and Ridge in Pennsylvania and adjacent States. The dark, very fossiliferous Rochester Shale, as much as 50 ft thick, lies stratigraphically close above the Keefer Sandstone from Pennsylvania to central West Virginia. Presumably, some of these marine shales may have been sources for some hydrocarbons found in the Lower Silurian siliciclastic reservoir rocks.

The brownish-black to black Middle to Upper Ordovician black shale facies, the "Utica facies" and lithologic equivalents, also contributed hydrocarbons to the Lower Silurian sandstone play (Cole and others, 1987; Laughrey, 1989). Laughrey (1989) also found traces of hydrocarbons from Middle Ordovician carbonate source rocks in some Lower Silurian reservoir rocks in western Pennsylvania. These data suggest several sources for oil and gas.

Timing and Migration

Cole and others (1987) suggested that the maximum generation of oil and gas from Ordovician and Devonian source beds was during the latest Pennsylvanian and Permian. This time interval corresponds to part of the Alleghany orogeny when structural traps and much fracture porosity were developed in the rocks of the Eastern Overthrust belt. Consequently, many traps were available for early filling, as recently generated hydrocarbons moved from the deeper parts of the Appalachian basin westward into areas of lower pressure and cooler strata. Gas that migrated into the reservoir at an early time may have blocked later cementation of the strata.

Depth of Occurrence

The upper reservoirs in the oil and associated-gas segment of the play lie at drilling depths of about 2,500 ft near Cleveland in northern Ohio, 1,800 ft east of Columbus in central Ohio, and 3,200 ft in southern Ohio. Eastern regional dip brings the upper reservoirs along the east edge of the segment to drilling depths of about 3,100 ft near Erie in northwestern Pennsylvania and to more than 6,000 ft along the Ohio River in southeastern Ohio. Reservoir sands in the nonassociated dry-gas segment of the play occur at drilling depths of about 1,800 to 1,900 ft in central New York, 10,000 ft in the Devils Elbow field of Centre County, Pa., 12,500 ft near the top of the Chestnut Ridge anticline in southwestern Pennsylvania, and 6,500 to 7,200 ft in the vicinity of Charleston in central West Virginia. Within the Eastern Overthrust belt, drilling depths to targets within the Lower Silurian sandstone play will vary greatly, depending upon the position of the targets in relation to structures in a specific thrust sheet.

Exploration Status

Much of the oil and associated-gas segment of the Lower Silurian sandstone play has been well explored by tens of thousands of wells, and some parts have undergone several drilling campaigns since exploitation began in the middle 1880's. Cable-tool wells were closely spaced in much of the shallower part of the play, and since the introduction of rotary drilling and hydraulic stimulation techniques, much infill drilling has further increased the drilling density. In contrast, much of the eastern dry-gas segment of the play remains unexplored. In the Valley and Ridge, for example, less than 500 wells have penetrated the Tuscarora and Clinch Sandstones in an area of about 45,000 mi^2.

Drilling for gas and oil in the Lower Silurian Clinton sands began in central Ohio in the 1880's and spread rather rapidly to northern and southern Ohio. The Cleveland gas field along Lake Erie's south shore was drilled during World War I. Although the initial yield of oil from Clinton wells was not large (the greatest well flow prior to hydraulic treatment was 550 barrels per day; Cottingham, 1951), Clinton wells are noted for their long productivity. Drilling for gas in the Lower Silurian play began in Erie County, N.Y., in the 1850's and spread eastward to Seneca County in central New York by 1885. Although several fields were developed for dry gas, the low permeability of these shallow sandstones inhibited extensive drilling in western New York. Gas fields were found widely in Ohio in the oil and associated-gas area during the 70 years following the drilling of the first Clinton gas wells near Lancaster in the 1880's. During the 1930's, several exhausted Clinton gas fields were converted to gas storage to augment local gas supplies during periods of peak demand. With the introduction of gas from the Gulf Coast and other sources by pipeline in the late 1940's, more than a dozen gas storage fields were developed in the Clinton sands of northern and central Ohio. At about the same time, several old Medina gas fields in New York were also converted to gas storage.

By 1950, geologists and drillers had demonstrated that a large area of Ohio's eastern counties and adjacent Pennsylvania was underlain by low-permeability, tight Clinton sand, Medina sand, or Whirlpool Sandstone that contained small amounts of oil or gas in almost every test well. However, these wells could not be stimulated to commercial productivity by "shooting" techniques employing nitroglycerin or other explosives. Although the sandstones had adequate porosity, in the range of 5 to 15 percent, which is sufficient to contain considerable gas or oil, the permeability was too low to permit adequate flow of hydrocarbons to the well bore for successful commercial exploitation.

The introduction of well stimulation by hydraulic fracturing techniques in the Appalachian basin in the mid 1950's drastically altered the Clinton-Medina production history, particularly in the tighter reservoir sands in eastern Ohio. Commonly, wells having small initial yield were stimulated into productive wells by hydraulic fracturing. Gas production rates increased from a few thousand cubic feet to several million cubic feet per day. Oil production increased from a small trace of oil to more than 100 barrels per day after stimulation. The East Canton field of Stark and Carroll Counties, Ohio, one of Ohio's better Clinton oil fields, has produced more than 50 million barrels of oil from the tight sand area, which was considered a dry area before the introduction of hydraulic-fracturing stimulation. At present, exploratory drilling in the oil and associated-gas segment of the Lower Silurian sandstone play is mainly along the east edge of the play from northwestern Pennsylvania southwest to Washington County, Ohio, along the Ohio River. In general, the volume of gas recovered from the Clinton sands in this area decreases downdip, from north to south.

Well stimulation by hydraulic fracturing also revitalized exploration for nonassociated dry gas in the eastern segment of the play. Reservoir rocks with 4 to 6 percent porosity and 0.01 to 0.2 mD permeability (Laughrey and Harper, 1986) responded well to hydraulic stimulation by both foam and gas. A large area from central New York through western Pennsylvania to central West Virginia has been explored in some detail during the past 30 years. Infill and stepout drilling have extended and amalgamated many of the older Medina gas fields in Chautauqua and Erie Counties, N.Y. The area is shown as one large field, the Lake Shore field, covering Chautauqua County and parts of adjacent Cattaraugus and Erie Counties (New York State Department of Environmental Conservation, 1986). Similar enlargement and consolidation of older fields have taken place in northwestern Pennsylvania and contiguous Ohio. A scattering of deep gas wells has been drilled in the play from north-central Pennsylvania to southern West Virginia. The large nonflammable component in Lower Silurian gas is of concern to explorationists drilling in the central and eastern parts of the nonassociated dry-gas segment of the play. In Devils Elbow Tuscarora Sandstone field, Centre County, Pa., only 35 percent of the well's gas from the Tuscarora Sandstone was flammable. The remaining 65 percent was largely nitrogen (Harper, 1981, p. 53). In contrast, in south-central West Virginia the carbon dioxide content of gas from the Tuscarora ranges between 12 and 80 percent (Patchen, 1968). Separating the gas stream into its several components and selling them individually may be an alternative to abandoning a well because it has a large percent of nonflammable gas.

The potential for finding additional undiscovered oil is low because much of the known oil-productive area has been well explored. Obviously, some additional volume of oil will be discovered by infill and wildcat wells. However, the amount will not be large, considering the initial yield of recently drilled Clinton wells, mainly in the tighter sands along the east side of the oil and associated-gas segment of the play. Initial yields range from 1 to 10 barrels per day in this area, with the majority near the lower end of the range.

The potential for the natural gas resource is considerably better, although the greatest part of the resource will be found in the nonassociated dry-gas segment of the play. The unexplored part of the play is large, and many anticlines are available, particularly in the Valley and Ridge. Inhibiting factors for natural gas recovery include decreased porosity and permeability with greater depth of burial, restriction of porosity to zones of fractures in a dominantly impermeable rock, and increasing degree of thermal maturation eastward with depth, as shown by greater CAI numbers, to an economic extraction limit of about CAI 4.5 to 5 on the east side of the Valley and Ridge or locally under the west edge of the Blue Ridge thrust sheet.

Ordovician Carbonate Shelf Play

The Ordovician carbonate shelf play includes carbonate rocks of Middle and Late Ordovician age throughout the Appalachian basin. The rocks of the play underlie the Queenston delta siliciclastic rocks in the northern part of the basin and grade laterally into siliciclastic rocks to the southeast in the Valley and Ridge from New York to Alabama. The play is underlain by dominantly dolomitic rocks of the Knox play beneath the Middle Ordovician Knox unconformity except in an area from central Pennsylvania to northern Virginia, where deposition was continuous from Early to Middle Ordovician and the unconformity does not exist. The Ordovician carbonate shelf play underlies about 176,000 mi^2 of the Appalachian basin (fig. 11).

In the western part of the basin, particularly along the east side of the Cincinnati arch and in the Cumberland saddle, the play is largely stratigraphic. To the east and deeper in the basin, in the Valley and Ridge of southwest Virginia and adjacent Tennessee, the play is structural, and fracture porosity is dominant. East and southeast of Lake Ontario (Area 3, fig. 11), the upper part of the Trenton Limestone contains a nonconventional shale-gas play (Orton, 1899) in which gas is derived from the overlying black Utica Shale source beds. Recent drilling in central New York has disclosed dolomitized carbonate rocks associated with subtle structural traps in the Ordovician carbonate shelf play (Rothman, 1989). Although the rocks of the play range in thickness from less than 500 ft to more than 1,500 ft (Miller, 1975), only a small percent are of reservoir quality at any specific locality.

Similar to other plays in the basin, the Ordovician carbonate shelf play may be subdivided into a western oil and associated-gas play of about 6,900 mi^2 lying west of the 2.5 CAI isograd and a larger nonassociated dry-gas play of 169,100 mi^2 to the east between the 2.5 and 4.5 CAI isograds (fig. 11).

Harris and others (1978) suggested that the CAI isograd pattern was developed largely before the thrusting and folding of the Alleghany orogeny. Consequently, the isograds cross the present structural grain of the Appalachian basin at an acute angle, particularly in the southern Appalachians, which is the only part of the play where oil is found in the Valley and Ridge. In contrast, to the north, the Valley and Ridge rocks all lie in the more mature dry-gas segment of the play.

Reservoir Rocks

Reservoir rocks of the Ordovician carbonate shelf play are dominantly fossiliferous calcarenites that are commonly associated with small disconformities. Porosity is enhanced locally by karstification or fracturing. In part of Ohio and in central New York, dolomitization appears to have enhanced porosity in the carbonate sequence. Reefal or karstic reservoirs in the play commonly have good porosity and permeability. Consequently, they form oil or gas reservoirs that quickly decline to small-volume stripper oil wells or are drowned by encroaching saltwater.

In the Valley and Ridge of southwest Virginia, carbonate rocks have been shattered and fractured in zones associated with thrust faults. Some of the oil in the Rose Hill and Ben Hur fields of Lee County, Va., may have been indigenous to the carbonate rocks and may have been released to newly formed fracture porosity reservoirs during an episode of thrusting.

In the nonconventional shale-gas area of eastern New York, beds of black shale in the Trenton Limestone appear to be both source and reservoir, as is the case with the younger Devonian gas shales. The interbedded limestone appears to act as an impermeable seal or a porous reservoir.

Traps and Seals

Except for areas of fracture porosity in structural traps, traps in the Ordovician carbonate shelf play are stratigraphic or are stratigraphic modified by small-scale structural features. Porosity and permeability decreasing to impermeability both horizontally and vertically seal hydrocarbons in these reservoirs. Commonly, sequences of interbedded shale and dense limestone are effective seals in much of the play area. Locally in the Cumberland saddle, gravity separation was effective, and saltwater underlies oil or gas. In this area, sudden release of reservoir pressure during drilling may permit rapid encroachment of saltwater, which can flood the well before recovery of much of the reservoir's contained hydrocarbons.

In the Rose Hill field of southwest Virginia, oil in the play was trapped beneath the Pine Mountain thrust sheet (Miller and Fuller, 1954). However, the seal was shattered in the vicinity of fensters in the thrust plate, and drilling near oil seeps in and adjacent to the fensters led to the discovery and development of the field.

In the shale-gas area of northeastern New York, beds of Trenton limestone appear to function as seals rather than

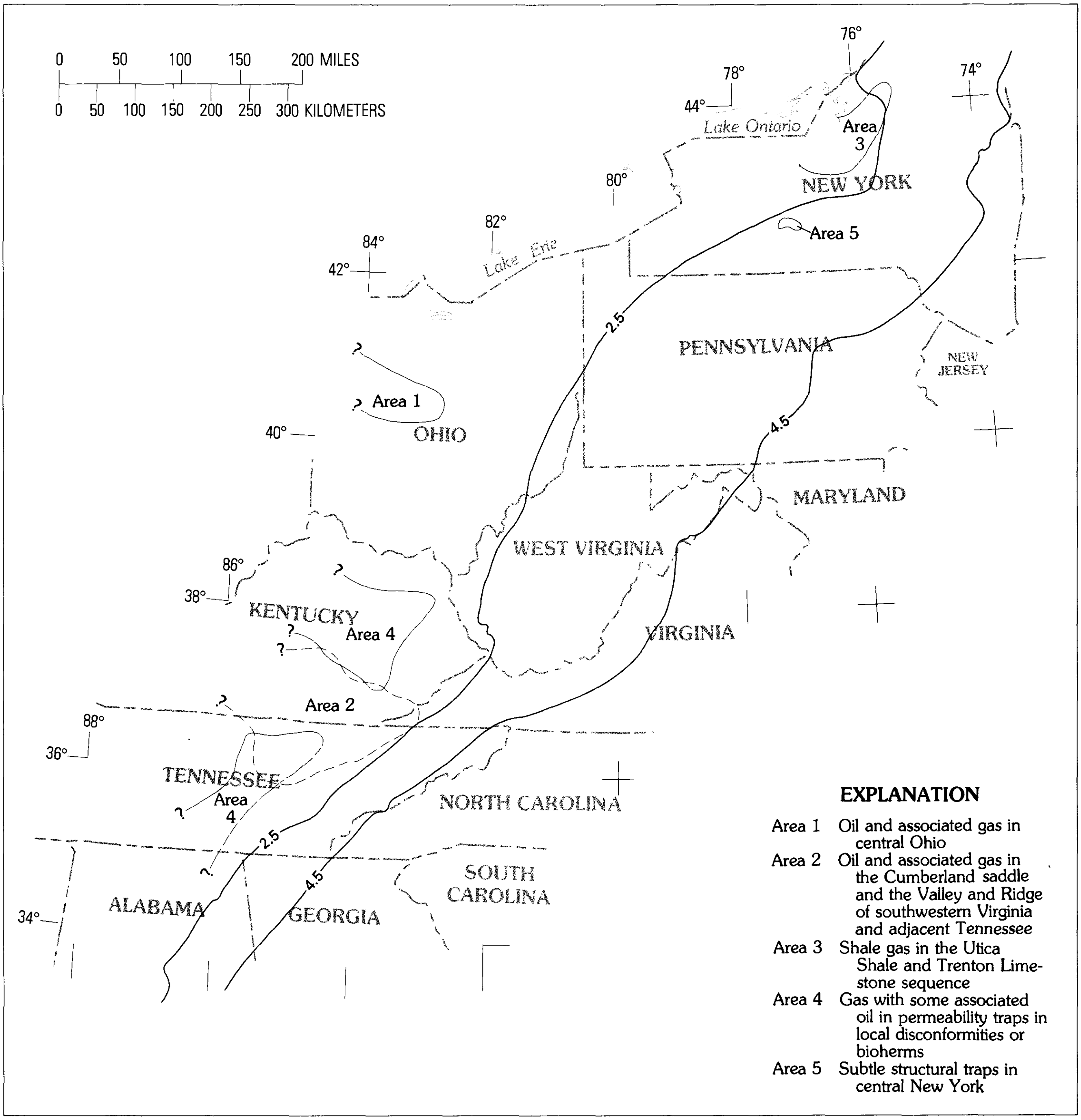

Figure 11. The Ordovician carbonate shelf play. The play is divided into a western oil and associated-gas segment of about 6,900 mi^2 lying west of the CAI 2.5 isograd and a larger nonassociated dry-gas segment of 169,100 mi^2 to the east between the 2.5 and 4.5 CAI isograds.

reservoirs. In this area the beds of shale and limestone are fractured, and the seals are incomplete. The fracturing occurred possibly during isostatic rebound from loading by Pleistocene continental glaciers. Gas seeps to the surface at many places, and drilling near conspicuous seeps led to the earliest discovery of pools and fields in this part of New York.

Source Beds

Black shales of the "Utica facies," rich in organic matter, are the logical source beds for oil and gas reservoired in the carbonate rocks of the Ordovician carbonate shelf play. In the Valley and Ridge, the black source beds, the Antes Shale of Pennsylvania and Maryland, the Paperville Shale of Virginia, the Blockhouse Shale of Tennessee, and the Athens Shale of Alabama, interfinger westward with carbonate rocks. Continued subsidence of the basin brought the black shales structurally deeper than their carbonate-rock equivalents. Hydrocarbons generated by thermal maturation migrated updip, possibly assisted by gravity-driven brines, into the areas of reefal and karstic reservoir rocks under the Appalachian Plateaus, particularly in the Cumberland saddle area. The Utica Shale and its lithologic equivalent, the Point Pleasant Formation of Ohio, overlie the Ordovician carbonate shelf play from New York to northwestern Ohio. Cole and others (1987) and Wallace and Roen (1988) have discussed the petroleum potential of the regionally extensive "Utica facies" and consider it one of the major source rocks of the basin. In the western part of the basin along the flank of the Cincinnati arch, CAI isograds, which are in the 1.5 to 2.0 range, indicate that the source beds are capable of yielding oil and gas, whereas to the east, the isograd range of 2.5 to 4.5 suggests that the source beds released oil earlier and have since generated large amounts of dry gas.

In the southwestern part of the basin, because of extensive Middle Devonian erosion, the Upper Devonian and Lower Mississippian black Chattanooga Shale lies upon the lower part of the Upper Ordovician carbonate sequence. In this area along the east flank of the Cincinnati arch, the Chattanooga Shale may have been the primary source of oil and gas in the Ordovician carbonate shelf play.

Timing and Migration

Cole and others (1987) suggested that migration of hydrocarbons from eastern source beds to western reservoir rocks in the Ordovician carbonate shelf play probably occurred in the Late Pennsylvanian and Permian during the onset of the Alleghany orogeny. Migration of hydrocarbons at this time would have made oil and gas readily available to fill structural traps generated by tectonic activity in the Eastern Overthrust belt segment of the play during the orogeny. Early arrival of hydrocarbons would have filled the fracture porosity systems with oil or gas and prevented their later cementation by calcite or other minerals.

Depth of Occurrence

In the Cumberland saddle and along the east flank of the Cincinnati arch from Ohio to Tennessee, oil and gas occur at depths ranging from less than 100 ft to more than 3,000 ft in the Ordovician carbonate shelf play. In the shale-gas fields of northeastern New York, drilling depths to the gas productive zone range from 500 ft in the north to more than 2,600 ft in the south. Gas has recently been found at about 7,500 ft in subtle traps in the play adjacent to the south end of Seneca Lake (Rothman, 1989). Oil and gas occur at depths of 1,000 to 2,000 ft in structural traps in the Rose Hill and Ben Hur fields of Lee County in Virginia's Valley and Ridge. Noncommercial amounts of gas have been found in the Valley and Ridge and the eastern part of the Appalachian Plateaus in structural traps in the nonassociated dry-gas segment of the play at depths as great as 5,000 ft. The porous zones containing the gas are near the crest of anticlinal traps, whereas the depth to the top of the play in adjacent synclines might be several times greater.

Exploration Status

Much of the western oil and associated-gas segment of the Ordovician carbonate shelf play has been relatively well explored, particularly along the east flank of the Cincinnati arch and the Cumberland saddle, where oil wells were first drilled in the late 1820's (Jillson, 1947). Much of the remainder of this segment of the play has been little explored, with the exception of the oil fields in Lee County, Va., which have produced about 300,000 barrels of oil mainly from fractured Trenton Limestone reservoirs during the past half century. Scant drilling has been done in the more deeply buried dry-gas segment of the play from central New York to central Alabama.

The first recorded occurrence of oil from the Ordovician carbonate shelf play was in March 1829 in the Cumberland saddle when Emerson and Stockton's salt well on Little Renox Creek, near Burkesville, Cumberland County, Ky., blew in and produced about 2,500 barrels of oil per day for about a week (Jillson, 1947). By 1860 Stockton's well, known locally as the Old American well, had produced more than 50,000 barrels of oil from the upper Sunnybrook sand (Jillson, 1947). A small number of wells drilled just after the Civil War from central Kentucky to northern Alabama found oil in the Ordovician carbonate reservoirs and began a series of local drilling campaigns in the Cumberland saddle and along the eastern flank of the Cincinnati arch of Kentucky and Tennessee that has continued sporadically to the present.

In the early 1880's, drilling to the Trenton Limestone on the crest of the Cincinnati arch at Findlay, Ohio, opened the giant Lima-Findlay oil field, which produced more than 390 million barrels of oil in the Ohio segment of the field (Cottingham, 1951). The excitement produced by large oil wells in the Lima-Findlay field induced considerable drilling down the eastern flank of the Cincinnati arch and into the western part of the Appalachian basin in central Ohio. Because the dolomitic and karstic reservoir facies in the Trenton Limestone of northwestern Ohio is absent in central Ohio, few of these test wells found even small amounts of oil or gas, and none was successful. Recently, however, with the drilling of many wells to the Trempealeau Formation and Rose Run Sandstone in the underlying Upper Cambrian and Lower Ordovician Knox play, gas has been found in the Ordovician carbonate shelf play in central Ohio north of Columbus (Wickstrom and Gray, 1985). Data on the reservoir characteristics are scant.

Having observed many local gas seeps and having been encouraged by stories of fortunes being made from oil and gas wells in the Trenton Limestone near Lima and Findlay in western Ohio during the 1890's, citizens of Oswego and adjacent counties in northeastern New York began drilling for gas in the area between Lake Ontario and the Adirondack Mountains (Orton, 1899). During the next two decades, several large gas fields were developed in the Trenton Limestone. Orton (1899) demonstrated that much Trenton gas in this part of New York came from nonconventional gas-shale reservoirs rather than from conventional carbonate reservoir rock. Production histories and well characteristics for the Trenton gas pools in northeastern New York are similar in many respects to the Devonian gas shales of the central Appalachians. Well cuttings from one Trenton gas field that were studied recently by A.M. Van Tyne (oral commun., 1990) showed that some of the black shale beds reported in the Trenton Limestone are actually porous zones of fossiliferous limestone. Interbedded impermeable limestones seal the gas-filled zones. Consequently, Orton's shale-gas play (area 3) has aspects of both a nonconventional shale-gas play and a conventional stratigraphic-trap play. Most of the Trenton gas fields in northeastern New York have been long abandoned. However, as recently as 1966, the Blue Tail Rooster field in Cayuga County, N.Y., produced gas from the Trenton Limestone. More recently, deep drilling to the Trenton and Black River Limestones of the play in the Finger Lakes area of central New York has encountered gas in dolomitized zones associated with subtle structural traps (Rothman, 1989). As yet, data are not available to identify the extent of the area where such traps may exist.

Butts (1927, p. 10) noted oil seeps in the vicinity of fensters in the Pine Mountain thrust sheet in the Valley and Ridge of Lee County, Va. Drilling began in the area of the Rose Hill oil field in 1942. Several small oil pools have been found in which zones of fracture porosity are associated with structural traps beneath the Pine Mountain thrust sheet near Rose Hill and Ben Hur in Lee County. Although the initial yield of some wells was spectacular, most wells rather quickly passed into stripper-well status. Water encroachment has been a problem in the area. To date, Virginia's oil production, almost exclusively from the Ordovician carbonate shelf play, has amounted to about 300,000 barrels. The petroleum geology of the Rose Hill area has been discussed in considerable detail by Miller and Brosge (1954, p. 205–227) and Miller and Fuller (1954).

The potential of the Ordovician carbonate shelf play is difficult to assess because many of the older well and pool data were never recorded or have been lost. Much of the area under the Appalachian Plateaus and the Valley and Ridge, excepting the Cumberland saddle and Lee County, Va., has been sparsely explored. Much of the oil in the Cumberland saddle and along the flank of the Cincinnati arch occurs in relatively small isolated pools. Since 1860 the Middle and Upper Ordovician rocks in this area have produced about 10 million barrels of oil (Bond and others, 1971), but much of the oil came from the Cincinnati arch area west of the Appalachian basin. Oil production from Virginia's Valley and Ridge is about 300,000 barrels, only about one-third of the minimum 1-million-barrel field-size cutoff established for play analysis evaluation in the U.S. National assessment (U.S. Geological Survey and U.S. Minerals Management Service, 1988, p. 27–46). Data for gas production are scant, particularly for the Trenton gas shales of New York. The main problems in attempting to assess the hydrocarbon potential of the Ordovician carbonate shelf play are the absence of well and pool data both old and new, the lack of deep drilling to the Trenton and Black River rocks in much of the area, and the unavailability of regional seismic data for evaluation of areas of subtle subsurface traps in the play.

Upper Cambrian and Lower Ordovician Knox Carbonate Shelf Play

The Knox play includes a sequence of subtidal to supratidal dolomite, dolomitic limestone, and limestone with small amounts of intercalated quartz sand and silt, chert, shale, and anhydrite. Dolomite is the dominant lithology of the sequence, which is generally several thousands of feet thick. Rocks of the Knox play underlie more than 176,500 mi^2 of the Appalachian basin from New York to Alabama and from the eastern flank of the Cincinnati arch east to the 4.5 CAI isograd in the Valley and Ridge or locally under the western edge of the Blue Ridge (fig. 12). The play is mainly a karstic-reservoir stratigraphic trap except for some structural traps in the Valley and Ridge of Tennessee and Virginia. At places along the Middle Ordovician unconformity at the top of the Knox play, some fine- to coarse-grained reservoir sandstones have formed where solution has dissolved the carbonate rock and enhanced the porosity and permeability of the siliciclastic residue. Nomenclature of rocks within the Knox play is complicated because different names have been applied to a specific stratigraphic unit in different parts of the basin (Harris, 1975). In general, the play contains all the strata below the Middle Ordovician unconformity to the base of the Copper Ridge Dolomite of the Knox Group of eastern Tennessee (or its stratigraphic equivalents).

The Knox play is herein subdivided into a relatively shallow western oil and associated-gas play about 41,000 mi^2 in extent and a deep eastern dry-gas play between the 2.5 and 4.5 CAI isograds in an area of about 163,900 mi^2 (fig. 12). In the oil and gas segment and along the west side of the dry-gas segment, stratigraphic traps or combination traps are dominant. To the east in most of the nonassociated dry-gas segment of the play, structural traps with zones of fracture porosity are paramount.

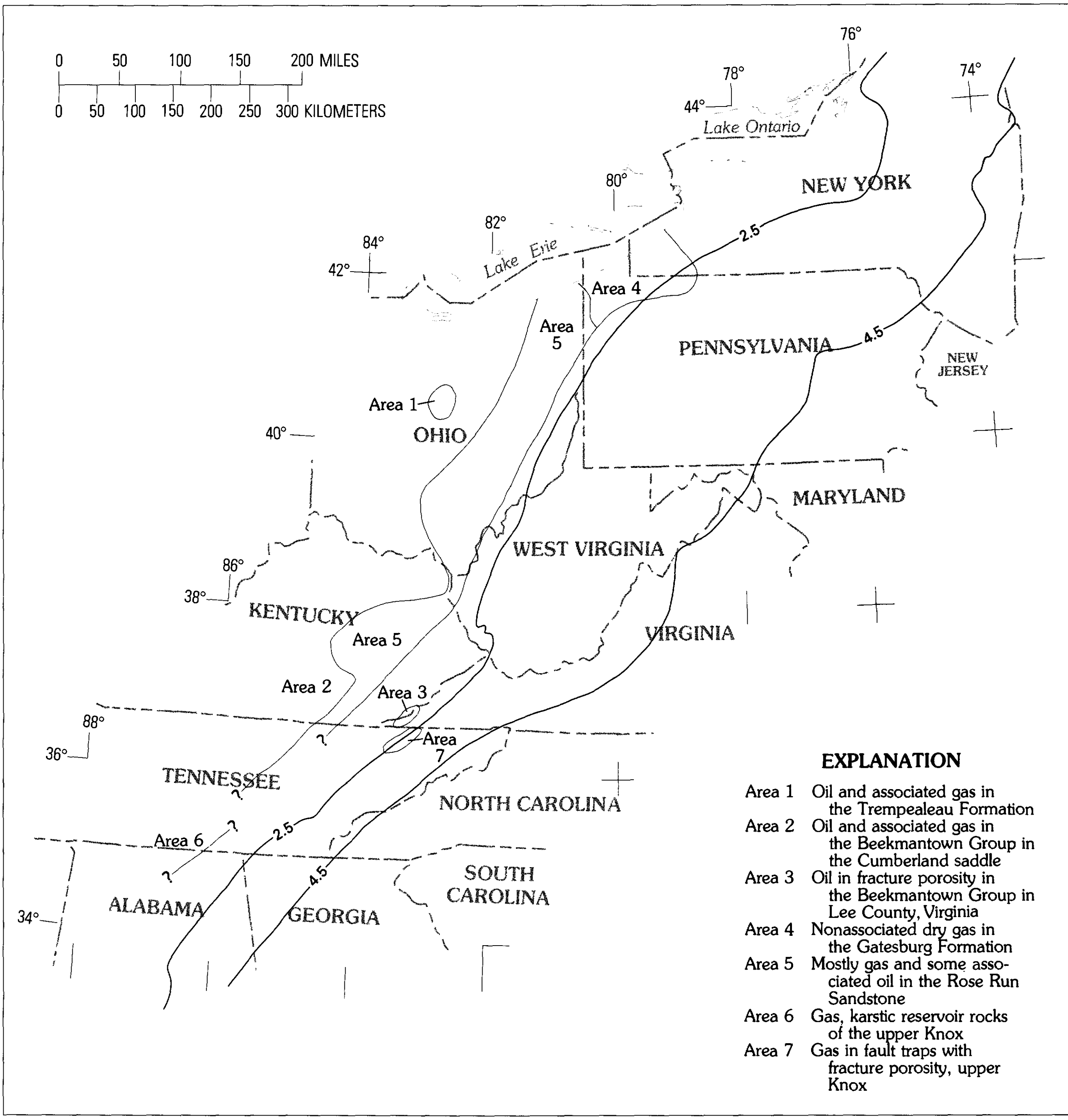

Figure 12. The Upper Cambrian and Lower Ordovician Knox carbonate shelf play. The play is divided into a relatively shallow western oil and associated-gas segment of about 41,000 mi^2 and a deep eastern dry-gas segment between the 2.5 and 4.5 CAI isograds in an area of about 163,900 mi^2.

Reservoir Rocks

In the oil and gas segment of the play, karstic erosional hills of Upper Cambrian dolomite with paleotopographic relief of as much as 150 ft lie directly below the Middle Ordovician unconformity (Dolly and Busch, 1972). They are the most important Knox play reservoirs in Ohio. The vugular open-textured dolomite in these residual hills has produced about 40 million barrels of oil in Morrow and contiguous counties in central Ohio. To the south, similar karstic reservoirs are associated with the Middle Ordovician unconformity in the Cumberland saddle of southern Kentucky and adjacent Tennessee. A major siliciclastic reservoir, the Rose Run Sandstone, extends south from northeastern Ohio at Lake Erie to Brown County along the Ohio

River in southwestern Ohio (Janssens, 1973, p. 26, fig. 16). The best development of productive Rose Run Sandstone is in Coshocton County in east-central Ohio (Atha, 1981; Coogan and Maki, 1988). Downdip to the east and south, the Rose Run is tightly bound by carbonate cements. Reservoirs are a combination of calcareous siliciclastic and sandy carbonate strata in the western part of the nonassociated dry-gas segment of the Knox play. To the east, structural traps with associated fracture porosity become dominant.

Traps and Seals

In the western part of the play, karstic solutional stratigraphic traps predominate. Some are a combination of stratigraphic trap modified by small-scale folding. Structural traps predominate to the east. Fracture porosity becomes progressively important eastward into the thicker broken formation zones in faulted sequences of the play in the Valley and Ridge, and locally beneath the Blue Ridge.

Shaly residuum, calcareous shale, and massive impermeable carbonate rocks in the lower part of the Ordovician carbonate shelf play are seals for the Knox play, particularly in central and north-central Ohio. Locally, the seal is incomplete, and Knox oil appears to have leaked into the basal units of the overlying play. In the Eastern Overthrust belt, thrust-faulted sequences of carbonate and fine-grained siliciclastic strata in the Rome Formation and Conasauga Group in the hanging-wall block of thrusts form seals for Knox traps in the footwall block.

Source Beds

The identification of source beds for oil and gas trapped in the Knox play is somewhat enigmatic. The greenish-gray to gray shale of the Wells Creek Formation at the base of the Ordovician carbonate shelf play from central Ohio to central Tennessee is low in organic carbon and does not appear to be an adequate source rock. Data from Cole and others (1987) strongly suggest that the Middle to Upper Ordovician black shale, the "Utica facies" of Wallace and Roen (1988), is the main source rock for Knox oil and gas in central Ohio. In the Cumberland saddle and southward along the eastern side of the Nashville dome in Tennessee, the Upper Devonian Chattanooga Shale is a possible source for oil and gas in the upper part of the Knox play. Laughrey (1989) suggested that Black River Group carbonates may have generated some oil and gas in Medina sand reservoirs. Because the Black River carbonate rocks make up the lower part of the Ordovician carbonate shelf play, they may also have contributed some hydrocarbons to Knox reservoirs just beneath the Middle Ordovician unconformity. Older shales below the Knox play do not appear to be good source rocks except possibly for some dark-gray to grayish-black shaly rocks in the western part of the Rome trough.

Timing and Migration

Cole and others (1987) suggested that oil generation and migration most probably occurred in the western part of the play during the late Paleozoic Era. However, a sufficient thickness of post-Ordovician sediments had accumulated at many places in the eastern part of the basin to have permitted some gas and oil generation earlier in the era from the more deeply buried source beds such as the "Utica facies." If it is assumed that migration of fluids began before and continued during the formation of structural traps during the Alleghany orogeny, an early filling of porous zones in the traps would be assured.

Depth of Occurrence

Gas and oil occur in the Lower Ordovician part of the Knox play in the Cumberland saddle area at drilling depths ranging from 1,300 to 1,700 ft. In central Ohio, the Upper Cambrian Copper Ridge Dolomite and its equivalent, the Trempealeau Formation, contain oil at depths of 2,850 to 3,550 ft. In eastern Ohio, the Rose Run Sandstone contains gas and oil at depths ranging from 6,000 to 7,200 ft. Dry gas occurs in the play locally at greater depths under Pennsylvania's segment of the Appalachian Plateaus to a maximum depth of 9,920 ft in McKean County in northwestern Pennsylvania. Gas with a considerable hydrogen sulfide content was found at 8,870 ft in a well drilled on the crest of the Shellsburg dome in the Valley and Ridge of western Bedford County, Pa. (Fettke, 1953). The top of the Knox play was found at a depth of 20,850 ft in the Amoco Producing Company's No. 1 Leonard Svets well in the Appalachian Plateaus of Somerset County, Pa. In southwest Virginia, oil occurs in the upper part of the Knox play at depths of 3,700 to 3,900 ft near Rose Hill, and gas was found in a faulted anticlinal trap at about 7,575 ft in the upper part of the Knox in Hancock County, Tenn.

Exploration Status

Drilling for oil in the Knox play began in the Cumberland saddle in the decades following the Civil War. Several fields were developed in the Lower Ordovician part of the play in both Kentucky and Tennessee, mainly as a result of drilling through the strata of the younger Ordovician carbonate shelf play and into the Knox play close to the Middle Ordovician unconformity. Most of the Knox fields in the Cumberland saddle were found by random drilling. Consequently, several vigorous drilling campaigns, interspersed with long periods of relative inactivity, have been conducted in the area during the past 100 years. At present, drilling in the play continues in the saddle area and outward northeast and east in Kentucky and east to southeast in Tennessee. Drilling has spread eastward across the Appalachian Plateaus and locally into the Valley and Ridge.

In the 75 years following the opening of the giant Lima-Findlay field in the Trenton Limestone of northwestern Ohio, only a scattering of wells was drilled to the Knox rocks in the western half of Ohio. This drilling resulted in the discovery of oil in five small fields in north-central Ohio (Dolly and Busch, 1972; Janssens, 1973, p. 26, fig. 16). In 1961, however, a boom quickly developed in Morrow County, where oil was found in Cambrian karstic paleotopographic reservoirs beneath the Middle Ordovician unconformity. Erosion had removed all the Lower Ordovician sequence in the Knox section, and significantly porous reservoirs had developed in a hilly topography beneath the erosion surface. Many prolific wells were found in Morrow County, which has produced about 40 million barrels of oil to date. Drilling continues in Morrow County but at a subdued rate.

Expectation of extending major discoveries along the unconformity to the northeast and southwest of Morrow County was not realized. Only a few small fields were found in the play in northern Ohio, where structure seems to be more important than in central Ohio (Janssens, 1973, p. 26, fig. 16; Coogan and Maki, 1988). Several gas wells were found in the sandy Gatesburg Formation, the equivalent of the Copper Ridge Dolomite of Late Cambrian age, in northwestern Pennsylvania. The presence of considerable saltwater in the Gatesburg gas-bearing zone apparently inhibited additional exploratory drilling in the northwestern part of Pennsylvania.

A scattering of very deep wells has penetrated the Knox play in the eastern part of the Appalachian Plateaus and in the Valley and Ridge from New York to Alabama. Only in southwest Virginia and adjacent east Tennessee have oil and gas been found in the Valley and Ridge part of the Knox play, although noncommercial amounts of gas have been encountered locally deep in the play. Most of the central and eastern parts of the Knox carbonate shelf play remains unexplored.

Rome Trough Play

The Rome trough play is a combination structural-stratigraphic trap play involving the Lower and Middle Cambrian sedimentary rocks that fill part of a complex graben, the Rome trough of McGuire and Howell (1963) or the Eastern Interior aulacogen of Harris (1978). The rocks of the Rome trough play underlie an area of about 40,300 mi^2 and fill part of the aulacogen from east-central Kentucky into southwestern Pennsylvania (fig. 13). Faults that formed the graben appear to have been initiated during a period of extensional tectonics associated with the opening of Iapetus, the ancestral Atlantic Ocean, during the Late Proterozoic. Reactivation of the Late Proterozoic normal faults was greatest during the Middle Cambrian when as much as 8,000 to 12,000 ft of pre-Knox sediments accumulated in the deeper parts of the Rome trough (Ryder, 1989). Subsidence of the trough recurred but on a lesser scale at other times during the Paleozoic Era (Harris, 1978), and stratigraphic units as young as the Lower Devonian Oriskany Sandstone show some thickening along the axis of the Rome trough.

Reservoir Rocks

Most of the reservoir rocks in the Rome trough are sandstones and sandy carbonate rocks (Ryder, 1989). The Lower and Middle Cambrian sequence contains considerable sandstone and quartzose siltstone; however, in much of the coarser grained siliciclastic rock the pores are tightly filled with carbonate or siliceous cement. Some beds are sufficiently porous and permeable to contain gas and saltwater. In the Sand Hill well (Hope Natural Gas Company No. 9634, Power Oil Company, Walker District, Wood County, W. Va.) in the Rome trough sequence, small, noncommercial volumes of gas were encountered in the basal Cambrian sandstone within 8 ft of the Precambrian basement complex.

Source Beds

Dark-grayish-black to black shales and grayish-black limestones of the Conasauga Group appear to be source beds in the Rome trough play of Kentucky and western West Virginia. In Mingo County in western West Virginia, grayish-black to very dark gray shale in the lower part of the play has gas-generating potential (Donaldson and others, 1975). However, the coarser grained siliciclastic reservoir rocks are not well developed in the play in Mingo County. Data on the geochemistry of the source rocks of the Rome Trough play are unavailable.

Timing and Migration

Very scant time and temperature data suggest that the Rome trough rocks in northern West Virginia and adjacent Pennsylvania probably passed through the oil generation zone and well into the hotter, nonassociated dry-gas zone during the Late Mississippian and Pennsylvanian. To the west, in eastern Kentucky, source beds may not have begun oil generation until the Permian, and migration within the trough may have occurred shortly thereafter.

Depth of Occurrence

The top of the Rome trough sequence dips eastward from a drilling depth of about 6,000 ft along the flank of the Cincinnati arch in east-central Kentucky to about 25,000 ft in southwest Pennsylvania. Oil and gas occur at depths of 5,800 to 7,500 ft in eastern Kentucky, whereas nonassociated dry gas has been produced briefly from a depth of 14,350 ft in Exxon Company's No. 1 Walter McCoy well in Jackson County, W. Va. (Patchen, 1977).

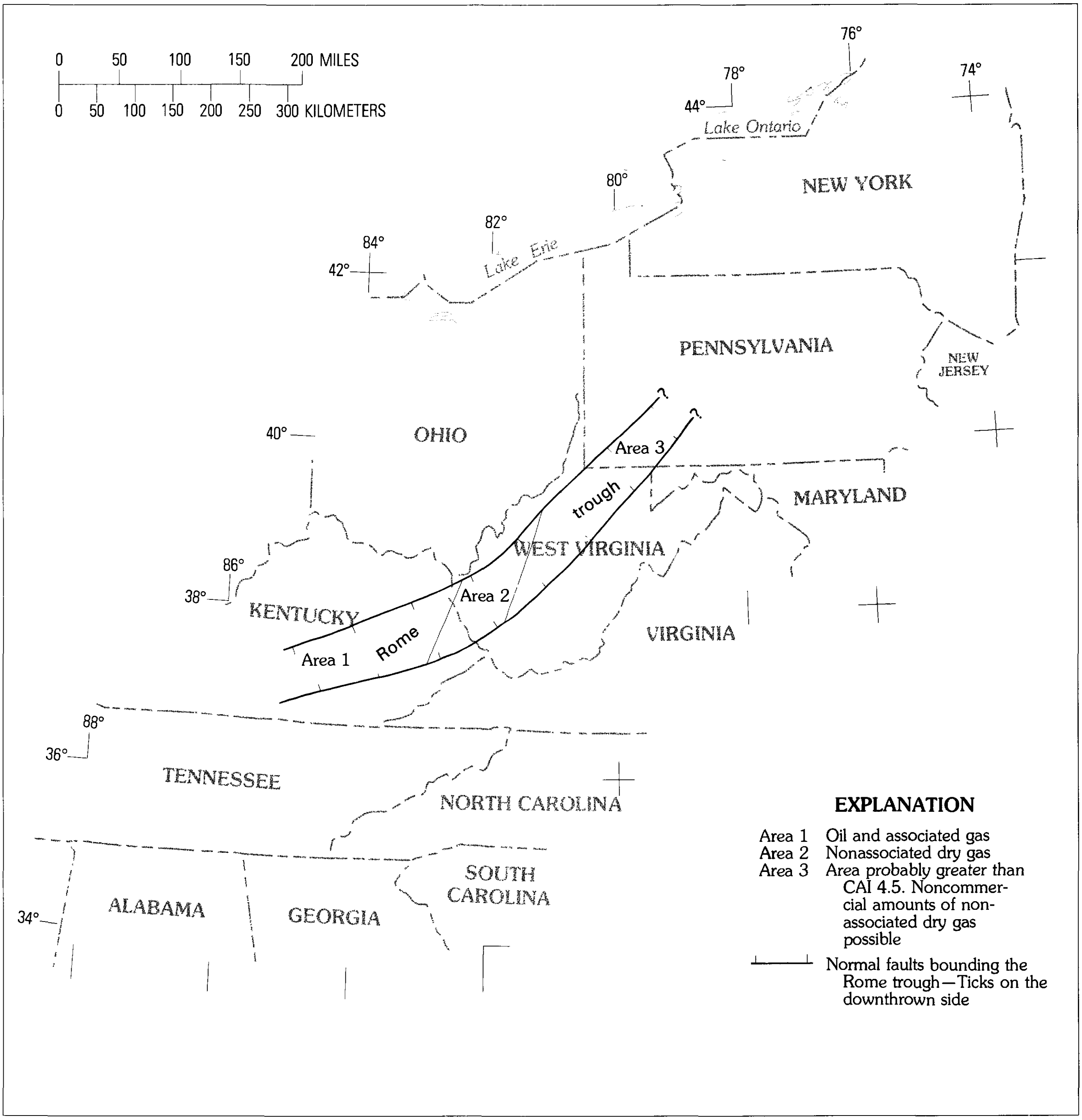

Figure 13. The Rome trough play. The play underlies an area of about 40,300 mi^2.

Exploration Status

The more than 40,000 mi^2 of the Rome trough play have had little exploration except in eastern Kentucky. Interest in drilling to the thick section of mainly Middle Cambrian rocks in the Rome trough was generated by Woodward's (1961) paper on a preliminary study of the subsurface of part of the Appalachian Plateaus and the suggested presence of a fault-bordered deep basin in eastern Kentucky and northwestern West Virginia. Several widely spaced deep wells drilled in eastern Kentucky in the late 1950's and early 1960's encountered small amounts of gas, oil, or saltwater at a number of places in the Rome trough rocks (McGuire and Howell, 1963; Sutton, 1981). Sufficient data accumulated to show that the Rome trough was a large graben of considerable complexity (Silberman, 1981; Sutton, 1981). One small oil pool, Marity, was found in the trough in Boyd County in northeastern Kentucky.

In the mid-1970's, Exxon extended exploration east along the Rome trough into western and central West Virginia. It drilled six deep wells, which entered Precambrian basement rocks at depths of 13,266 to 20,222 ft after penetrating 5,000 to 8,000 ft of Rome trough rocks. Small amounts of dry gas were found in several wells. The Exxon No. 1 Walter McCoy well in Jackson County produced gas at a rate of 5 million cubic feet per day for a short time before the daily yield decreased to 1 million cubic feet per day and saltwater encroached to spoil the well. The well was shut in after producing dry gas for about 6 months (Patchen, 1977). In the mid-1980's, wells drilled to the Rome trough play in Johnson County, Ky., found gas and a small amount of oil.

To date, all oil or gas pools in the Rome trough play have been small. However, because the play is deep in eastern Kentucky and deeper in West Virginia and Pennsylvania, relatively few exploratory wells have been drilled into the trough. Encouraging data include the production of some oil and gas, as well as the presence of both source beds and reservoir rocks, within the complex graben fill in the Rome trough play. Offsetting these favorable factors are the increasing depth to target zones eastward in the play, the great cost per well in most of the play, and the probable excessively high degree of thermal maturation in the deeper parts of the play in western and central Pennsylvania.

VIRTUALLY EXHAUSTED PLAYS

In addition to the principal plays discussed, several regionally extensive and many local plays are present in the younger Paleozoic rocks in the Devonian, Mississippian, and Pennsylvanian sequences in Kentucky, Ohio, Pennsylvania, and West Virginia. The probability of finding large volumes of gas or oil in these plays is remote because they occupy the extensively drilled western segment, where more than half of the 750,000 wells in the basin were drilled. Many of the plays in these younger Paleozoic rocks were essentially drilled up by 1920, and their contained hydrocarbons have been extracted to the limits of economic production. Secondary recovery techniques have produced additional amounts of oil from siliciclastic reservoir rocks in several of these plays, particularly from the Berea, Weir, and Big Injun sands in the Lower Mississippian sequence. Pools of oil or gas remaining to be discovered in these plays will be small and will fall below the lower cutoff of 1 million barrels of oil or 6 billion cubic feet of gas specified for inclusion in pool evaluation by play-analysis methodology for the U.S. Geological Survey and U.S. Minerals Management Service's national assessment (1988, p. 27–46) of undiscovered conventional oil and gas resources. In consideration of these factors, the pools were accorded only a small portion of the oil and gas resources estimated for the Appalachian basin.

Unfortunately for resource assessment, production data for most of these plays are scant because many were discovered and extensively exploited between 1859 and 1890, which was when the first major drilling campaigns began in the basin. Regulations on drilling were almost nonexistent during those times, and very few volumetric data remain from this hectic period of exploration and development. In West Virginia, for example, channel filling and sheet sandstones of Pennsylvanian age produced more than 28 million barrels of oil (Cardwell and Avary, 1982). The Lower Mississippian Keener, Big Injun, Squaw, and Weir sands in the same State produced more than 175 million barrels of oil, and the basal Mississippian Berea Sandstone (de Witt, 1970) produced more than 68 million barrels of oil in West Virginia (Cardwell and Avary, 1982) during this same time interval. Data for natural gas from these sands for the period 1859–95 in West Virginia are not available. Sparse production records from States contiguous to West Virginia are insufficient to permit assessment of oil and gas recovered from the shallow plays during the early period of drilling in the Appalachian basin. For plays in several States, production data, even to the present decade, are inadequate for definitive pool-size analysis and play analysis.

The siliciclastic sands and carbonate reservoir rocks in the shallow plays of the basin have been so thoroughly perforated in their nonproductive parts by wells drilled to test older and deeper plays that the younger Paleozoic plays are mainly in a terminal stage of primary exploitation. An example of a single-State play that has been of great importance in the past but is nearly completely explored at present is the Silurian and Devonian Corniferous karstic play of east-central Kentucky. The play contains karstic carbonate reservoir rocks of Middle to Late Silurian and Early Devonian ages. The larger fields in the Corniferous were drilled and delineated mainly just after World War I. Many wells produced oil prolifically, and a hectic drilling campaign developed as the Corniferous reservoirs were explored. Corniferous pools in the four-county area of Estill, Lee, Powell, and Wolfe Counties produced more than 90 million barrels of oil by primary and secondary recovery methods between 1918 and 1970 (Ray, 1971, p. 1266). A more recent example of a single-State carbonate-reservoir play is the Fort Payne play of northeastern Tennessee. In the decade from 1969 to 1979, more than 8 million barrels of oil were produced from the Fort Payne Formation in eastern Tennessee (Milici and others, 1979). Although a modest drilling campaign continues to the present in the Fort Payne, much of the main productive area was explored during the 1970's, and only small parts of the play remain relatively sparsely drilled (Milici and others, 1979). Although some oil pools remain to be found in the Fort Payne play, undoubtedly they will be small in size and in volume.

All possibilities of finding additional oil or gas from the late Paleozoic plays have not been exhausted, particularly in the more deeply buried parts of the plays in southern West Virginia and contiguous parts of Kentucky and Virginia. Undoubtedly, small amounts of oil and gas will be found in the late Paleozoic plays but in decreasing volumes as the undrilled parts of the basin shrink in size. A considerable amount of the undiscovered resources in these younger plays will be found fortuitously in wells drilled to explore more deeply buried strata in the Paleozoic sequence.

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Chapter J

Middle Eocene Intrusive Igneous Rocks of the Central Appalachian Valley and Ridge Province—Setting, Chemistry, and Implications for Crustal Structure

By C. SCOTT SOUTHWORTH, KAREN J. GRAY, and JOHN F. SUTTER

A summary of the distribution, chemistry, and radiometric age dates of middle Eocene intrusive igneous rocks in the Valley and Ridge province of Virginia and West Virginia

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EVOLUTION OF SEDIMENTARY BASINS—APPALACHIAN BASIN

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Middle Eocene Intrusive Igneous Rocks of the Central Appalachian Valley and Ridge Province—Setting, Chemistry, and Implications for Crustal Structure

By C. Scott Southworth, Karen J. Gray, *and* John F. Sutter

Abstract

Middle Eocene basalt and rhyolite dikes, sills, plugs, and diatremes intrude allochthonous Paleozoic sedimentary rocks of the Valley and Ridge province of the central Appalachian basin. Two main areas of silicic igneous rocks surrounded by basaltic rocks are found in Pendleton County, W. Va., and Highland County, Va. A bimodal distribution in this suite with alkaline trends is shown on projection diagrams to be a mafic group (basalt-picrobasalt-basanite) and a felsic group (trachyte-trachydacite-rhyolite). Major-element and trace-element geochemistry of 52 samples (24 basalt, 18 trachydacite and rhyolite, and 10 intermediate), 25 consistent radiometric (11) and paleomagnetic (14) dates of middle Eocene age (about 48 Ma), diatremes, and minor contact metamorphism support a mode of rapid emplacement through a deep-seated fracture system. A Hf/3-Th-Ta ternary diagram shows that the nepheline-normative basalts lie in the field of alkaline within-plate basalts associated with slow intraplate extension. The low levels of the lithophile elements K, Rb, and Cs in the felsic rocks indicate a mantle origin with little or no crustal contamination.

A K-Ar and an $^{40}Ar/^{39}Ar$ date (about 148 Ma) of Late Jurassic age and geochemical data indicate that not all of the igneous rocks in Pendleton County, W. Va., are Eocene. Late Jurassic alkalic dikes were emplaced along a cross-strike basement fracture zone during Mesozoic extension. A change in regional strike of the alkalic dikes indicates a variation in stress across this zone. Northwest-trending middle Eocene intrusive rocks in Pendleton County, W. Va., are parallel to dikes of Late Jurassic extension. However, northeast-trending middle Eocene rocks in Highland County, Va., suggest that a local variation of the stress field may have reactivated an existing fabric of structural weakness. Consistent radiometric dates of middle Eocene age support the interpretation that the igneous activity was the result of a change in stress associated with a major reorganization of global plate motion from 53.5 to 37.5 Ma.

Structural discontinuities in the allochthonous Paleozoic country rock are used to interpret the general orientation of crustal structures that were conduits for the igneous rocks. The proposed tectonic model is extensional reactivation of two basement fracture zones: a strike-parallel growth fault of Late Proterozoic to early Paleozoic age and a cross-strike basement fault. Continental extension may have been the result of changes in motion of the North American plate.

INTRODUCTION

Mesozoic and Cenozoic igneous rocks that intruded allochthonous folded and thrust-faulted Paleozoic sedimentary rocks of the central Appalachian Valley and Ridge province provide evidence of tectonic and igneous activity long after the occurrence of the Alleghanian orogeny. Late Jurassic dikes are attributed to Mesozoic extension. Geochemistry of the middle Eocene igneous rocks shows that they are associated with an extensional tectonic environment (Gray and Diecchio, 1983; Gray and Gottfried, 1986). However, no structural setting for the tectonic model of the Eocene igneous rocks has been proposed. Geologic mapping, geochemical analyses, radiometric dating, compilation of known exposures, and published paleomagnetic data of the igneous rocks have provided insight into this problem. Mesozoic and Cenozoic intrusive igneous rocks are spatially associated with both surface and subsurface Pale-

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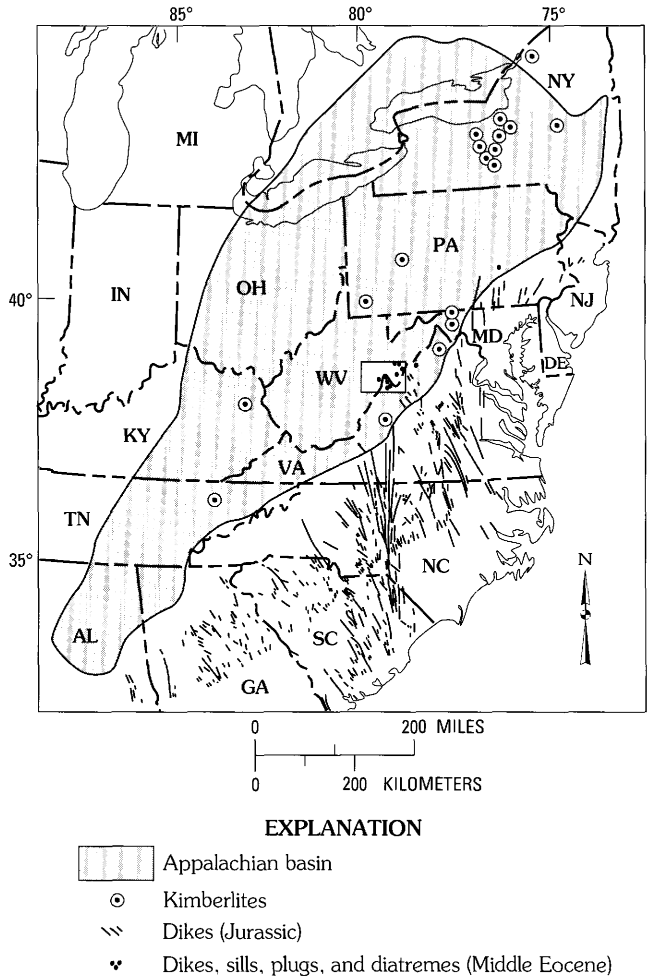


Figure 1. Regional map of the Appalachian basin (shaded) showing the distribution of late Paleozoic to Cretaceous kimberlites along the basin axis, Early Jurassic diabase dike swarms in the Appalachian Piedmont and Blue Ridge, Late Jurassic alkalic dikes in the eastern portion of the basin in the Shenandoah Valley, Va., and the middle Eocene dikes, sills, plugs, and diatremes in the central Appalachian Valley and Ridge province (in the box). The box delimits the area of figure 5. Modified from Dennison (1983) and Ragland and others (1983).

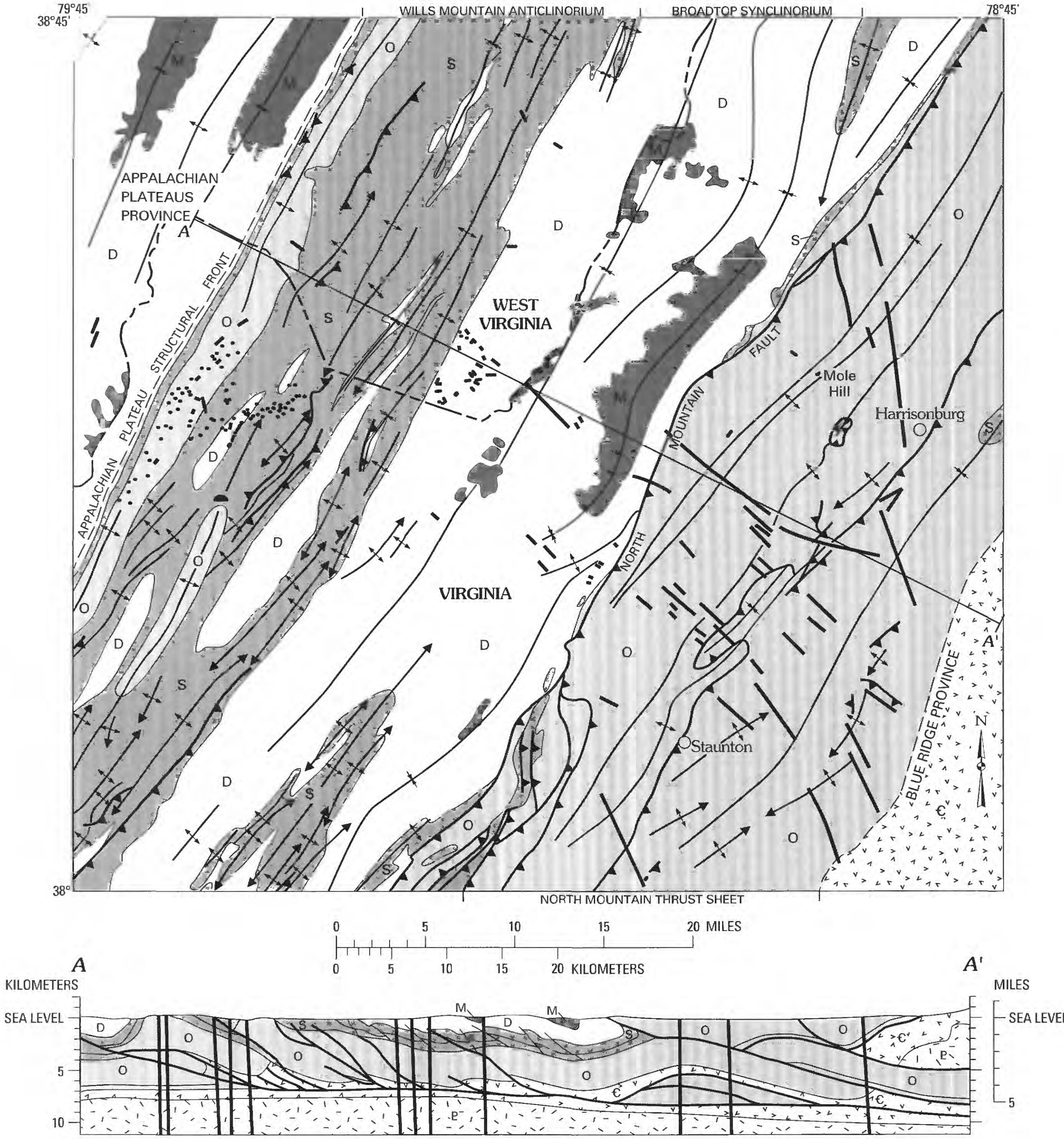
ozoic structures. If the conduits for the igneous rocks were reactivated crustal fractures, then the relationship of basement fractures to structures in the allochthonous rocks could be investigated in this region of "thin-skinned" deformation.

Three general suites of intrusive igneous rocks are found in the Appalachian basin: (1) Mississippian to Cretaceous kimberlites, (2) Late Jurassic alkalic dikes, and (3) Eocene dikes, sills, plugs, and diatremes of mafic to felsic composition (fig. 1). This paper discusses mainly the Eocene intrusive rocks in the Valley and Ridge province of the central Appalachians; however, a general review of the other intrusive rocks and their structural settings follows.

Kimberlites occur in the Appalachian basin (Parrish and Lavin, 1982), and two localities are found in the Valley and Ridge province: Clear Spring, Md. (de Witt and Perry, 1977; Kappler and others, 1986), and Mt. Horeb, Va. (Sears and Gilbert, 1973, 1975) (fig. 1). No isotopic ages are available for these two kimberlites; however, the other kimberlites show a decrease in apparent age from Mississippian to Permian northward across Tennessee to Cretaceous in New York (Parrish and Lavin, 1982). Two models for the origin of kimberlites in the Appalachian Plateaus province have been proposed. Parrish and Lavin's (1982, 1983) tectonic model for the kimberlites in Pennsylvania and New York invokes a crustal zone of weakness at the intersection of cross-strike faults with strike-parallel growth faults. The growth faults are believed to be extensional structures related to the Early Cambrian Rome trough and the Ordovician Martinsburg trough. Dennison's (1983) keel-line model invokes isostatic reactivation of fractures parallel to the axis of the basin.

A group of northwest-trending, near-vertical, Late Jurassic dikes occurs in central Virginia (Johnson and Milton, 1955; King, 1961, 1971; De Boer and Snider, 1979), where they cross the Blue Ridge anticlinorium into the Shenandoah Valley (Dennison and Johnson, 1971) (fig. 2). These dikes are an unusual suite of alkalic rocks that include nepheline syenite, teschenite, and picrite (Johnson and others, 1971). A teschenite dike and a nepheline syenite dike in Ordovician carbonate rocks in the Shenandoah Valley north of Staunton, Va. (fig. 3, samples 1 and 2), yielded potassium-argon (K-Ar) ages of about 155 Ma (Zartman and others, 1967; Marvin, 1968; and Johnson and others, 1971) by use of the new decay constants and isotopic abundance ratios for K-Ar (Steiger and Jager, 1977). Table 1 provides the recalculated data of all published K-Ar ages in this area, and the sample locations are shown in figure 3. Biotite from a mica pyroxenite dike in Pendleton County, W. Va. (fig. 3, sample 3), yields an $^{40}Ar/^{39}Ar$ plateau age of 147 Ma (table 2 and fig. 4). Contrary to what has been published on recent maps of the area (Manspeizer and others, 1989), this dike appears to mark the known western limit of this Late Jurassic event. The variation in trend of the Late Jurassic dikes in the Shenandoah Valley (fig. 2) probably represents a change in the stress field of the basement during emplacement. In general, the northwest trend of the dikes suggests a northeast-oriented axis of greatest tension or least compres-

Figure 2. Generalized geologic map of the Shenandoah Valley and Valley and Ridge province of the central Appalachian foreland fold and thrust belt showing the Late Jurassic alkalic dikes and middle Eocene intrusive igneous rocks. Generalized geology after Milici and others (1963) and Cardwell and others (1968). Cross section modified from Woodward and others (1985); vertical lines in cross section are schematic dikes. ▶



EXPLANATION

- Mississippian rocks (M)
- D Devonian rocks
- S Silurian rocks
- O Ordovician rocks
- Є Cambrian rocks
- Ꝑ Proterozoic rocks

- Contact
- Anticline—Showing crestline and direction of plunge where known
- Syncline—Showing trough line
- Overturned syncline—Showing trace of axial surface and direction of dip of limbs
- Thrust fault—Sawteeth on upper plate
- Igneous dike
- Igneous sill, plug, or diatreme

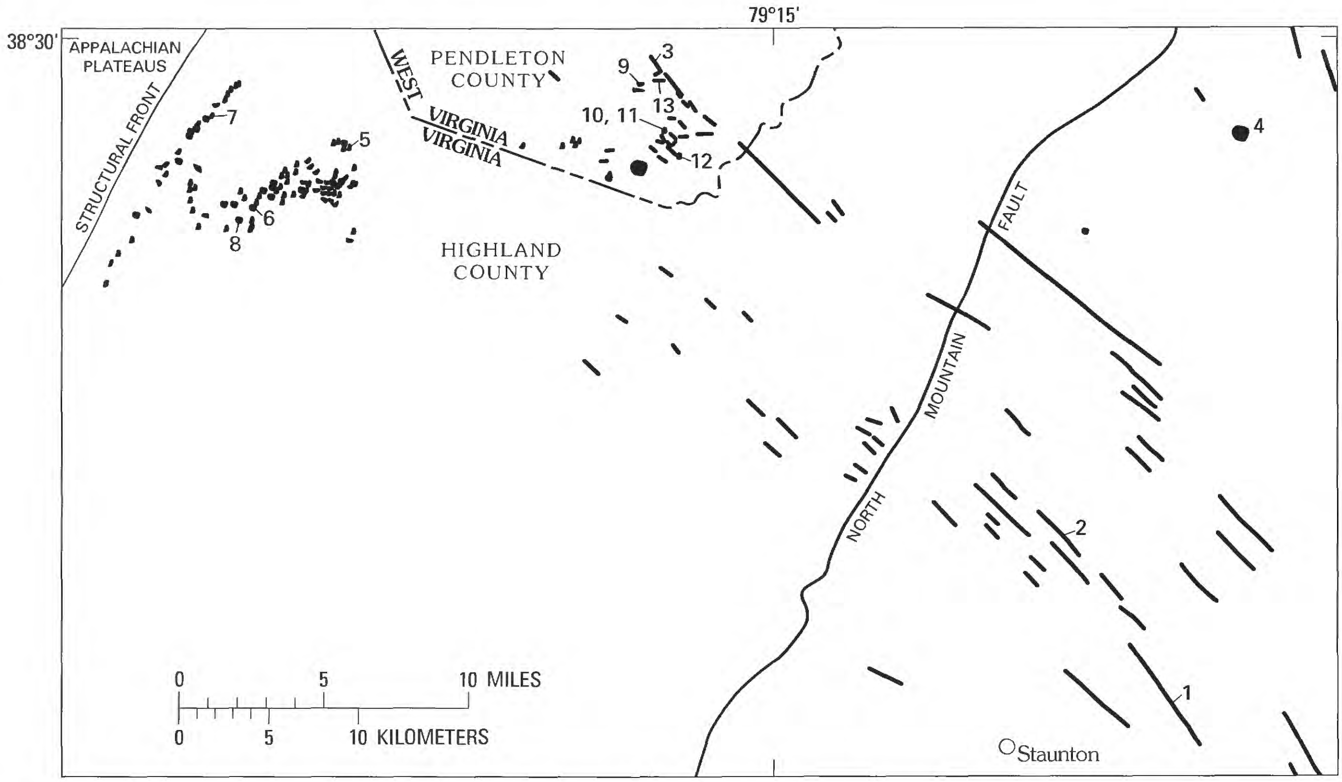


Figure 3. Late Jurassic and middle Eocene intrusive igneous rocks from the Great Valley to the Appalachian Plateaus structural front. Radiometric age data by K-Ar and $^{40}Ar/^{39}Ar$ methods are listed for the numbered samples in table 1.

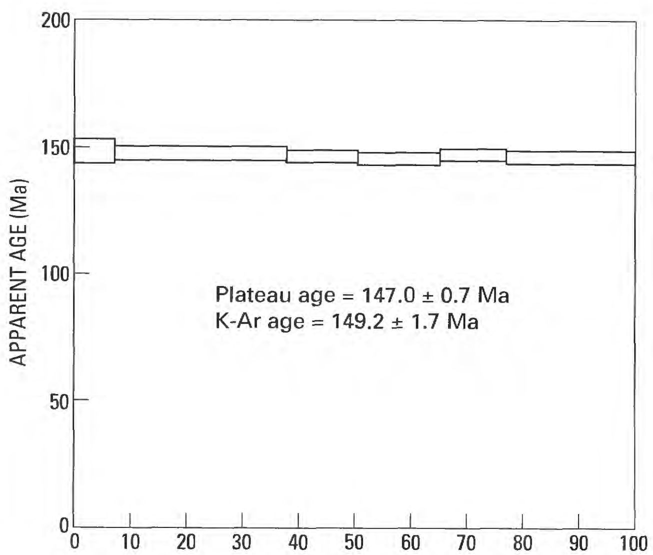


Figure 4. $^{40}Ar/^{39}Ar$ age spectrum data for Late Jurassic mica pyroxenite dike. (See table 1, sample 3, and fig. 3, sample 3.)

sion; this interpreted orientation of the stress ellipse is coaxial with Alleghanian deformation.

Mica pyroxenite dikes, similar to the dated Late Jurassic dike, occur near Martinsburg, W. Va. (Mann, 1955; Donaldson and others, 1964), and Front Royal, Va. (Young and Bailey, 1955). These dikes are undated, as is a kimberlite near Mt. Horeb, Va. (Sears and Gilbert, 1973, 1975).

Intrusive rocks that range in composition from basalt to rhyolite occur as dikes, sills, plugs, and diatremes in the western portion of the Valley and Ridge province near the Appalachian Plateaus structural front (fig. 2). These intrusive rocks were long thought to be Mesozoic (Darton and Diller, 1890; Johnson and Milton, 1955; and Zartman and others, 1967). However, in an attempt to date the Devonian Tioga Ash Bed (Johnson and others, 1971; Dennison, 1975), Fullagar and Bottino (1969) dated an andesite sill (fig. 3, sample 6), which was Eocene. Eleven K-Ar and $^{40}Ar/^{39}Ar$ dates and paleomagnetic data of 14 samples show a consistent age of middle Eocene for the igneous rocks in this region. These are the youngest igneous rocks in the Eastern United States and recently have been called the Shenandoah igneous province (McHone, 1988; Vogt, 1991). Previous workers (Zartman and others, 1967; Fullagar and Bottino, 1969; Dennison and Johnson, 1971;

Table 1. K-Ar and $^{40}Ar/^{39}Ar$ ages for intrusive rocks in the central Appalachian Valley and Ridge Province
[B, biotite; H, hornblende; WR, whole rock; Do., ditto]

Sample (see fig. 3)	Rock unit or type	Mineral	Geochemical sample number (from tables 3 and 4)	K (%)	^{40}Ar (moles/gram × 10^{-9})	Apparent age* (Ma)	Reference
	Late Jurassic						
1	Nepheline syenite dike	B				148 ± 7	Zartman and others (1967).
	do	H				157 ± 8	Do.
2	Teschenite dike	B				156 ± 5	Johnson and others (1971).
	do	H				155 ± 10	Do.
3	Mica pyroxenite dike	WR		2.56	0.666	143.8 ± 1.8	This work; supersedes Core and others (1974) and Ressetar and Martin (1980).
	do	WR		2.56	.677	146.2 ± 1.7	Do.
	do	B		6.10	1.644	149.2 ± 1.7	Do.
	Middle Eocene						
4	Olivine basalt plug	WR	46			48 ± 1	Wampler and Dooley (1975).
5	Tephrite basanite dike	—	38			44	Hunt (1974).
6	Trachydacite dike	B	31			48.1 ± 1.1	Fullagar and Bottino (1969).
	do	B				48.4 ± 1.3	Do.
7	Trachydacite dike/sill	B	29, 52	6.34	.532	47.7 ± 0.6	This work; supersedes Core and others (1974) and Ressetar and Martin (1980).
8	Basalt plug	WR	36, 51	.766	.0470	35.0 ± 0.5	Do.
9	Basalt dike	WR	49	1.19	.0903	43.1 ± 2.1	Do.
10	Basalt dike	WR	18	1.24	.0998	45.8 ± 0.6	Do.
11	Basalt dike	WR		1.06	.0881	47.3 ± 0.8	Do.
12	Trachydacite dike	WR	21, 47	3.78	.284	42.8 ± 0.5	Do.
	do	WR		3.71	.292	44.8 ± 0.6	Do.
13	Basalt dike	WR				47.1	Ressetar and Martin (1980).

* All apparent ages have been recalculated on the basis of decay constants and isotopic abundance ratios for potassium and argon recommended by Steiger and Jager (1977). The conversion tables published by Dalrymple (1979) were used in the recalculations.

Table 2. $^{40}Ar/^{39}Ar$ age spectrum data for biotite in a Late Jurassic mica pyroxenite dike
[Sample 3, fig. 3 and table 1; J = 0.004833]

Temperature (°C)	$^{40}Ar/^{39}Ar$ (measured)	$^{36}Ar/^{39}Ar$ (measured)	$^{39}Ar_K$ (% of total)	$^{40}Ar_R$ (% of total)	Age[1] (Ma)
600	28.67	0.03676	6.88	62.2	148.9±2.2
800	18.83	.00400	30.73	93.7	147.7±1.2
900	18.26	.00236	12.81	96.2	147.0±1.1
1,025	18.17	.00247	14.76	96.0	146.0±1.1
1,100	18.55	.00302	11.85	95.2	147.7±1.1
1,400	18.60	.00368	22.98	94.2	146.6±1.2
Total gas	19.25	.00563	100	91.4	147.2
				Plateau (800°C–1,400°C) age =	147.0±0.7
				Conventional K-Ar age =	149.2±1.7

[1] Biotite mineral separate of >99% purity was irradiated together with neutron flux monitor DY–8C–71 (Sutter and Smith, 1979) in the Central Thimble Facility of the U.S. Geological Survey TRIGA reactor (GSTR) at the Federal Center in Denver, Colo. (Dalrymple and others, 1981). Corrections for argon isotopes produced during irradiation are those suggested by Dalrymple and others (1981) for the Central Thimble. Decay constants and isotopic abundance ratios are those recommended by Steiger and Jager (1977). The definition of an age "plateau" is that proposed by Fleck and others (1977), and the error in age (1 sigma) has been calculated by use of the equation suggested by Dalrymple and others (1981).

Rader and others, 1986) attribute this igneous activity to the 38th parallel lineament of Heyl (1972).

One purpose of this investigation is to reexamine the geochemical data base of the intrusive rocks in the Highland County, Va., and Pendleton County, W. Va., region and to add to isotopic evidence in support of a new interpretation of the tectonic environment. Minor-element geochemical data suggest a tectonic environment of continental extension (Gray and Diecchio, 1983; Gray and Gottfried, 1986). Surface and inferred subsurface structures in the allochtho-

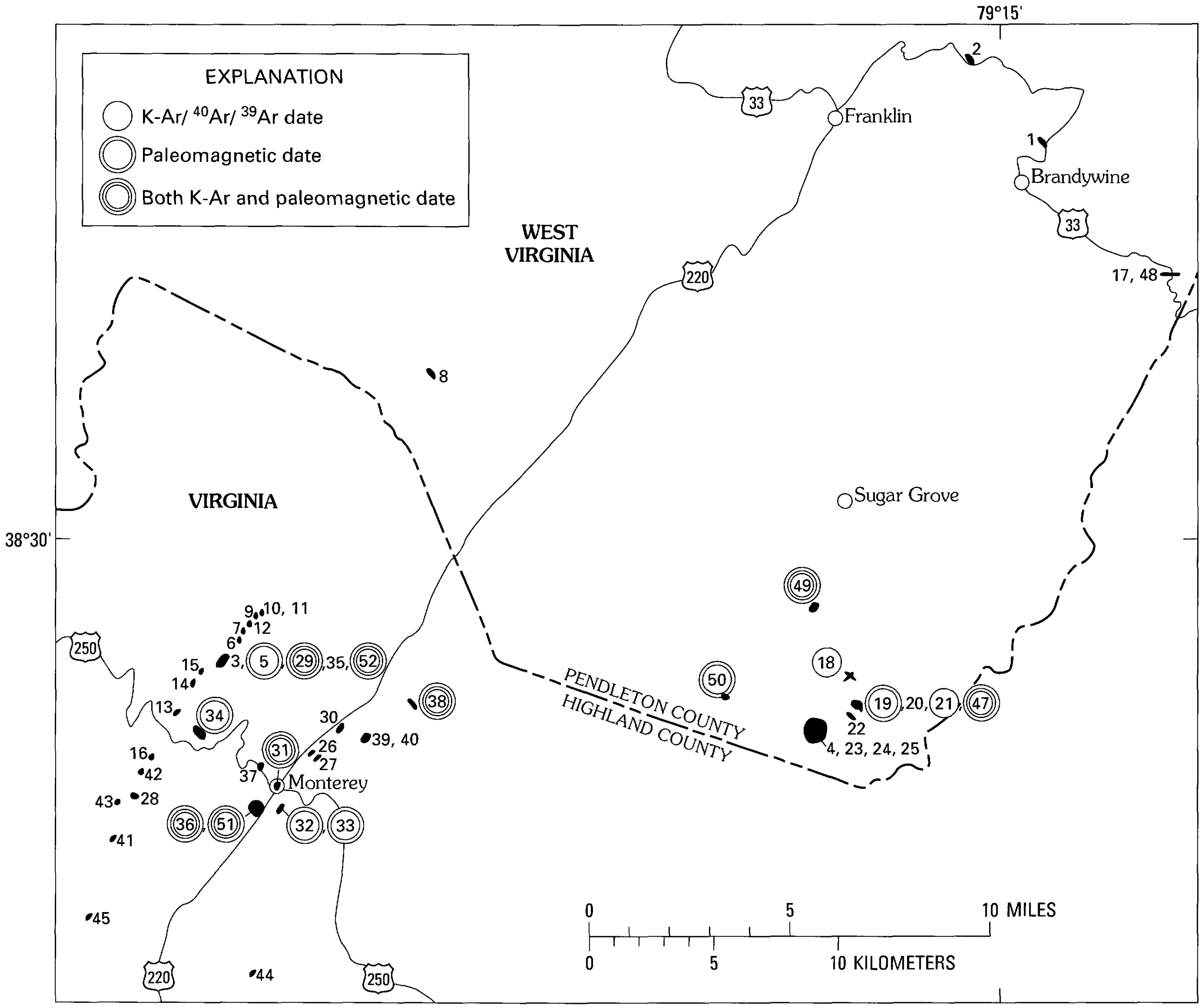


Figure 5. Intrusive igneous rocks in the study area. Numbers refer to geochemical data in tables 3 and 4. Data originally compiled on 1:24,000-scale topographic maps.

nous Paleozoic host rocks are used to support this tectonic model of emplacement. Since the distribution of Late Jurassic and middle Eocene intrusive rocks in this region has been unclear (Rader and others, 1986; Manspeizer and others, 1989), we define the respective areas of igneous activity by showing the location of samples with radiometric and paleomagnetic data. Trace-element geochemical signatures of the Jurassic and Eocene rock suites appear to be different (Gray and Gottfried, 1986); therefore, this method is used to show that both Late Jurassic and middle Eocene rocks spatially overlap.

EOCENE INTRUSIVE IGNEOUS ROCKS

Eocene intrusive igneous rocks of mafic and felsic composition (Fullagar and Bottino, 1969; Hunt, 1974; Lovlie and Opdyke, 1974; Wampler and Dooley, 1975; Ressetar and Martin, 1980) occur in the Valley and Ridge province as dikes, sills, plugs, and diatremes (fig. 5). K-Ar and ^{40}Ar/^{39}Ar dates (table 1 and fig. 3) and paleomagnetic data (Lovlie and Opdyke, 1974; Ressetar and Martin, 1980) suggest that most of the igneous rocks in this region are Eocene. Geochemical data of dated samples from sites in figure 5 and from table 1 are shown in tables 3 and 4. In general, K-Ar dates suggest that the Eocene igneous activity was short lived (probably not more than a few million years). These Eocene intrusive rocks represent the youngest known igneous activity in the Eastern United States.

The igneous rocks were first recognized by Rogers (1884) and have been studied by Darton and Diller (1890), Darton (1894, 1899), Darton and Keith (1898), Butts

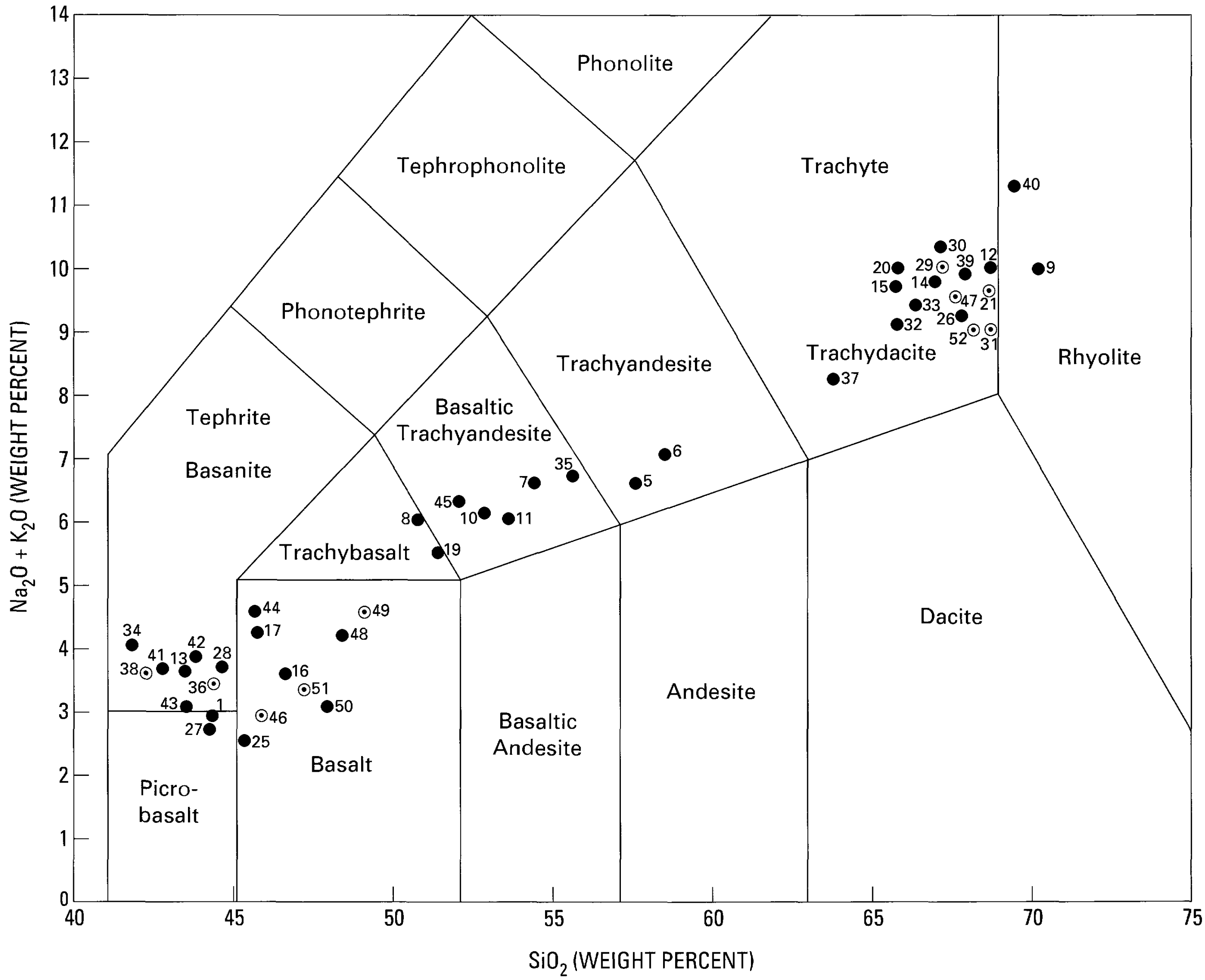


Figure 6. Classification of the middle Eocene intrusive igneous rocks on the basis of silica content versus Na_2O + K_2O (after Le Bas and others, 1986). Circles denote dated samples. Sample numbers from figure 5 and table 3.

(1933), Johnson and Milton (1955), Garner (1956), Core (1971), Johnson and others (1971), Sutter (1976), Gray and Diecchio (1983; unpub. data, 1992), Rader and others (1986), and Gray and Gottfried (1986). Field mapping suggests that the igneous activity was restricted to portions of Highland County, Va., and Pendleton County, W. Va. The distribution of known igneous rocks is partly due to good exposures in agricultural valleys underlain by carbonate and shale rocks and to extensive mapping in the adjacent areas (Garner, 1951; Kapnicky, 1956; Duncan and others, 1969; Kettren, 1970; Lesure, 1982).

On the basis of major-element geochemistry, the igneous rocks can be classified after LeBas and others (1986) (fig. 6, table 3). This classification shows a primarily bimodal distribution on the basis of silica content vs. Na_2O + K_2O (fig. 6). The mafic rocks (SiO_2 of 42 to 52 weight percent) occur within the basalt (9), picrobasalt (2), and basanite (8) fields, while the felsic rocks (SiO_2 of 64 to 71 weight percent) cluster within the trachyte-trachydacite (15) and rhyolite (2) fields. Nine samples are intermediate in composition (fig. 7). Seven samples from diatremes include picrobasalt (2), basalt (4), and one andesite that are altered and contaminated by country rock; therefore, the geochemical data are provided at the end of the table and are not further analyzed.

The mafic rocks are widely distributed and surround two areas of silicic activity in Highland County, Va., and Pendleton Co., W. Va. The easternmost outcrop of Eocene age (48±1 Ma; K-Ar whole-rock age recalculated by use of new constants) is Mole Hill, an olivine-spinel basalt plug intruded into Ordovician carbonate rocks of the Shenandoah Valley (Wampler and Dooley, 1975) (fig. 3 and table 1, sample 4). The basalts are predominantly very fine grained and are dark gray (*N* 3) to black (*N* 1). Several dikes and

Table 3. Bulk rock analysis by optical spectroscopy for dikes, sills, and plugs

[Performed in the laboratories of the U.S. Geological Survey. H. Smith, analyst. Six altered and contaminated samples at the end of the table are from indicates Eocene age determined by: A, K-Ar and $^{40}Ar/^{39}Ar$; B, paleomagnetic data (Lovlie and Opdyke, 1974; Ressetar and Martin, 1980); and C, both

	Picrobasalt		Tephrite Basanite							
	1*	27	13	28	34B	36C	38C	41	42	43
SiO_2	42.6	41.6	43.0	43.3	41.0	44.4	41.5	43.2	43.4	44.0
Al_2O_3	12.6	13.3	16.4	14.9	14.6	14.1	14.8	15.6	16.1	13.2
Fe_2O_3	5.8	4.9	5.3	5.6	5.3	3.5	7.0	3.7	5.8	4.6
FeO	4.6	6.7	7.9	7.6	8.3	8.2	6.4	9.4	7.6	7.5
MgO	9.4	7.4	6.7	6.4	8.0	10.1	8.7	8.8	6.4	11.8
CaO	13.3	13.5	10.9	10.8	11.4	12.2	11.6	11.4	11.1	13.0
Na_2O	2.2	1.5	2.8	1.9	2.6	2.3	3.0	2.1	2.2	1.9
K_2O	.54	1.1	.75	1.7	1.4	1.1	.54	1.5	1.7	1.1
H_2O^+	3.2	1.0	1.3	2.7	1.9	1.2	1.8	1.4	1.9	.54
H_2O^-	1.8	1.8	.51	1.3	1.0	.55	1.4	.55	.92	.32
TiO_2	2.5	2.3	2.9	2.7	3.2	2.2	2.7	2.7	2.8	2.2
P_2O_5	1.1	.35	.52	.55	.41	.47	.38	.55	.58	.48
MnO	.13	.17	.20	.20	.19	.19	.19	.19	.21	.18
CO_2	.07	4.9	.02	.05	.37	.12	.13	.1	.3	.04
Total	99.84	100.52	99.20	99.70	99.67	100.63	100.14	101.19	101.01	100.86

	Basalt									Trachybasalt	
	16*	17	25	44	46A	48	49C	50B	51C	8	19B
SiO_2	43.3	43.4	42.3	45.5	45.6	46.8	47.8	45.4	47.4	49.0	48.3
Al_2O_3	16.4	15.9	13.2	17.3	14.9	14.4	13.8	13.5	13.0	17.8	20.4
Fe_2O_3	6.6	9.0	4.8	4.9	3.4	9.05	4.38	5.21	2.85	5.0	4.3
FeO	3.8	4.0	6.0	7.5	7.2	4.18	7.77	6.11	8.38	4.1	4.2
MgO	4.3	5.6	9.7	5.1	10.0	5.52	6.80	7.34	9.73	2.2	2.1
CaO	11.3	7.7	11.7	10.1	12.4	8.00	8.28	10.45	11.83	8.9	5.7
Na_2O	2.0	2.7	1.6	3.2	2.2	2.88	3.18	1.97	2.33	4.1	4.4
K_2O	1.3	1.4	.80	1.3	.70	1.19	1.30	.98	1.04	1.7	.80
H_2O^+	3.4	3.0	1.9	.93	.73	3.63	3.25	4.84	.96	.80	2.6
H_2O^-	2.8	2.6	1.7	.67	.47	1.55	.77	2.01	.25	1.0	2.4
TiO_2	1.8	2.9	1.8	2.9	1.5	2.86	2.41	2.10	2.10	1.9	1.5
P_2O_5	.75	1.1	.39	.63	.36	.78	.64	.64	.46	1.0	1.1
MnO	.19	.21	.18	.22	.19	.24	.20	.20	.18	.19	.42
CO_2	.87	.26	4.5	.13	.1	.16	.26	.26	.12	.92	.44
Total	98.81	99.77	100.57	100.38	99.75	101.24	100.69	101.01	100.63	98.61	98.66

diatreme breccias are porphyritic basalt with large olivine and augite phenocrysts. The basalts are nepheline normative. The trachydacite and rhyolites are predominantly aphanitic and medium to light gray (*N* 5 to *N* 7) and weather to yellowish gray (5*Y* 8/1). However, some felsic rocks are porphyritic with phenocrysts of feldspar, biotite, and (or) hornblende.

Outcrops of the igneous rocks are discontinuous, and exposures range in width from less than 1 m to over 100 m. Mafic rocks are generally resistant to erosion and form topographic knobs (fig. 8) and ridges, whereas felsic rocks are more likely to be deeply weathered to saprolite (fig. 9). The igneous rocks crop out at elevations ranging from 548 m in valley bottoms to 1,329 m on ridges. Exposed contacts of the igneous rocks with Ordovician to Devonian sedimentary rocks show little contact metamorphism. Diatremes and volcanic breccias indicate rapid and forceful emplacement. Breccia zones as much as 2 m thick in carbonate rock (fig. 10) suggest volatile exchange of CO_2 by gas fluidization during intrusion (Johnson and others, 1971). The Ugly Mountain diatreme in Pendleton County, W. Va., is one of several large diatremes that shows layered breccia composed predominantly of the Paleozoic host rock. Columnar-jointed aphanitic basalt (fig. 11) and volcanic glass suggest near-surface emplacement.

Some Eocene dikes have orientations that parallel the northwest trend of Late Jurassic dikes, so relationships between age and strike (Core and others, 1974) are tenuous. Eocene dikes and sills trend both northwest and northeast. The conjugate trends suggest that either (1) the stress field changed, (2) two stress fields were active, or (3) the intrusions were emplaced along near-surface fractures not diatremes; the seventh sample is a basalt dike. All analyses are in weight percent. Sample localities are shown in fig. 5. Letter adjacent to sample no. A and B. Samples with an asterisk (*) have geochemical signatures of Late Jurassic igneous rocks]

Trachyte-Trachydacite														
12	14	15	20	21A	26	29C	30	31C	32B	33B	37	39	47C	52C
67.5	65.8	65.7	64.0	67.0	65.4	65.2	65.6	66.8	64.1	64.8	61.2	65.8	66.4	67.1
16.2	17.9	17.5	18.2	16.6	17.2	16.8	18.1	18.5	17.6	19.3	17.0	16.8	16.9	17.0
3.0	2.2	2.8	3.6	2.4	3.0	1.1	1.2	1.4	2.9	1.8	4.1	2.3	2.35	.97
.28	.28	1.1	.66	.96	.16	2.0	.36	.29	.60	.20	.48	.16	.98	1.81
.24	.26	.58	.14	.18	.16	.19	.24	.21	.40	.09	1.4	.23	.02	.37
.63	1.6	1.8	.90	.88	1.2	1.5	1.4	1.0	2.0	1.6	2.5	1.4	1.18	1.35
6.0	6.0	6.2	5.0	5.7	5.1	4.1	5.7	4.6	5.3	5.3	4.9	5.6	4.90	4.62
4.0	3.7	3.5	4.7	3.8	4.0	5.6	4.4	4.2	3.7	4.0	3.0	4.0	4.38	4.26
.70	.87	.54	1.6	.96	1.3	2.6	.88	1.9	.9	1.5	1.6	.7	1.04	1.21
.50	.63	.56	.55	.24	.67	.34	.62	1.20	1.5	.92	3.1	1.6	.47	.47
.16	.30	.36	.04	.04	.30	.20	.47	.19	.38	.50	.79	.35	.15	.29
.04	.13	.15	.08	.06	.09	.06	.11	.07	.13	<.01	.23	.11	.08	.15
.07	.03	.13	.04	.03	.11	.18	.05	.02	.04	.04	.10	.02	.26	.20
<.01	<.01	.09	<.01	.01	.01	.25	.04	.011	.03	.02	.03	.02	.41	.24
99.32	99.70	101.01	99.51	98.86	98.70	100.12	99.17	100.39	99.58	100.08	100.43	99.09	99.52	100.04

									Diatreme Breccias: Altered and Contaminated						
Basaltic Trachyandesite					Trachyandesite		Rhyolite		Picrobasalt		Basalt				Andesite
7	10	11	35	45	5B	6	9	40	4	23	2*	3	18A	22	24*
52.4	50.3	49.0	52.5	51.7	53.3	54.1	68.6	68.9	38.3	34.8	40.0	37.5	44.3	43.0	53.7
17.4	16.5	16.2	18.7	17.5	18.0	15.4	16.3	16.3	11.8	11.4	19.9	10.3	17.9	15.4	12.6
7.7	8.4	7.2	4.3	6.4	4.3	5.7	1.6	1.4	11.3	9.1	9.7	1.5	7.1	5.3	3.0
1.8	1.9	1.8	2.2	3.6	1.2	1.5	.08	<.01	.12	.72	1.1	1.0	6.1	7.5	1.3
2.2	2.2	1.7	1.3	2.6	1.2	1.8	.21	.10	8.3	5.6	3.8	4.8	3.7	4.9	3.3
5.7	6.7	6.9	5.7	7.9	5.7	5.8	.66	.39	12.0	18.0	3.0	17.7	3.0	7.9	9.0
4.5	4.2	3.8	4.4	4.4	4.2	4.3	6.0	6.3	.72	.81	<.01	.80	2.5	3.1	1.9
1.9	1.8	1.9	2.0	1.9	1.9	2.4	3.9	5.1	.86	.72	.80	2.9	1.6	1.4	2.9
1.2	1.5	1.8	1.3	.6	1.6	1.2	.60	.5	3.8	2.9	8.1	3.0	4.4	1.2	2.1
1.8	1.9	3.2	4.0	1.0	3.6	2.8	.60	.47	6.0	3.8	8.9	3.4	4.6	2.0	2.6
1.8	2.0	1.9	1.8	1.6	1.7	1.3	.16	.18	1.6	1.5	3.2	.26	2.3	2.0	.54
.45	.47	.46	.81	.93	.73	.34	.04	.05	.38	.37	2.1	.09	.72	.79	.19
.17	.32	.19	.08	.17	.06	.13	.02	.06	.26	.23	.06	.08	.22	.19	.10
.01	.43	2.6	1.9	.6	1.3	2.2	.01	.02	4.8	9.8	.01	15.7	.44	6.3	6.4
99.03	98.62	98.65	100.99	100.90	98.79	98.97	98.78	99.78	100.22	99.75	100.67	99.03	98.88	100.98	99.63

related to the trend of the basement fracture conduit. The intrusive rocks undoubtedly utilized preexisting Alleghanian fractures. Longitudinal joints, cross joints, and oblique fracture sets provided conduits for dikes (figs. 9 and 12), while bedding surfaces provided conduits for sills (figs. 10, 13, and 14).

Minor mineralization is associated with some dikes (Mitchell and Freeland, 1986). Sulfide minerals occur in a trachybasalt dike near the Ugly Mountain, W. Va., diatreme (fig. 5, sample 19). Local residents report that drilling of the diatreme in the late 1960's yielded shows of gold and uranium. Herbert and Young (1956) speculated that dikes provided the hydrothermal fluids for sulfide mineralization near Timberville, Va. Brucite marble, containing 17 percent brucite, has been recognized recently in the Hightown, Va., quarry at the contact of an Eocene trachydacite dike with dolomite of the Lower Ordovician Beekmantown Group (Giannini and others, 1987) (fig. 12).

MODELS OF EMPLACEMENT

Geochemical Models

Trace-element geochemistry of 46 samples is provided in table 4. Both the major-element and stable trace-element geochemistry indicate alkaline trends (tables 3 and 4). The Zr abundance is 600 ppm in sample 33 (table 4), a level which is considered to be the lower boundary for peralkaline rocks. A Hf/3-Th-Ta ternary diagram (fig. 15) shows that the basalts lie in the field of alkaline within-plate basalts; the tectonic environment associated with this rock

Table 4. Trace-element analysis for dikes, sills, and plugs

[Work performed in the laboratories of the U.S. Geological Survey. R. Johnson, analyst. All samples analyzed by INAA except Sr, Nb, and Y, which
Eocene age determined by: A, K-Ar and $^{40}Ar/^{39}Ar$; B, paleomagnetic data (Lovlie and Opdyke, 1974; Ressetar and Martin, 1980); and C, both A and

	Picrobasalt		Tephrite Basanite							
	1*	27	13	28	34B	36C	38C	41	42	43
Large Cations										
Rb	23.2	19.1	18	28.6	30	24	60	34	30	29
Ba	4,475	1,760	429	430	509	340	470	363	403	361
Sr.....	1,190	772	692	770	642.8	619.8	608.7	638.5	804.4	–
Cs	32.2	.36	.30	.36	<.4	<2.0	3.6	<.7	.8	.31
High-Valence Cations										
Th	5.21	2.07	2.99	2.62	2.8	2.7	2.4	2.7	2.6	2.17
U	1.12	2.5	.95	<2	.6	<2.0	<3.0	<4.0	<3.0	.64
Zr.....	155	61	135	175	140	–	120	195	190	128
Hf	3.50	2.93	4.21	4.22	4.1	3.5	3.8	4.2	4.4	3.53
Nb	76	27	38	33	32.8	30.1	25.9	33.2	28.9	–
Ta	5.31	1.62	2.38	2.12	2.44	2.06	1.97	2.27	2.26	1.84
Th/U ..	4.58	.84	3.152	–	4.7	–	–	–	–	3.4
Zr/Hf ..	43.56	20.75	32.03	41.48	34.1	–	31.6	46.4	34.2	36.2
Ferromagnesian Elements										
Co	27.5	50.4	44.9	40.0	48.6	52.8	65.5	55.8	41.4	55.7
Zn	108	76	93	98	91	96	110	111	109	94.4
Cr.....	486	236	43.1	26.2	21.1	381.0	294	209	22.5	627
Sc.....	35.2	32.8	25.1	22.0	31.90	30.70	38	30.70	22.50	34.3
Rare Earth Elements										
La	47.4	20.7	27.2	21.0	28	27	22	26	27	23.5
Ce	96.2	38.3	53.2	52.0	53	49	44	49	50	45.3
Nd	47	21	29	28.0	29	27	20	27	29	28.5
Sm	8.9	4.97	7.04	6.0	7.4	6.3	6.1	6.8	6.9	6.50
Eu	2.57	1.55	1.97	2.10	2.22	1.81	1.85	2.16	2.20	1.72
Gd	8.1	6.1	6.8	7.8	7.3	5.8	5.5	7.4	6.8	5.9
Tb	.92	.66	.885	.90	.98	.78	.85	.84	.85	.72
Tm	<.2	.25	.35	.33	.38	.34	.24	.31	.42	.29
Yb	1.64	1.80	1.92	2.04	2.2	1.8	1.7	1.9	2.2	1.74
Lu	.240	.248	.39	.30	.31	.27	.25	.30	.32	.242
Y	22	17	26	21	24.1	22.4	19.6	27.2	23.8	–

	Basalt					Trachybasalt		Basaltic Trachyandesite				
	16*	17	25	44	46A	8	19B	7	10	11	35	45
Large Cations												
Rb	174	32.1	20	19	17	41.8	20.5	25	35	38	41	42
Ba	3,890	1,580	570	449	385	782	709	870	800	681	657	773
Sr.....	1,900	772	684	1,049	547.2	1,190	1,090	1,030	946	806	–	1080.8
Cs	50.5	.50	.42	<.7	<.9	.34	.83	1.28	.33	.34	2.3	.7
High-Valence Cations												
Th	16.8	4.26	2.85	3.7	3.5	5.50	6.28	5.90	4.82	4.72	5.3	5.7
U	2.7	1.2	<3	<3.0	<2.0	1.50	1.5	1.15	1.68	1.22	1.2	1.9
Zr.....	241	171	112	260	150	277	257	261	265	256	250	336
Hf	5.14	4.55	2.97	5.1	2.5	6.93	5.57	7.09	6.36	6.09	6.6	7.7
Nb	122	55	38	31.7	30.4	51	70	52	50	45	–	42.7
Ta	6.30	2.86	2.09	2.78	1.51	3.42	3.84	3.75	3.10	3.03	3.65	4.25
Th/U ..	6.24	3.47	–	–	–	3.67	4.105	5.13	3.01	3.88	4.4	3.0
Zr/Hf ..	46.92	37.64	41.75	50.9	60.0	40.00	46.12	36.87	41.74	42.02	37.9	43.6
Ferromagnesian Elements												
Co	41.0	25.8	46.8	28.9	52.5	11.77	18.5	18.1	27.1	22.3	6.2	17.7
Zn	86	80	78	107	89	94	11.8	97	96.5	78	94	126
Cr.....	313	3.0	380	36.4	378.0	5.4	4.5	4.3	3.8	3.93	1.6	1.0
Sc.....	21.1	13.69	26.2	17.50	36.70	9.02	8.48	12.48	13.76	12.18	5.74	10.30
Rare Earth Elements												
La	128	41.3	26.4	35	29	50.6	46.8	61.7	57.3	42.3	46	54
Ce	174	77.7	48.9	66	44	96.4	93.4	101.6	95.7	83.5	91	107
Nd	61	42	25.9	35	21	46.4	44.7	55	48.4	42	47	54
Sm	10.8	9.11	5.58	8.3	4.8	10.35	9.98	11.0	10.25	8.41	9.4	9.9
Eu	2.80	2.68	1.61	2.66	1.53	2.97	2.54	3.04	2.91	2.51	2.97	3.16
Gd	7.2	8.8	5.7	8.3	6.1	8.7	9.2	9.2	9.3	7.5	9.2	9.5
Tb	1.19	1.12	.71	1.09	.84	1.20	1.16	1.20	1.20	.95	1.18	9.5
Tm	<.2	<.5	.32	.37	.46	.389	<.1	.55	.45	.34	.42	.65
Yb	3.0	2.48	1.61	2.7	2.7	3.16	2.50	3.25	3.14	2.32	2.8	2.9
Lu	.41	.36	.24	.40	.46	.459	.318	.456	.465	.343	.37	.41
Y	26	36	22	23.4	27.9	31	36	32	43	27	–	23.1

were analyzed by XRF. All analyses are in parts per million. No trace-element data are available for samples 47–52. Letter adjacent to sample no. indicates B. Samples with an asterisk (*) have geochemical signatures of Late Jurassic igneous rocks]

Trachyte-Trachydacite												
29C	30	31C	32B	33B	37	39	12	14	15	20	21A	26
Large Cations—Continued												
114	96	92	70	80.5	64	90	99.3	75	78	68	80	91.9
1,100	1,290	1,030	3,050	2,890	1,017	1,200	1,300	1,550	1,690	1,680	1,280	1,430
–	369.8	198.1	–	433.3	492.9	347.7	145	595	591	319	239	330
1.2	<.3	<.2	.4	<.4	.4	.2	.276	.154	.170	.530	.254	.152
High-Valence Cations—Continued												
8.9	14.2	16.9	12.6	14.95	10.9	14.4	14.1	9.07	8.67	23.1	22.2	15.8
2.6	3.6	3.1	2.4	3.9	2.8	2.8	2.24	1.8	2.19	5.25	4.8	5.1
402	586	490	463	601	408	505	369	575	546	346	330	459
9.3	13.2	11.9	11.7	13.15	9.0	12.5	10.3	13.5	12.9	10.82	10.48	12.43
–	83.0	81.9	–	78.6	79.9	79.9	111	65	58	170	160	114
4.56	6.08	6.33	5.23	6.02	5.31	5.99	7.19	4.36	4.30	10.25	9.90	7.21
3.42	3.9	5.45	5.25	3.6	3.9	5.1	6.31	4.70	3.96	4.39	4.65	3.12
43.2	44.4	41.3	39.6	45.7	45.3	40.4	35.91	42.74	42.44	31.98	31.16	36.88
Ferromagnesian Elements—Continued												
.6	.6	.7	1.0	.6	1.1	.2	.75	.501	1.62	6.12	2.62	5.77
86	31	85	160	138	95	61	81	74	78	26.2	14.5	87.8
<3.0	<8.0	<9.0	<9.0	<10.0	<10.00	<10	2.33	.90	2.71	1.08	1.6	2.1
.96	.8	1.13	1.22	1.52	2.01	.82	.271	.766	.94	.378	.316	.722
Rare Earth Elements—Continued												
65	86	139	92	70	83	128	22.2	74.2	64.7	86.8	104.9	75.4
107	150	188	153	117	130	139	109	107	116.5	144	170	131
48	59	89	70	49	62	108	15.9	46.2	41.2	41	50.0	38.8
7.2	10.0	14.6	11.4	7.8	9.6	17.1	3.63	7.80	7.56	8.0	8.70	7.10
1.81	2.60	3.00	3.15	2.37	2.93	4.16	1.63	2.27	2.08	1.89	1.58	1.78
–	8.2	10.2	9.3	6.3	6.3	13.1	4.4	4.75	5.4	9.1	9.0	6.3
–	1.27	1.82	1.51	.97	1.01	1.88	.51	.764	.83	1.01	.98	.87
–	.37	<.30	.54	<.30	<.30	.73	<.08	<.08	.39	<.1	<.1	<.09
3.2	3.9	4.3	3.9	2.8	3.1	4.7	3.71	2.44	2.91	4.65	3.99	3.58
.47	.50	.57	.53	.41	.44	.62	.444	.338	.455	.654	.610	.491
–	34.5	41.5	–	26.5	31.4	37.6	22	26	28	41	40	32

				Diatreme Breccias: Altered and Contaminated						
Trachyandesite		Rhyolite		Picrobasalt		Basalt				Andesite
5B	6	9	40	4	23	2*	3	18A	22	24*
Large Cations—Continued										
34.1	50	102.5	100	16	17.2	20	159	33	29.4	146
2,190	840	1,340	1,170	480	381	2,110	2,695	1,660	691	385
961	553	155	73.3	278	300	305	1,940	338	961	269
.28	.55	.30	.3	.28	.58	1.59	34.75	1.52	.45	3.16
High-Valence Cations—Continued										
5.22	6.30	15.38	17.6	2.73	2.34	10.1	5.80	10.19	4.88	35.7
1.69	1.65	2.81	3.5	.52	<2	2.42	2.00	1.74	1.07	7.5
264	241	349	534	163	83	173	316	190	170	264
6.33	6.60	10.65	13.6	2.55	2.50	4.22	7.15	4.49	4.40	10.9
55	58	122	136.8	31	26	175	28	71	46	289
3.61	3.92	7.61	9.38	1.56	1.45	8.8	2.26	3.25	2.66	15.5
3.08	3.78	5.47	5.03	5.28	–	4.13	2.60	5.51	4.54	4.79
41.77	35.70	32.78	39.2	64.17	33.01	40.96	43.54	40.24	38.69	24.11
Ferromagnesian Elements—Continued										
3.84	15.3	.39	5.7	51.4	35.2	30.4	2.5	21.3	34.2	8.43
34.5	80.6	37.7	17	80	61	108	52.6	91.9	91.0	107
1.9	2.6	1.99	<9.0	527	276	323	11.55	3.4	20.3	43.9
5.56	9.32	.33	.32	26.9	23.4	30.6	2.02	11.56	14.09	8.06
Rare Earth Elements—Continued										
46.0	42.9	56.4	73	23.3	21.7	84.1	34.4	58.5	45.0	90.2
89.5	100	152.3	147	41.7	40.6	135	59.8	94.5	78.6	82
42.1	44.7	32.6	54	19.5	20.6	70	22.4	39	36	51
9.65	9.32	6.10	9.0	4.70	4.67	13.7	4.03	7.97	7.62	11.3
2.94	2.37	1.89	2.40	1.44	1.40	3.28	1.11	2.26	2.25	1.64
9.1	7.7	6.6	8.9	4.9	4.3	12.1	3.30	9.2	6.7	12.7
1.14	1.01	.716	1.41	.733	.625	1.09	4.41	1.00	.85	1.69
<.9	.401	<.09	.78	<.4	<.4	<.2	.15	.330	<.1	<.2
2.80	2.90	3.38	5.8	1.46	1.41	1.66	1.60	2.37	1.89	5.5
.402	.420	.471	.81	.243	.24	.25	.251	.32	.27	.84
30	28	29	51.5	20	17	34	9	33	21	85

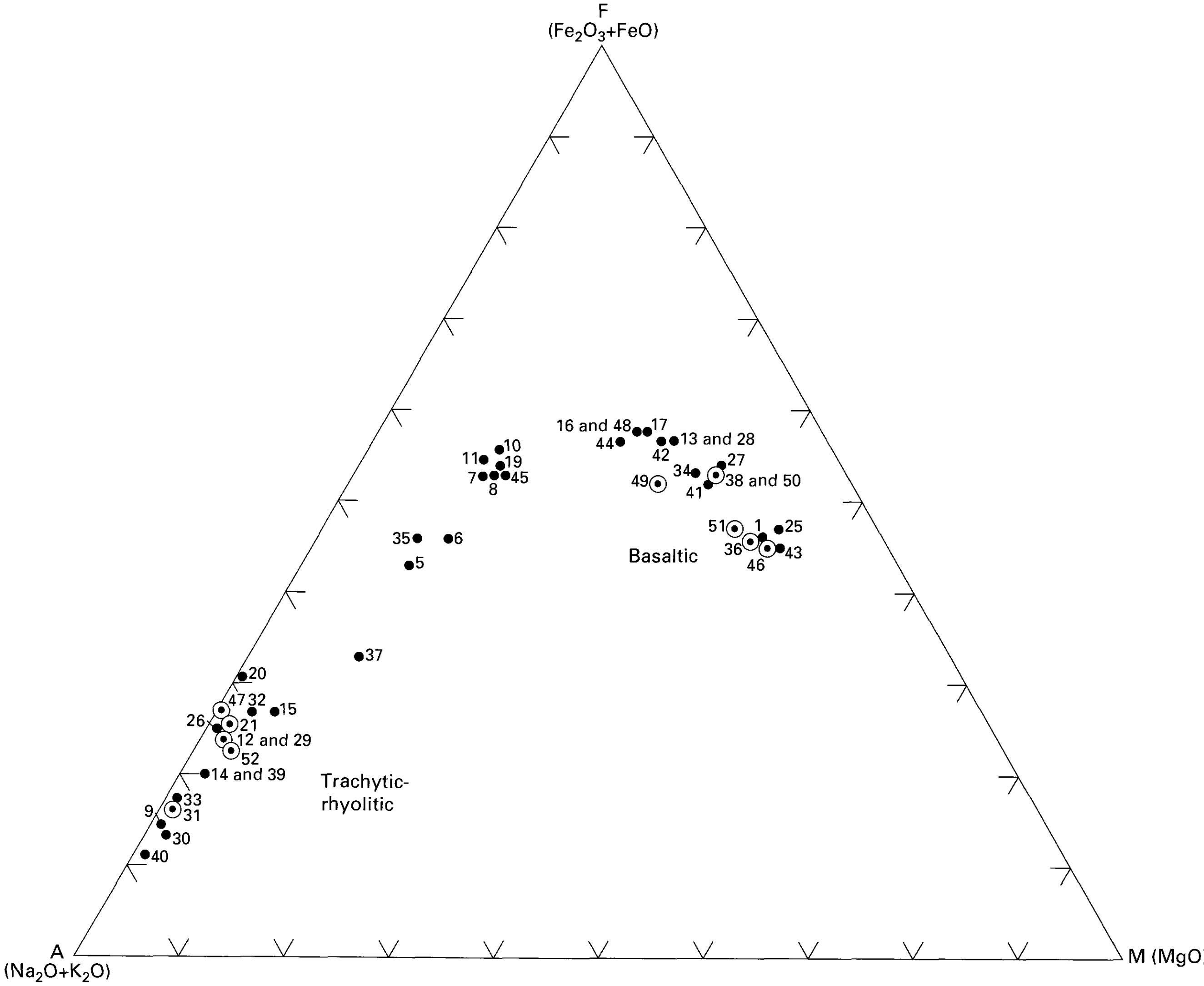


Figure 7. AFM projection showing basaltic to trachytic-rhyolitic composition of samples in table 3. Sample localities shown in figure 5. Circles denote dated samples.

type is slow intraplate extension (Wood, 1980). Several samples (1, 2, 16, and 24) fall outside of the boundary for alkaline within-plate basalts. Although these samples have not been dated, they have geochemical signatures similar to those of the Late Jurassic rocks (Gray and Gottfried, 1986). The Late Jurassic suite shows an unusual enrichment in Nb, Ta, U, and Th, and this enrichment pulls them out of the normal alkaline field because the diagram uses two of these elements. The low abundance levels of lithophile elements K, Rb, and Cs in the felsic rocks indicate a mantle origin with little or no crustal contamination. On a logarithmic plot of Th versus Ta, the Eocene mafic and felsic rocks show a remarkable linearity, which suggests that they are cogenetic (Gray and Diecchio, 1983; unpub. data, 1992; Gray and Gottfried, 1986). This correlation supports conclusions made by Hall (1975) on the basis of major-element chemistry. The light rare earth elements (REE's) are enriched and the heavy REE's are depleted, so the REE plots (fig. 16) have a steep slope that is similar to those associated with continental rifting (Condie, 1976).

Considered as a whole, the trace-element geochemistry of the Eocene igneous rocks suggests a mantle source, extensional tectonics, a common source for both the mafic and felsic rocks, and little crustal assimilation. These factors can best be explained by a mode of rapid emplacement through a deep-seated fracture zone. Such a fracture zone would allow magma to rise rapidly without assimilating continental crust. The existence of diatremes and volcanic breccia and the fact that there is little contact metamorphism support a model in which emplacement was rapid and explosive. The close spatial association of Late Jurassic and Eocene igneous rocks in this region indicates that such a fracture zone could have been a zone of crustal weakness in the Mesozoic that was reactivated in the

Figure 8. Trimble Knob, a basalt diatreme intruded in Devonian Millboro Shale. View is to the north toward Monterey, Va.; relief is approximately 73 m. (Sample 8, fig. 3 and table 1, and samples 36 and 51, fig. 5 and tables 3 and 4.)

Figure 10. A sill of explosion breccia in Ordovician Beekmantown Dolomite, Hightown, Va., quarry. Rounded clasts of dolomite as much as 7 mm in diameter are due to corrosion by CO_2 gas fluidization. View is to the east. (Sample 3; fig. 5 and tables 3 and 4.)

Figure 9. A peridotite porphyry (Garner, 1956) dike in Silurian Tuscarora Quartzite has weathered to saprolite. View to the north along Route 33 in West Virginia. (Sample 2, fig. 5 and tables 3 and 4.) Possibly a Late Jurassic dike.

Figure 11. Columnar-jointed basalt east of Hightown, Va., suggests near-surface emplacement. (Sample 34, fig. 5 and tables 3 and 4.) Paleomagnetic coreholes are visible to the right of the hammer (Lovlie and Opdyke, 1974; Ressetar and Martin, 1980).

Figure 12. The northwest face of the abandoned Virginia Department of Highways and Transportation quarry in Hightown, Va. Near-vertical, branching basalt (B) dikes crosscut an older basaltic trachyandesite (A) sill in the 70° southeast-dipping Ordovician Beekmantown Dolomite; breccia (C) is shown in figure 10. Brucite marble (Giannini and others, 1987) occurs here as an alteration product. Width of basalt dikes is approximately 1 m. (Samples 3, 5, 29, 35, and 52, fig. 5 and tables 3 and 4.)

Figure 13. Trachybasalt sill in vertical beds of Devonian Millboro Shale. The concordant intrusion is not offset by a fault; displacement by branching is similar to the exposure in figure 12. View is to the northeast, just south of Sugar Grove, W. Va. (Sample 19, fig. 5 and tables 3 and 4.)

Cenozoic. Differentiation of the magma probably occurred at great depth, where the fractionation could have occurred without melting or assimilating crustal rocks. The felsic rocks are generally not rich in phenocrysts, and therefore a shallow magma chamber probably did not exist for a long period of time before emplacement.

Previous Tectonic Models

Tectonic models proposed for the origin of the Jurassic and Eocene intrusive rocks invoke either regional cross-strike structures (fig. 17), hotspots, or a combination of both. Zartman and others (1967), Fullagar and Bottino (1969), Dennison and Johnson (1971), King (1971), Heyl (1972), and Rader and others (1986) attribute the igneous activity to a structural lineament along the 38th parallel (Heyl, 1972) (fig. 17). However, geologic data are insufficient to extend the 38th parallel lineament east of the Irving-Paint Creek fault zone in Kentucky (fig. 17). Sutter (1976) suggested the transcurrent Cornwall-Kelvin fracture zone as the conduit of magma. Sykes (1978) and Metcalf (1982) proposed that the igneous activity was due to the

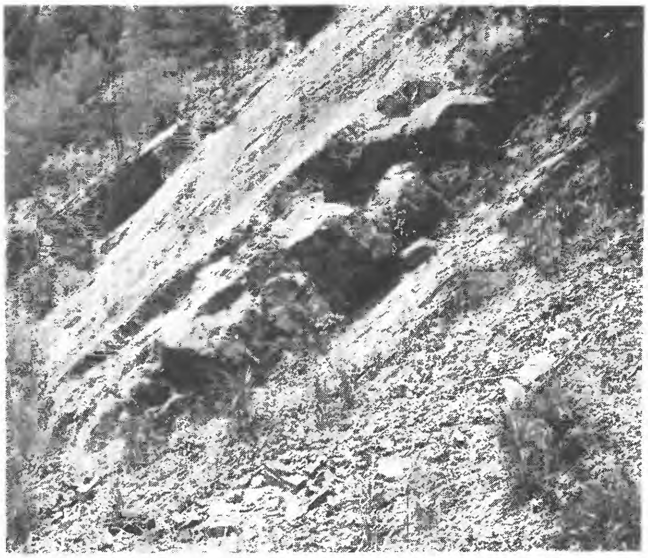


Figure 14. Trachybasalt sill in shale beds of the Devonian Brallier Shale. View is to the southwest, just south of Sugar Grove, W. Va. Note paleomagnetic coreholes (Ressetar and Martin, 1980) near the center. (Sample 8, fig. 3 and table 1, and sample 49, fig. 5 and table 3.)

westward extension of the offshore Norfolk fracture zone onto the continent (fig. 17). McHone and others (1987) suggested that the extension of the Kane fracture zone onto the continent was the conduit for the Eocene intrusive rocks and the Bermuda seamount. Core and others (1974) suggested that the 38th parallel structure passed over a hotspot. De Boer and Snider (1979) also proposed a hotspot model.

Dennison and Johnson (1971) suggested that the 70-milligal negative Bouguer gravity anomaly in this region signified an area of maximum domal uplift that was due to isostatic rebound. They also postulated that the thermal springs to the south were heated by a slow-cooling, Eocene felsic pluton. Perry and others (1979) later determined that there was no connection between the exposed Eocene igneous rocks and the thermal springs. Bollinger and Gilbert (1974) recognized an apparent low heat flow and an earthquake shadow zone in this region.

Proposed Tectonic Model

The relationship between structures in the basement and structures in the allochthonous cover rocks of the Valley and Ridge province becomes important in formulating a tectonic model for the intrusive rocks. Indirect basement involvement on the overlying structures is believed to be that of normal faults in the basement that extend into and through potential zones of décollement to initiate tectonic ramps (Jacobeen and Kanes, 1974; Wiltschko and Eastman, 1983; and Shumaker, 1986). The basement faults would control the location of the tectonic ramps of the duplex structures of Cambrian to Ordovician rocks and resultant anticlinoria of Silurian to Devonian rocks (fig. 2, cross section). The vertical correlation of northeast-trending surface structures to basement faults is problematic because of tectonic transport of the Alleghanian orogeny. Cross-strike structures that parallel the direction of tectonic transport may, however, overlie a northwest-trending subsurface fault (Wheeler, 1986). The coincidence of some surface and inferred subsurface structures in this region suggests a tectonic model of reactivated cross-strike and strike-parallel basement faults (fig. 18). Extensional growth faults of Late Proterozoic to early Paleozoic age may have been reactivated by compressional tectonics of the late Paleozoic Alleghanian orogeny and by extensional tectonics of the Mesozoic and early Cenozoic eras.

Reactivated growth faults in the central Appalachians are well documented (Root, 1978; Shumaker, 1986). Jacobeen and Kanes (1974), using seismic reflection data, interpreted a down-to-the-southeast normal fault in basement rocks beneath the Wills Mountain anticline to the north of this study area. Ryder (1988) interprets similar normal faults beneath the Appalachian Plateaus structural front in this study area as continental margin rifted during the Cambrian. It has also been suggested that reactivated growth faults in the Appalachians are causally related to kimberlite intrusions (Parrish and Lavin, 1983) and areas of seismicity (Bollinger and Wheeler, 1983).

Northwest-trending transform faults of the Cambrian Rome trough, interpreted from regional gravity data (Kane, 1983; Rice, 1983), border this region (fig. 17, nos. 6 and 7). Lateral changes in duplex blocks of Cambrian and Ordovician carbonate rocks (Wilson and Shumaker, 1988) occur across the zone of the Eocene igneous rocks (fig. 17, no. 10). The differences in shortening of the duplex blocks across this zone (Wilson and Shumaker, 1988) may be represented by northwest-trending lineaments of the Appalachian Plateaus province (Gwinn, 1964; Rodgers, 1970; Kulander and Dean, 1978; and Wheeler, 1986). The Bartow lineament (Wheeler, 1986; fig. 17, nos. 5 and 8) is believed to be the lateral boundary of the Browns Mountain and Elkins Valley allochthonous blocks that underwent differential tectonic transport in the Alleghanian orogeny (Kulander and Dean, 1978). Stratigraphic studies suggest that the Bartow lineament controlled sedimentation during much of Middle and Late Devonian time at the Appalachian Plateaus structural front (Wheeler, 1986). Yielding and Dennison (1986) report that tectonic activity along the eastern end of the 38th parallel lineament (fig. 17, no. 9) is indicated by lithologic variations in Upper Devonian to Upper Mississippian rocks on the plateau of West Virginia.

Sykes (1978) and Metcalf (1982) place the continental extension of the Jurassic Norfolk fracture zone (fig. 17, no. 4) near the area where the unusual alkalic suite of Late Jurassic dikes changes regional strike. Down-to-the-northeast basement faulting, and both uplift and subsidence

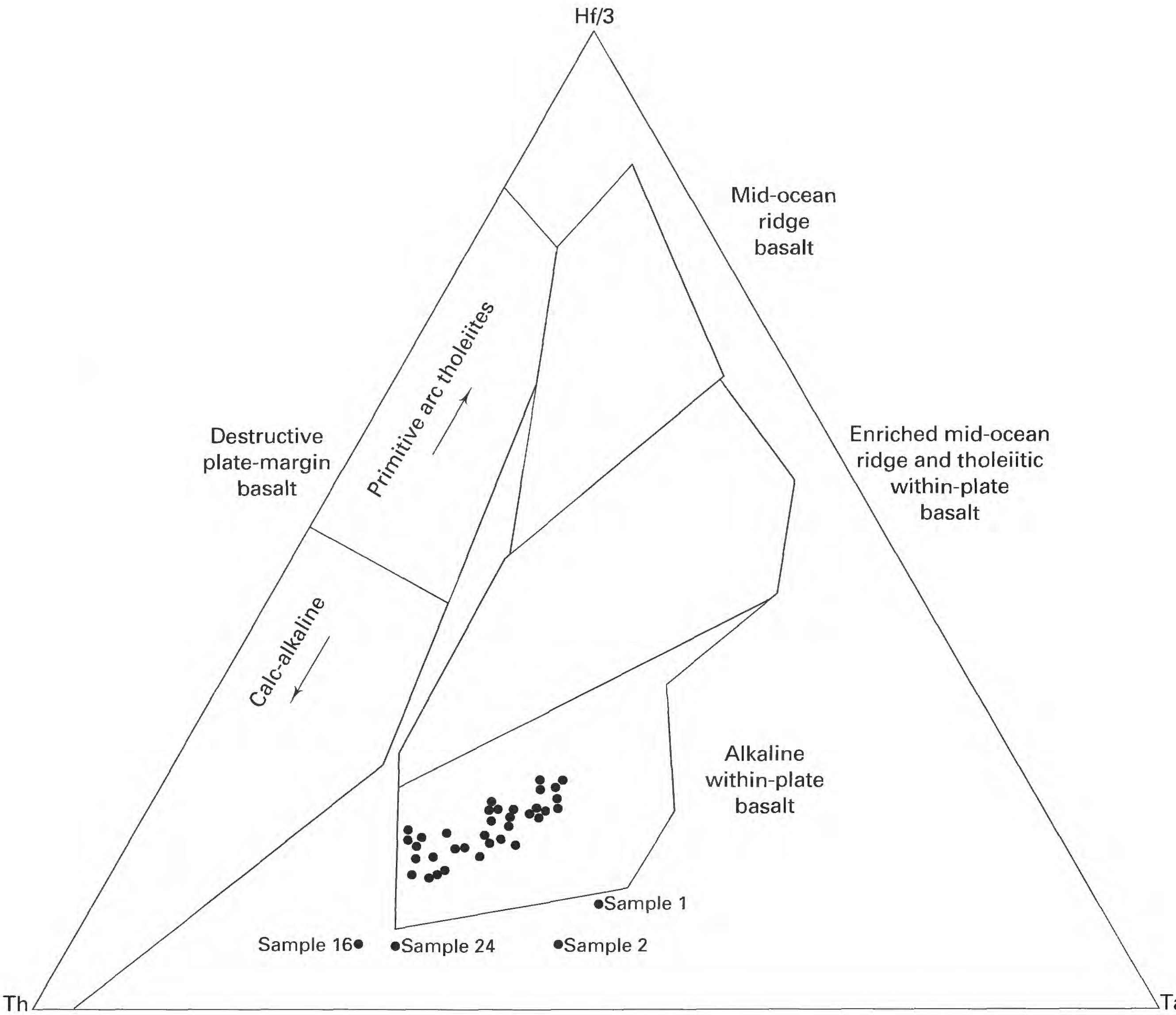


Figure 15. Hf/3-Th-Ta ternary diagram for tectonic setting of basalts (after Wood, 1980) showing the field of samples in the Valley and Ridge province.

during the Eocene, has been interpreted from stratigraphy in the Coastal Plain where the Norfolk fracture zone projects on land (Cederstrom, 1945; Powars and others, 1987).

The drainage divides of seven tributaries of the Potomac and James Rivers are found across this zone of intrusive rocks (fig. 17). These highlands form a linear zone of headwaters that equally divide over 100 km of longitudinal drainage. The divides of the Jackson River and South Branch Potomac River coincide with a structural culmination of the Wills Mountain anticline at Hightown, Va. This structural culmination is near the duplex boundary suggested by Wilson and Shumaker (1988) and is in the center of the Eocene activity. The 100-km-long region of high topography is the structural culmination of the Wills Mountain anticline and the fold belt on the plateau.

We propose that an extensionally reactivated cross-strike basement fracture and a strike-parallel growth fault near the Appalachian Plateaus structural front are the deep fracture conduits for the Eocene igneous rocks (fig. 18*A*, *B*). The near-perpendicular trends of the basement fracture zones may define part of a rift and (or) transform fault system that borders basement blocks. Northwest-trending Late Jurassic dikes were emplaced along a cross-strike basement fracture zone that extends into Pendleton County, W. Va. Some middle Eocene intrusive rocks were emplaced along the same cross-strike basement fracture zone. Northeast-trending intrusive rocks in Highland County, Va., are parallel to inferred growth faults. The conjugate trend of dikes presents a mechanical problem of two stress-field directions. Northeast- and northwest-trending middle Eocene rocks suggest that a local variation of a consistent stress-field orientation may have reactivated an existing fabric of structural weakness (fig. 18*C*).

The orientation of the stress and strain ellipse for this region is interpreted to have varied throughout geologic time (table 5). Northwest-oriented least compressive stress (σ_3) prevailed during Late Proterozoic and early Mesozoic rifting (table 5). The interpreted orientation of the stress and strain ellipse of the Late Paleozoic Alleghanian orogeny (northwest-oriented σ_1) is coaxial to Late Jurassic extension (northeast-oriented σ_3) (table 5). Conjugate trends of middle Eocene intrusive rocks (fig. 18) suggest that both stress regimes were active. The occurrence of two nearly perpendicular stress fields is mechanically impossible, and a change in stress field is unlikely over short periods of geological time. However, a north-south-oriented maximum compressive stress (σ_1) that bisects the acute angle of the conjugate dike trend could account for the two orientations.

Data from well breakouts and Cenozoic fault orientations show that the Eastern United States is characterized by northeast to east-northeast compressional stress (Zoback and Zoback, 1989). Relaxation of this stress orientation can account for the northeast trend of middle Eocene rocks. The "Atlantic coastal stress province" shows northwest-oriented maximum compression, but these data are eliminated (Zoback and Zoback, 1989) because they are inconsistent with the rest of the region.

The cause of continental extension of this region during the middle Eocene is interpreted to be the result of a change in plate tectonic motion. Manspeizer and others (1989) and Vogt (1991) suggest that plate-kinematic reorganizations caused the middle Eocene igneous activity and the formation of the Bermuda Rise. Over 56 events worldwide indicate a major reorganization of global plate motion from 53.5 to 37.5 Ma (Rona and Richardson, 1978). A specific event of plate reorganization, Chron 19, occurred at 44 Ma (McGowran, 1989). The main, edifice-building phase of Bermuda volcanism (45–33 Ma), the formation of the Bermuda Rise (45–40 Ma), and reorganization of the Pacific plate motion are thought to be related to the Middle Eocene intrusive rocks (Vogt, 1991). The range of radiometric ages of 48 to 35 Ma for igneous rocks in this region suggests a causal relationship. The apparent offset of northwest-trending vertical dikes by low-angle thrust faults has been observed at several exposures by the lead author, Donaldson and others (1964), and Johnson and others (1971).

SUMMARY

The central Appalachian basin has experienced at least three episodes of igneous activity since the late Paleozoic Alleghanian orogeny. Late Paleozoic to Cretaceous kimberlite dikes and plugs intruded along the basinal axis. Hypothetical crustal fractures along the basin axis were perhaps reactivated because of isostatic rebound (Denison, 1983). Late Jurassic dikes intruded rocks of the Shenandoah Valley and the Valley and Ridge province. This unusual suite of alkalic igneous rocks, and the more extensive, Early Jurassic mafic dike swarms of the Appalachian Piedmont and Blue Ridge, is the result of Mesozoic continental extension related to the opening of the Atlantic Ocean. Finally, middle Eocene basalt and rhyolite dikes, sills, plugs, and diatremes were intruded into the Paleozoic rocks of the Valley and Ridge province. Geochemical data suggest that the source of magma was upper mantle to lower crust and related to continental extension. The Eocene igneous activity was short lived, areally restricted, and sometimes explosive; no evidence of extrusive flows is preserved. Radiometric data show that the region of the youngest igneous rocks in the Eastern United States also experienced igneous activity in the Late Jurassic.

The tectonic model proposed here for the origin of the middle Eocene intrusive rocks is the extensional reactivation of basement fracture zones. The northwest-trending basement fracture zone may be inferred from structural discontinuities in the overlying allochthonous rocks of Paleozoic age. An apparent change in stress field marked by the change in orientation of Late Jurassic dikes may delineate the cross-strike basement fracture zone. The western limit of Late Jurassic activity occurs in the area of Eocene rocks in Pendleton County, W. Va. Strike-parallel growth faults of Late Proterozoic to Early Cambrian age may have provided the fracture conduit for northeast-trending Eocene intrusive rocks in Highland County, Va. Conjugate trends of middle Eocene rocks suggest that a local variation of a consistent stress field may have reactivated existing fabrics of structural weakness. The cause of middle Eocene continental extension is interpreted to be the result of a change in plate motion that is recognized worldwide.

ACKNOWLEDGMENTS

The authors wish to thank D.L. Core for $^{40}Ar/^{39}Ar$ data in table 2. Technical reviews by William C. Burton, Albert J. Froelich, and J. Gregory McHone (Wesleyan University) greatly improved the text. We would like to thank the landowners of Highland County, Va., and Pendleton, County, W. Va., for providing access to exposures.

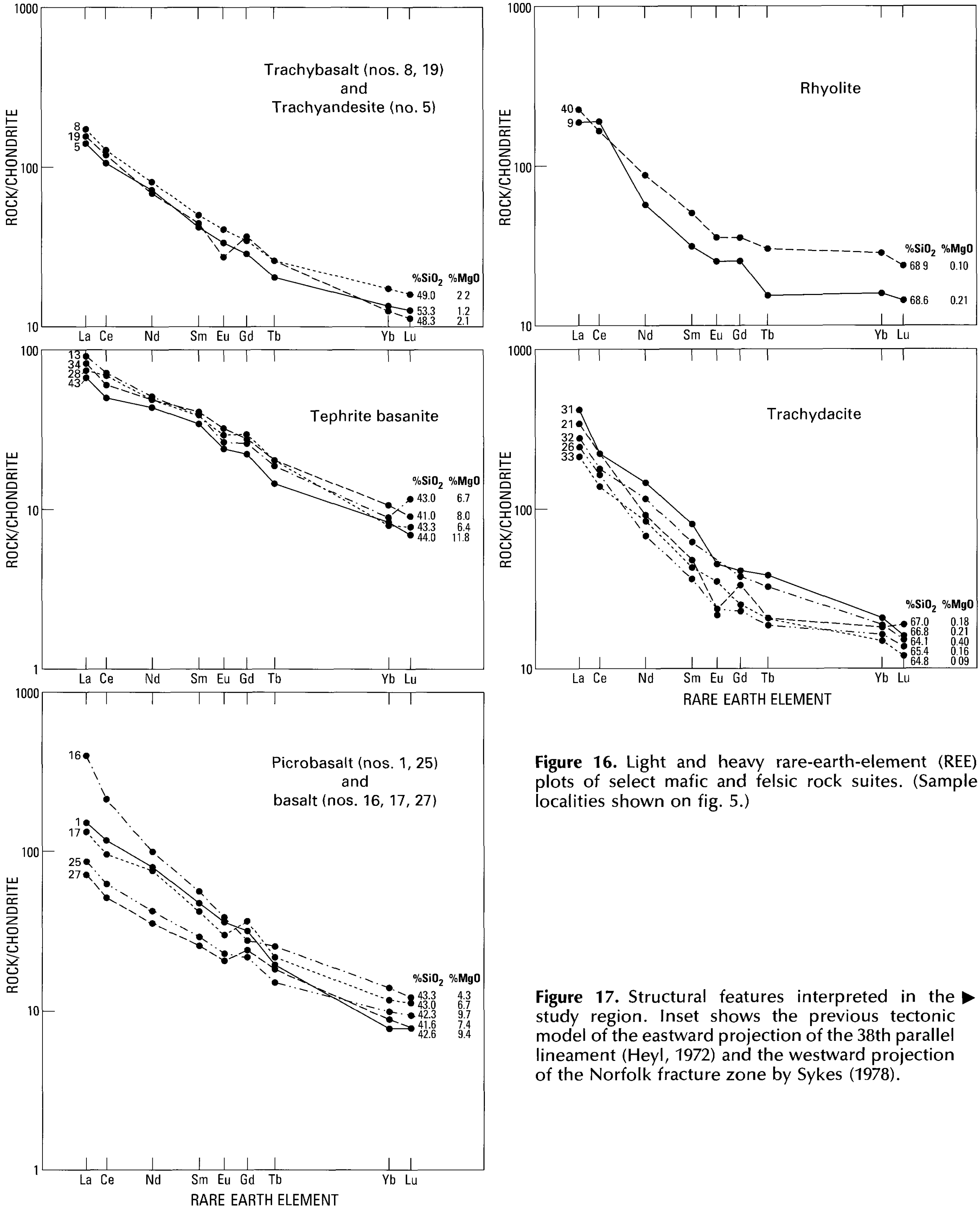
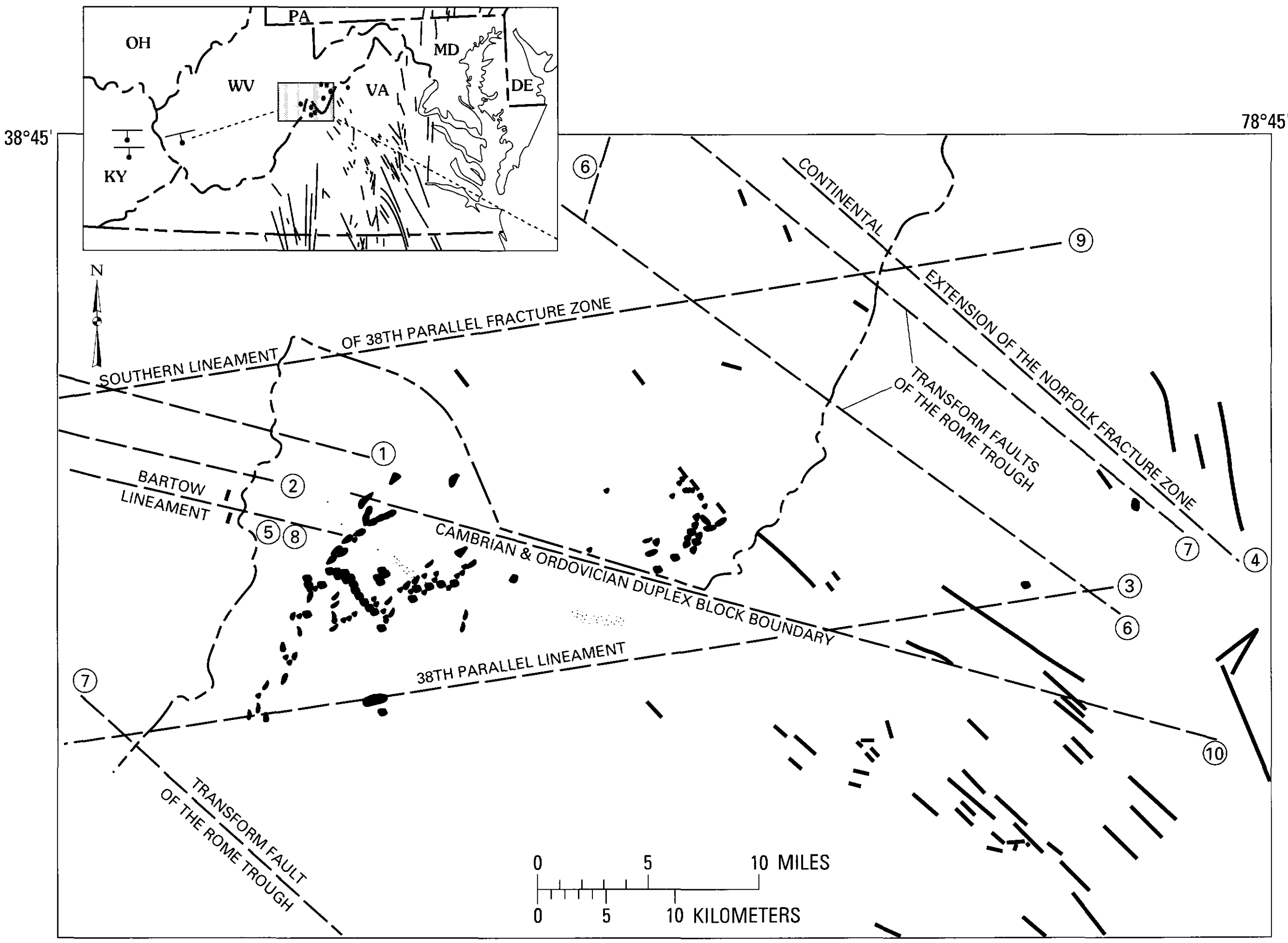


Figure 16. Light and heavy rare-earth-element (REE) plots of select mafic and felsic rock suites. (Sample localities shown on fig. 5.)

Figure 17. Structural features interpreted in the ▶ study region. Inset shows the previous tectonic model of the eastward projection of the 38th parallel lineament (Heyl, 1972) and the westward projection of the Norfolk fracture zone by Sykes (1978).



EXPLANATION

- Plugs and diatremes
- Igneous dikes and sills
- Drainage divides of the Potomac and James Rivers
- Fault

Structural lineament (reference; age)

1. Gwinn, 1964; Pennsylvanian
2. Rodgers, 1970; Pennsylvanian
3. Heyl, 1972; Precambrian
4. Sykes, 1978; Jurassic
5. Kulander and Dean, 1978; Pennsylvanian
6. Kane, 1983; Cambrian
7. Rice, 1983; Cambrian
8. Wheeler, 1986; Devonian
9. Yielding and Dennison, 1986; Devonian to Mississippian
10. Wilson and Shumaker, 1988; Pennsylvanian

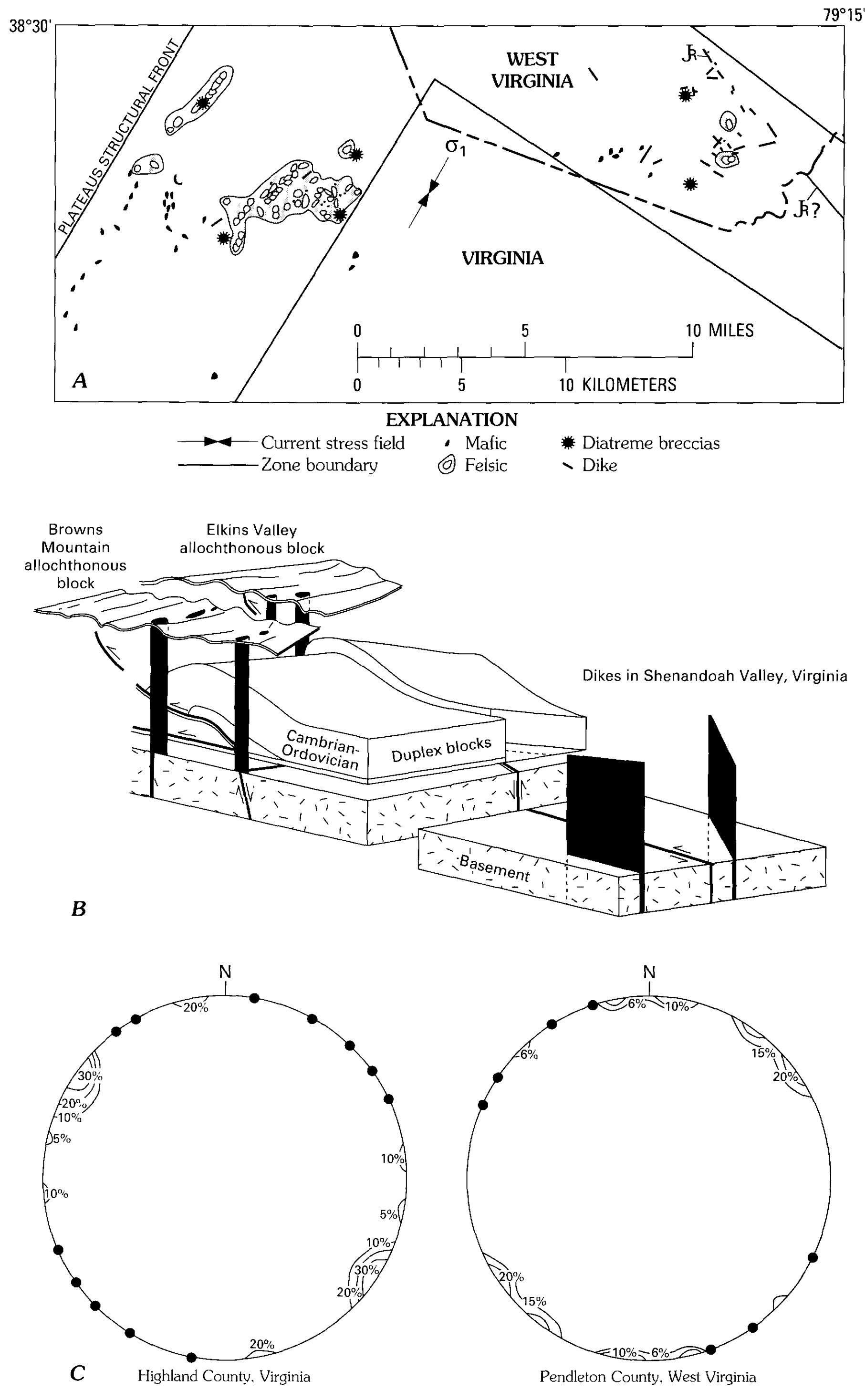
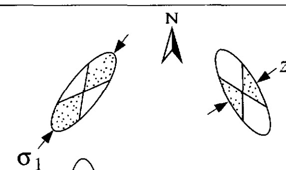
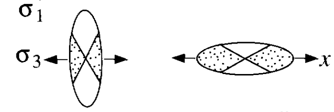
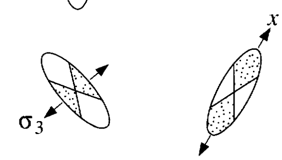
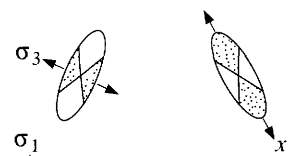
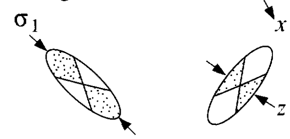
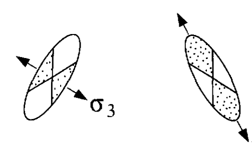


Figure 18. *A*, Proposed tectonic model of the Late Jurassic and middle Eocene intrusive rocks. The northwest-trending zone is a cross-strike basement fault that was active in Late Jurassic and middle Eocene time. The northeast-trending zone is a strike-parallel growth fault of Late Proterozoic to Cambrian age that extended in middle Eocene. *B*, Schematic block diagram illustrates the possible relationship of basement fracture zones to Alleghanian structures and Late Jurassic and middle Eocene igneous activity. Schematic diagram is parallel to the northwest-trending zone. *C*, Equal-area stereographic projections (lower hemisphere) of poles to strikes of near-vertical dikes and sills. Highland County, Va.: N = 43; contour percent = 30, 20, 10, and 5. Pendleton County, W. Va.: N = 47; contour percent = 20, 15, 10, 6, and 4; ● = 2 percent.

Table 5. Variations in structure, tectonics, and stress fields of the central Appalachian region from Late Proterozoic to present time

[σ_1, direction of maximum compressive stress; σ_3, direction of least compressive stress; x, axis of greatest principal strain; z, axis of least principal strain]

Geologic age	Geologic feature	Geologic event	Tectonic regime	Interpreted elipse orientations	
				Stress	Strain
Tertiary to Holocene	High-angle thrust faults	Spreading Mid-Atlantic Ridge	Compression		
Middle Eocene	Dikes, sills, and diatremes	Change in plate tectonic motion	Extension		
Late Jurassic	Dikes	Continental rifting to form the Atlantic Ocean	Extension		
Early Jurassic	Grabens, dikes, and sills	Continental rifting to form the Atlantic Ocean	Extension		
Permian to Pennsylvanian	Folds and low-angle thrust faults	Continent-to-continent collision of the Alleghanian orogeny	Compression		
Early Cambrian to Late Proterozoic	Grabens and normal faults	Continental rifting to form the Iapetus Ocean	Extension		

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