DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Oil and Gas Resources of the Cincinnati Arch, Ohio, Indiana, Kentucky, and Tennessee

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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INTRODUCTION

Arch location and size

The U.S.A. part of the Cincinnati arch is a 500 mi-(800 km-) long, 100 to 250 mi- (160 to 400 km-) wide positive feature that extends from western Ohio and north central Indiana, through central Kentucky and central Tennessee, to northwestern Alabama (fig. 1). The arch is flanked on the west by the Illinois basin and the Mississippi embayment and on the east by the Appalachian basin. The northern and southern ends of the arch are bounded by the Michigan basin and Black Warrior basin, respectively. In outcrop, the Cincinnati arch is defined by circular- to oval-shaped areas of Middle and Upper Ordovician strata (King and Beikman, 1974). In the subsurface the arch is defined by the -1.0 and -1.5 km structure contour lines drawn on top of Precambrian basement rocks (King, 1969). The Cincinnati arch covers an area of about 63,000 sq mi (162,000 sq km).

Structural setting

The southern and central parts of the Cincinnati arch are subdivided into three structural elements: the Nashville dome in central Tennessee; the Jessamine dome (Lexington dome) in northern Kentucky; and the intervening Cumberland saddle (figs. 1 and 2). North of Cincinnati, Ohio the arch bifurcates into an eastern positive element, the Findlay arch, and a western positive element, the Kankakee arch (figs. 1 and 2). The Findlay arch plunges into the Chatham sag in Canada and reappears to the northeast as the Algonquin arch. The boundary between rocks of the Grenville Province (1.0 Ga) and older rocks of the Central Province (1.4 Ga) to the west is located within the basement rocks of the Cincinnati arch (Bass, 1960; McCormick, 1961, Engle, 1963).

The Kentucky part of the Cincinnati arch is disrupted by extensional faults that involve Precambrian basement rocks and overlying sedimentary rocks. Major extensional faults in this region are the Irvine-Paint Creek, Kentucky River, Lexington, and Brumfield faults (figs. 1 and 2). The east-trending, down-to-the-south, Irvine-Paint Creek and Kentucky River faults (McDowell and others, 1981; Black, 1986a,b) form the northern margin of the Rome trough, a major graben system that trends eastward to northeastward through eastern Kentucky, central West Virginia, and western Pennsylvania (McGuire and Howell, 1963; Wagner, 1976; Cardwell, 1977; Harris, 1978). The Rome trough and its north-bounding faults terminate against the north-northeast trending, down-to-the-east Lexington fault (fig. 1; Black, 1986b). East-trending faults, subparallel to the Irvine-Paint Creek and Kentucky River fault zones reappear a short distance west of the Lexington fault as the Brumfield fault zone (McDowell and others, 1981; Black, 1986b). Farther west, the Brumfield fault zone merges with the Rough Creek fault zone, the northern boundary of the Rough Creek graben (Moorman syncline) in the Illinois basin (fig. 1; Ross, 1963; Lumm and Nelson, 1985; Black, 1986a). The Brumfield fault zone defines the northern limit of the Cumberland saddle (fig. 1).

Figure 1. Tectonic map of Ohio, Indiana, Kentucky, Tennessee and adjacent states showing the U.S.A. part of the Cincinnati arch and its subprovinces (outlined by heavy line) and major tectonic elements of the region. The map is taken from King (1969). Structure contours, in kilometers below mean sea level, are drawn on top of Precambrian basement rocks. Structure contours of King (1969) were modified to conform to data from drill holes 2 and 3 and numerous unidentified drill holes. Additional modifications to King's (1969) map are based on the work of Sutton (1974), Harris (1975), Milici (1980), Black (1986a), and Ryder (1987). Drill holes are identified as follows: 1. Ohio Division of Geological Survey core hole No. 2580, sec. 12, T. 3N., R. 14E., Liberty Township, Seneca County, Ohio; 2. Cities Service Company No. A-1 O-G Garrett, Carter coordinates 7-I-57, Casey County, Kentucky; 3. Associated Oil and Gas Exploration Company No. 1 Sells, Carter Coordinates 3-A-54, Pickett County, Tennessee; 4. Dupont and Company No. 1 Monitoring well, sec. 16, T.3S., R.35E., Davidson County, Tennessee. Major tectonic features are identified as follows: AB, Appalachian basin; AFTB, Appalachian fold and thrust belt; BF, Brumfield fault; BGF, Bowling Green fault; BRF, Blue Ridge fault; BWB, Black Warrior basin; CS, Cumberland saddle; FA, Findlay arch; GL, Glasgow lineament; IB, Illinois basin; IPCF, Irvine-Paint Creek fault; JD, Jessamine dome; KA, Kankakee arch; KOT, Kentucky and Ohio trough; KRF, Kentucky River fault; LF, Lexington fault; LPF, Logansport fault; MB, Michigan basin; MCF, Mount Carmel fault; ME, Mississippi embayment; NCIT, North-central Indiana trough; ND, Nashville dome; PMF, Pine Mountain fault; RCF, Rough Creek fault; RCG, Rough Creek graben; RT, Rome trough; WF, Warfield fault. Exposed rocks in the Appalachian fold and thrust belt are identified as follows: wavy-line pattern, highly metamorphosed rocks of middle and early Paleozoic age; random-dash pattern, granitic and mafic plutonic rocks chiefly of middle Paleozoic age; cross pattern, metamorphic and plutonic rocks chiefly of Middle Proterozoic age; stippled pattern, sedimentary rocks of Early Cambrian and Late Proterozoic ? age and volcanic rocks of Late Proterozoic age; dash pattern, deformed sedimentary rocks of Cambrian through Pennsylvanian age; horizontal line pattern, sedimentary and volcanic rocks of Triassic and Jurassic age; small open circles, sedimentary rocks of Cretaceous, Tertiary, and Holocene age. XX', YY', and ZZ' are lines of geologic cross section shown in figure 2. Major cities are identified as follows: Cc, Chicago; Ch, Chattanooga; Ci, Cincinnati; Cl, Charleston; Co, Columbus; Cv, Cleveland; E, Evansville; F, Frankfort; Fi, Findlay; FW, Fort Wayne; I, Indianapolis; K, Knoxville; L, Louisville; N, Nashville; P, Pittsburgh; R, Roanoke; T, Toledo.

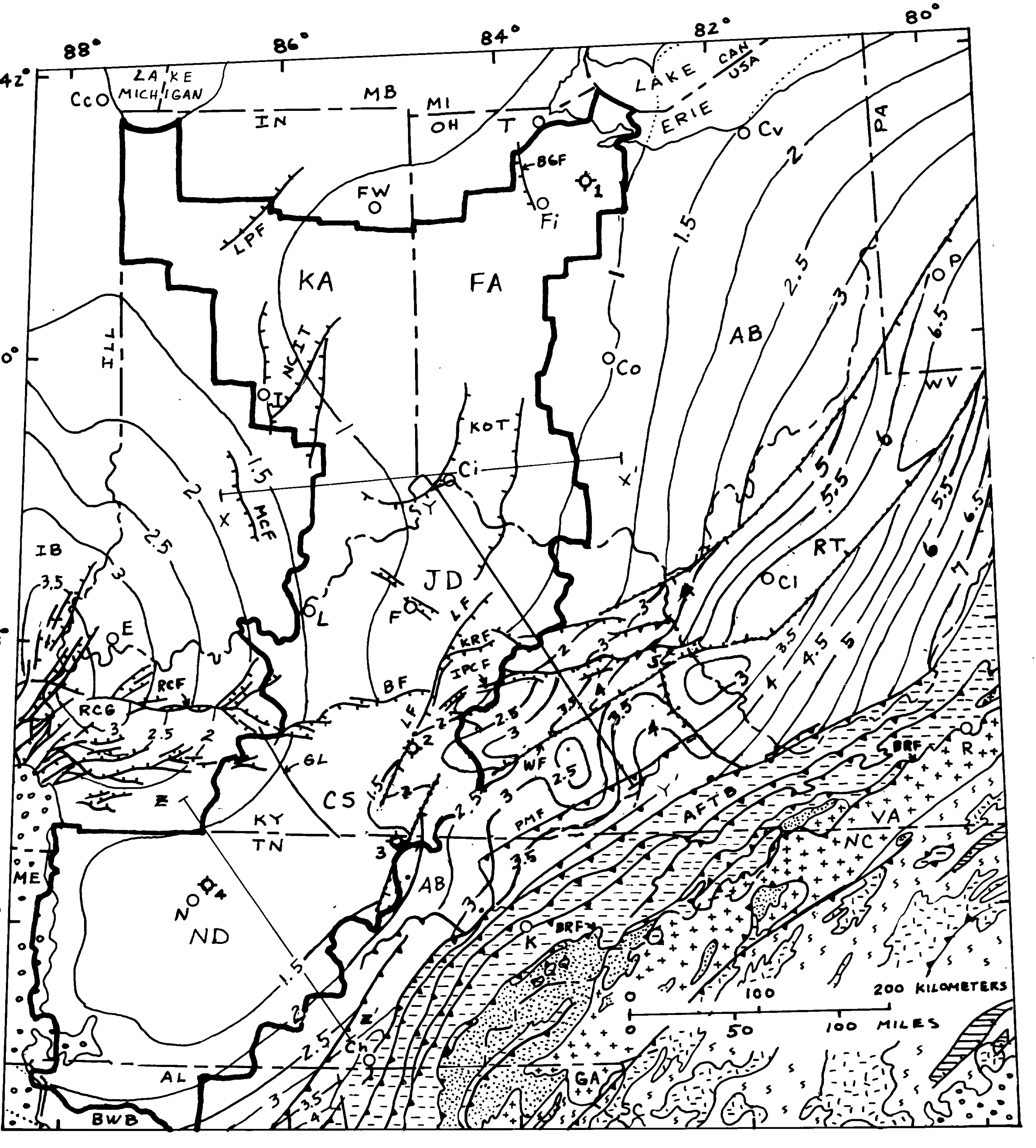
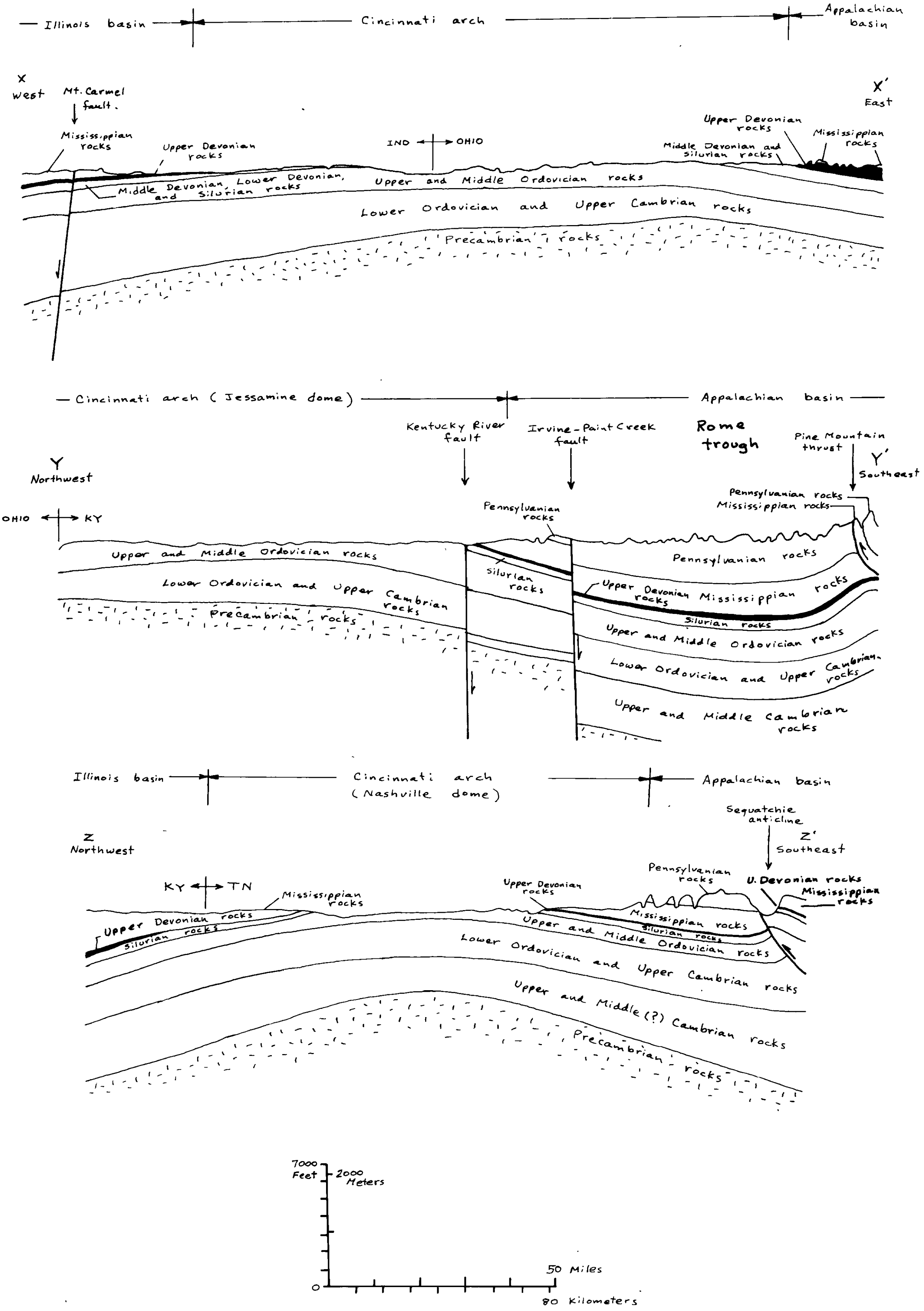

88°
86°
84°
82°
80°
42°
40°
38°
36°
LAKE MICHIGAN
CcO
MB
IN
MI
OH
T
LAKE ERIE
CAN
USA
Cv
PA
BGF
FW
Fi
1
LPF
KA
FA
1.5
2
2.5
3
AB
P
6.5
ILL
NCIT
I
Co
WV
KOT
6
Ci
X
X'
MCF
SY
5
5.5
IB
3.5
JD
RT
Cl
L
F
LF
E
KRF
IPCF
J
4
4.5
7
RCF
BF
RCG
GL
WF
2.5
R
BRF
CS
PMF
Y
AFTB
VA
KY
TN
NC
ME
AB
N
ND
K
Q
0
100
200 KILOMETERS
50
100 MILES
Z
Ch
GA
AL
BWB

Figure 2. Geologic cross sections X-X', Y-Y', and Z-Z' through selected parts of the Cincinnati arch. Lines of section are identified on figure 1. The sections are modified slightly from Renfro and Feray (1970) and Bennison (1978).


Illinois basin
Cincinnati arch
Appalachian basin
X
west
Mt. Carmel fault
Mississippian rocks
Upper Devonian rocks
IND
OHIO
Upper Devonian rocks
Mississippian rocks
Middle Devonian and Silurian rocks
X′
East
Middle Devonian, Lower Devonian, and Silurian rocks
Upper and Middle Ordovician rocks
Lower Ordovician and Upper Cambrian rocks
Precambrian rocks
Cincinnati arch (Jessamine dome)
Appalachian basin
Kentucky River fault
Irvine-Paint Creek fault
Rome trough
Pine Mountain thrust
Y
Northwest
Y′
Southeast
OHIO
KY
Pennsylvanian rocks
Pennsylvanian rocks
Mississippian rocks
Upper and Middle Ordovician rocks
Pennsylvanian rocks
Lower Ordovician and Upper Cambrian rocks
Silurian rocks
Upper Devonian rocks
Mississippian rocks
Precambrian rocks
Silurian rocks
Upper and Middle Ordovician rocks
Lower Ordovician and Upper Cambrian rocks
Upper and Middle Cambrian rocks
Illinois basin
Cincinnati arch (Nashville dome)
Appalachian basin
Sequatchie anticline
Z
Northwest
Z′
Southeast
KY
TN
Mississippian rocks
Pennsylvanian rocks
Upper Devonian rocks
U. Devonian rocks
Mississippian rocks
Upper Devonian rocks
Silurian rocks
Mississippian rocks
Silurian rocks
Upper and Middle Ordovician rocks
Lower Ordovician and Upper Cambrian rocks
Upper and Middle (?) Cambrian rocks
Precambrian rocks
7000 Feet
2000 Meters
0
50 Miles
80 Kilometers

Precambrian basement rocks in the Ohio, Indiana, and Tennessee parts of the Cincinnati arch have been disrupted by extensional faults to a lesser degree than those in the Kentucky part of the arch. The Bowling Green and Logansport faults (fig. 1; Green, 1957) and the fault-controlled Kentucky and Ohio and north-central Indiana troughs (fig. 1; Black, 1986a) are examples of basement-involved faults in Ohio and Indiana. Although not identified on figure 1, Harris (1975) recognized several extensional faults in the basement rocks of the Nashville dome.

All of the basement faults and associated rift features of the Cincinnati arch were most active in Early through Middle Cambrian time. However, many of these faults were rejuvenated at least once in later Paleozoic time some with a reversal of the original relative offset. Black (1986b) suggested that many of the fault-controlled basement blocks in Kentucky have a strike-slip component of motion.

The thinning and truncation of Silurian and Lower and Middle Devonian strata beneath Upper Devonian strata of the Cincinnati arch in Kentucky and Tennessee (Freeman, 1951; McDowell and others, 1981; Miller and others, 1966; fig. 1) suggests that the most active phase of growth of the arch occurred between Early Silurian and Late Devonian time. However, Wilson (1962) and Borella and Osburne (1978) presented lithofacies, biofacies, and thickness data that suggest that the Jessamine and Nashville domes, or their precursers, were present in Middle and Late Ordovician time. According to Quinlan and Beaumont (1984), the Cincinnati arch is a lithospheric flexure formed by load induced stresses related to thrust faulting in the Appalachian orogen. Several studies indicate that the axis of the arch (or precursors to the arch) may have shifted progressively westward from Late Cambrian to Late Devonian time (Cable and Beardsley, 1984; Stearns and Reesman, 1986).

Stratigraphic framework

The sedimentary record of the Cincinnati arch consists of three depositional sequences, each of which is bounded by regional unconformities (fig. 3). Following Sloss (1963), these sequences, in ascending order, are the Cambrian and Lower Ordovician (Sauk) sequence, the Middle Ordovician through Silurian (Tippecanoe) sequence, and the Devonian through Mississippian (Kaskaskia) sequence. Each sequence records an initial incursion of a shallow sea over the region, followed by a general stabilization of the seaway, and finally the withdrawal of the seaway and the widespread exposure of the region to subaerial weathering. The Cambrian and Lower Ordovician (Sauk) sequence is confined to the subsurface of the arch as is most of the Middle Ordovician part of the Middle Ordovician through Silurian (Tippecanoe) sequence. The remainder of the Tippecanoe sequence and the Devonian through Mississippian (Kaskaskia) sequence either crop out or occupy the shallow subsurface on the flanks of the arch.

The total thickness of the sedimentary record along the Cincinnati arch increases southward from about 2800 ft (0.85 km) on the Findlay arch, to about 3500 ft (1.1 km) on the Jessamine dome, to about 5500 ft (1.7 km) on the Nashville dome. The sedimentary sequence thickens on the flanks of the arch to a maximum of about 8800 ft (2.7 km) in the westernmost part of the Rome trough.

Source rocks

The major oil and gas source rocks on the Cincinnati arch are the uppermost Middle and Upper Ordovician Utica Shale and equivalent units and the Upper Devonian Chattanooga Shale (fig. 3). The Point Pleasant Formation equivalent of Wickstrom and others (1985) at the northern end of the Findlay arch is the western part of a 100- to 300-ft- (30- to 90-m-) thick black shale sequence of the Utica and Antes Shales which extends across much of Ohio, Pennsylvania, West Virginia, and New York. This black shale sequence may also extend into northernmost Kentucky and southernmost Indiana along the northeast trending Sebree trough (Bergstrom and Mitchell, 1987). Cole and others (1987) have identified this black shale sequence in Ohio as the Point Pleasant Formation and have determined that its average total organic content (TOC) is 1.30 weight percent. Of the 150 samples used to calculate the average, 85 samples contained greater than 2 percent TOC. Most of the 150 samples were located either on or near the Findlay arch. Cole and others (1987) concluded that the shales of the Point Pleasant Formation constitute a good oil-prone source rock (fig. 3).

The Chattanooga Shale occupies the Cumberland saddle and the Nashville dome and ranges in thickness from about 10 to 40 ft (3-12 m) (Conant and Swanson, 1961). Samples of the Chattanooga Shale collected near the southern end of the Nashville dome, along the Alabama-Tennessee border, have an average TOC of 16.27 weight percent and an average oil yield of 13.9 gallons/ton (Rheams and Neathery, 1984). Along the east flank of the Nashville dome, the average oil yield of the Chattanooga Shale ranges from 7.5 gallons/ton in the lower part of the Dowelltown Member to 9.0 gallons/ton in the lower part of the Gassaway Member (Conant and Swanson, 1961). Rheams and Neathery (1984) also reported that their samples of the Chattanooga Shale appear to follow a maturation trend between type I (oil prone) and type II (oil and gas prone) kerogen. These results seem to differ from those of Breger (1979) who implied that the Chattanooga Shale in eastern Tennessee is composed predominantly of type III (gas prone) kerogen.

Burial history, thermal maturation, timing of migration, and entrapment

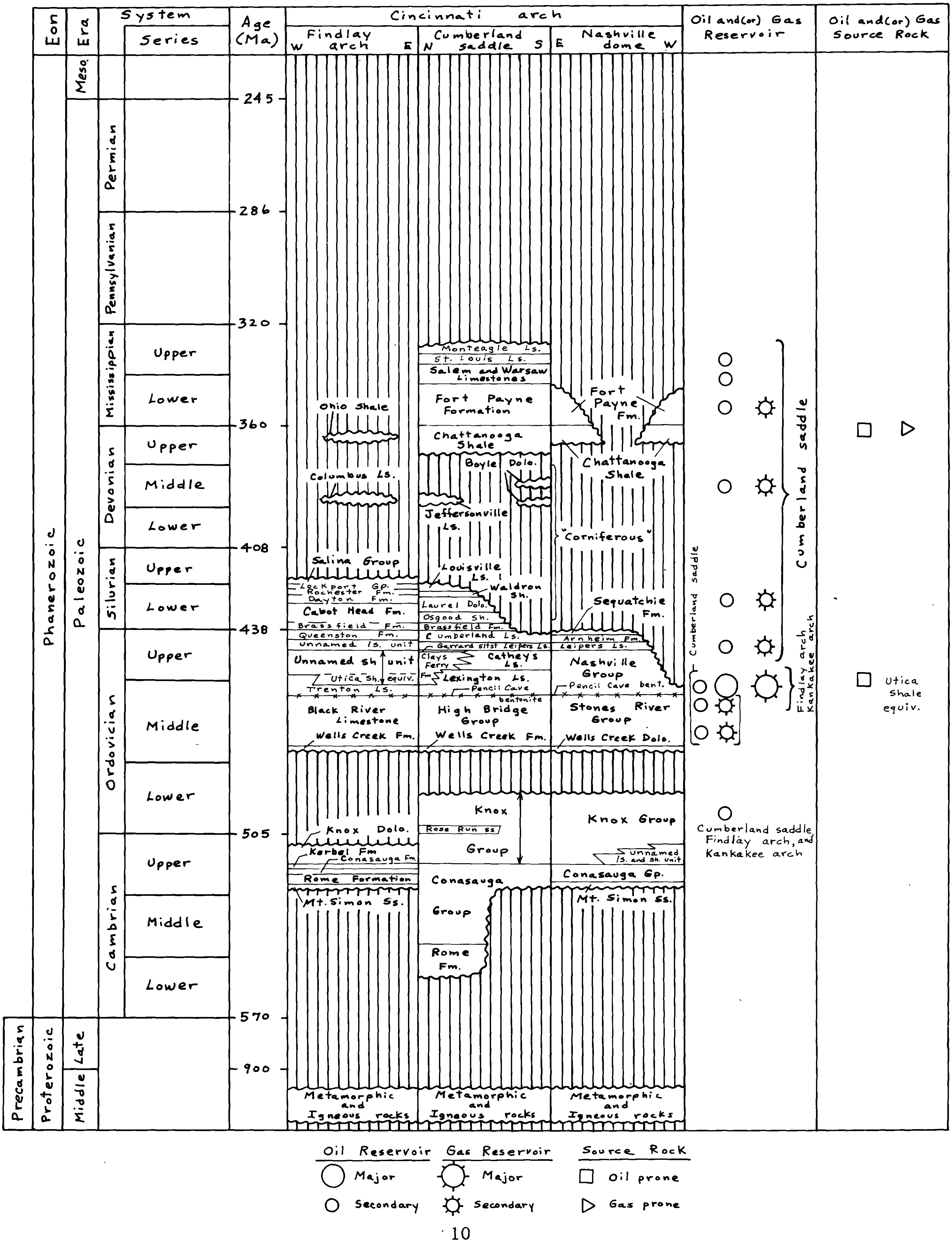
Harris and others (1978) showed that the Ordovician and Upper Devonian strata of the Cincinnati arch are dominated by conodont alteration index (CAI) values less than 1.5 except for the Cumberland saddle area where the values range from 1.5 to 2.0. These CAI values indicate that the Ordovician and Upper Devonian strata of the Findlay arch, Jessamine dome, and Nashville dome are immature with respect to oil and gas generation whereas these strata in the Cumberland saddle are mature with respect to oil generation. The higher level of thermal maturity achieved in the Cumberland saddle, in comparison to the arch, probably is the result of the Rome trough and its thicker sedimentary sequence that occupies the eastern part of the saddle. In the Appalachian basin, east of the Cincinnati arch, the Ordovician and Upper Devonian strata have achieved a level of thermal maturity that supported both oil and gas generation (Harris and others, 1978).

An evaluation of maturity indices for the Ordovician Point Pleasant Formation and the Upper Devonian Ohio Shale (equivalent to Chattanooga Shale, fig. 3) by Cole and others (1987) corroborates the results of Harris and others (1978) for the Findlay arch and the Ohio part of the Appalachian basin. Cole and others (1987) also suggested that the Ordovician and Devonian source rocks in the northwestern Ohio part of the Michigan basin are in the oil generation window. Transformation ratios ($S_1/S_1 + S_2$) and thermal alteration index (TAI) values were used by Cole and others (1987) to define the maturity trends for the Point Pleasant Formation whereas vitrinite reflectance (Ro) values were used to define the maturity trends for the Ohio Shale. S_1 and S_2 represent, respectively, the integral of the first and second hydrocarbon peak generated during Rock-Eval pyrolysis (Tissot and Welte, 1978).

Based on fluid inclusion temperatures in veins in the Stones River Group and an estimated geothermal gradient, Stearns and Reesman (1986) suggested that the Chattanooga Shale of the Nashville dome was buried beneath 7,500 to 12,000 ft (2.3 - 3.7 km) of overburden by the end of Permian time. Temperatures derived from fluid inclusions in sphalerite (125^o - 243^oC) and fluorite (108^o - 132^oC) in the Knox Group in the central Tennessee mineral district are within the oil generation window (DeGroodt, 1973; Seal and others, 1985). The discrepancy between the higher paleotemperatures derived from fluid inclusions and the lower paleotemperatures derived from CAI values is mitigated by the fact that most of the fluid inclusion data come from the Elmwood mine (Kyle, 1976). This mine is located at the northern end of the Nashville dome, close to the eastern part of the Cumberland saddle where Harris and others (1978) recorded CAI index values between 1.5 and 2 with an inferred temperature range between 50 and 140^oC.

A time-temperature reconstruction of eastern Ohio, following Waples (1980), suggests that initial oil generation in the Point Pleasant Formation and the Ohio Shale occurred in Pennsylvanian and Triassic time, respectively (Cole and others, 1987). For this reconstruction to be consistent with available maturation data, an initial thermal gradient of $1.6^oF/100$ ft ($29^oC/km$) was required, followed by a mid-Triassic heat pulse at the time of maximum burial with a geothermal gradient of $2.0^oF/100$ ft ($37^oC/km$). Their time-temperature reconstruction for northwestern Ohio (Cole and others, 1987), where a geothermal gradient of $2.5^oF/100$ ft ($45^oC/km$) was estimated at the time of maximum burial, indicated that initial oil generation in the Point Pleasant Formation and Ohio Shale occurred in Permian and Cretaceous time, respectively As dictated by the thermal maturation indices, the time-temperature reconstruction for the

Figure 3. Stratigraphic correlation chart for Precambrian and Phanerozoic rocks of the U.S.A. part of the Cincinnati arch. Also identified on the chart are the oil and gas reservoirs and source rocks in the basin. The chart is based on the following publications and drill holes: Associated Oil and Gas Exploration Company No. 1 Sells (drill hole No. 3, figure 1), Cities Service Company No. A-1 O-G Garrett (drill hole no. 2, figure 1), Dupont and Company No. 1 Monitoring Well (drill hole no. 4, figure 1), Harris (1964, 1975), Janssens (1973, 1977), McDowell and others (1981), Miller and others, (1966), Ryder (1987), Wickstrom and others (1985), Wilson and Miller (1972), and Wilson and Sutton (1973). Absolute age (in Ma) is from the Geological Time Scale compiled by Palmer (1983). The time scale is nonlinear.


Eon
Era
System
Series
Age (Ma)
Cincinnati arch
Findlay arch W E
Cumberland saddle N S
Nashville dome E W
Oil and(or) Gas Reservoir
Oil and(or) Gas Source Rock
Phanerozoic
Paleozoic
Meso
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Precambrian
Proterozoic
Late
Middle
Upper
Lower
Upper
Middle
Lower
Upper
Lower
Upper
Middle
Lower
Upper
Middle
Lower
245
286
320
360
408
438
505
570
900
Monteagle Ls.
St. Louis Ls.
Salem and Warsaw Limestones
Fort Payne Formation
Ohio Shale
Fort Payne Fm.
Chattanooga Shale
Boyle Dolo.
Columbus Ls.
Chattanooga Shale
Jeffersonville Ls.
"Corniferous"
Salina Group
Louisville Ls.
Waldron Sh.
Lockport Gp.
Rochester Fm.
Dayton Fm.
Laurel Dolo.
Sequatchie Fm.
Cabot Head Fm.
Osgood Sh.
Brassfield Fm.
Brassfield Fm.
Queenston Fm.
Cumberland Ls.
Unnamed ls. unit
Garrard siltst Leipers Ls.
Arnheim Fm.
Leipers Ls.
Unnamed sh unit
Clays Ferry
Catheys Ls.
Nashville Group
Utica Sh. equiv.
Fm
Lexington Ls.
Trenton Ls.
Pencil Cave bentonite
Pencil Cave bent.
Black River Limestone
High Bridge Group
Stones River Group
Wells Creek Fm.
Wells Creek Fm.
Wells Creek Dolo.
Knox Dolo.
Knox Group
Knox Group
Rose Run ss
unnamed ls. and sh. unit
Kerbel Fm
Conasauga Fm.
Rome Formation
Conasauga Group
Conasauga Gp.
Mt. Simon Ss.
Mt. Simon Ss.
Rome Fm.
Metamorphic and Igneous rocks
Metamorphic and Igneous rocks
Metamorphic and Igneous rocks
Cumberland saddle
Cumberland saddle
Findlay arch Kankakee arch
Cumberland saddle, Findlay arch, and Kankakee arch
Utica Shale equiv.
Oil Reservoir
Major
Secondary
Gas Reservoir
Major
Secondary
Source Rock
Oil prone
Gas prone

Findlay arch area showed that no oil had been generated there (Cole and others, 1987).

Although time-temperature reconstructions have not been published for the Cumberland saddle, oil was probably generated there from the Chattanooga Shale in Pennsylvanian and Permian time. Based on the CAI values of Harris and others (1978) and on the Ro values of Barrows and others (1979), the Chattanooga Shale and equivalent units probably have not generated oil on the Kankakee arch, Jessamine dome, and Nashville dome.

Time-temperature reconstructions and thermal maturation data indicate that, except for the Cumberland saddle, oil and gas accumulations on the arch would have had to migrate there from adjacent basins. Following Woodward (1958) and Oliver (1986), the majority of this migrated oil and gas probably came from the Appalachian basin. Peak generation of oil and gas in the Appalachian basin and its subsequent westward migration toward the Cincinnati arch probably occurred in Pennsylvanian and Permian time when major source rock units were buried beneath a thick sequence of thrust-belt derived terrigenous clastic rock. Evidence for major hydrocarbon migration during the Alleghany orogeny (Pennsylvanian and Permian time) is supported by the illitization of Middle Ordovician bentonite beds in the Jessamine and Nashville domes and the adjacent Appalachian basin (Elliott and Aronson, 1987) and by the 322 to 278 Ma dates from authigenic potassium feldspar in Cambrian carbonates in deeply buried parts of the Appalachian basin (Hearn and others, 1987). According to these investigators, the authigenic illite and K-feldspar were produced by westward migrating, gravity driven, warm to hot saline solutions that contained hydrocarbons and ore-forming fluids.

Oliver (1986) suggested a phase of Middle Ordovician hydrocarbon migration from the Appalachian basin to account for oil in the Trenton Limestone on the Findlay and Kankakee arches. He reasoned that these oil accumulations were trapped (presumably by stratigraphic means) prior to the formation of the arches. This interpretation is possible, but, more likely, Trenton oil accumulated during nearly simultaneous phases of Pennsylvanian and Permian migration from the Appalachian basin to the Findlay arch (Cole and others, 1987) and from the Michigan and(or) Illinois basins to the Kankakee arch (Keith, 1981b). Paleotopography associated with unconformities, truncated units beneath unconformities, facies-controlled permeability barriers, basement-controlled anticlines and faults, and the broad domes of the arch would have been available then to trap migrating hydrocarbons.

Between 4200 and 6500 ft (1.3-2.0 km) of upper Paleozoic rocks may have been eroded from the arch during post-Paleozoic uplift (Stearns and Reesman, 1986; Cole and others, 1987). Therefore, large quantities of oil and(or) gas originally trapped on the arch, may have been exhumed and eventually removed by subaerial processes. Possible vestiges of such accumulations have been reported by Meyer and Sweeney (1968).

Hydrocarbon occurrence

The majority of the known oil and gas accumulations on the Cincinnati arch are located on the Findlay arch, Kankakee arch, and Cumberland saddle (figs. 3 and 4). The giant Lima-Indiana field (Moody and others, 1970) on the Findlay and Kankakee arches produces oil and gas from the dolomitized upper part of the Trenton Limestone (figs. 3 and 4). The oil and gas in this field has been trapped by a combination of anticlinal closure along the crest of the Findlay arch, the northwest plunge of the Kankakee arch, and an abrupt facies change from porous dolomite to impermeable limestone (Keith, 1981b; Gray, 1983; Coogan and Parker, 1984). The Knox Dolomite is the only other oil producing unit on the Findlay and Kankakee arch (fig. 3.). However, this Knox production is limited to the small Tiffin field (fig. 4), where both the Trenton Limestone and Knox Dolomite are oil bearing (DeBrosse and Vohwinkel, 1974), and to the now-abandoned Redkey field (fig. 4) (Bond and others, 1971).

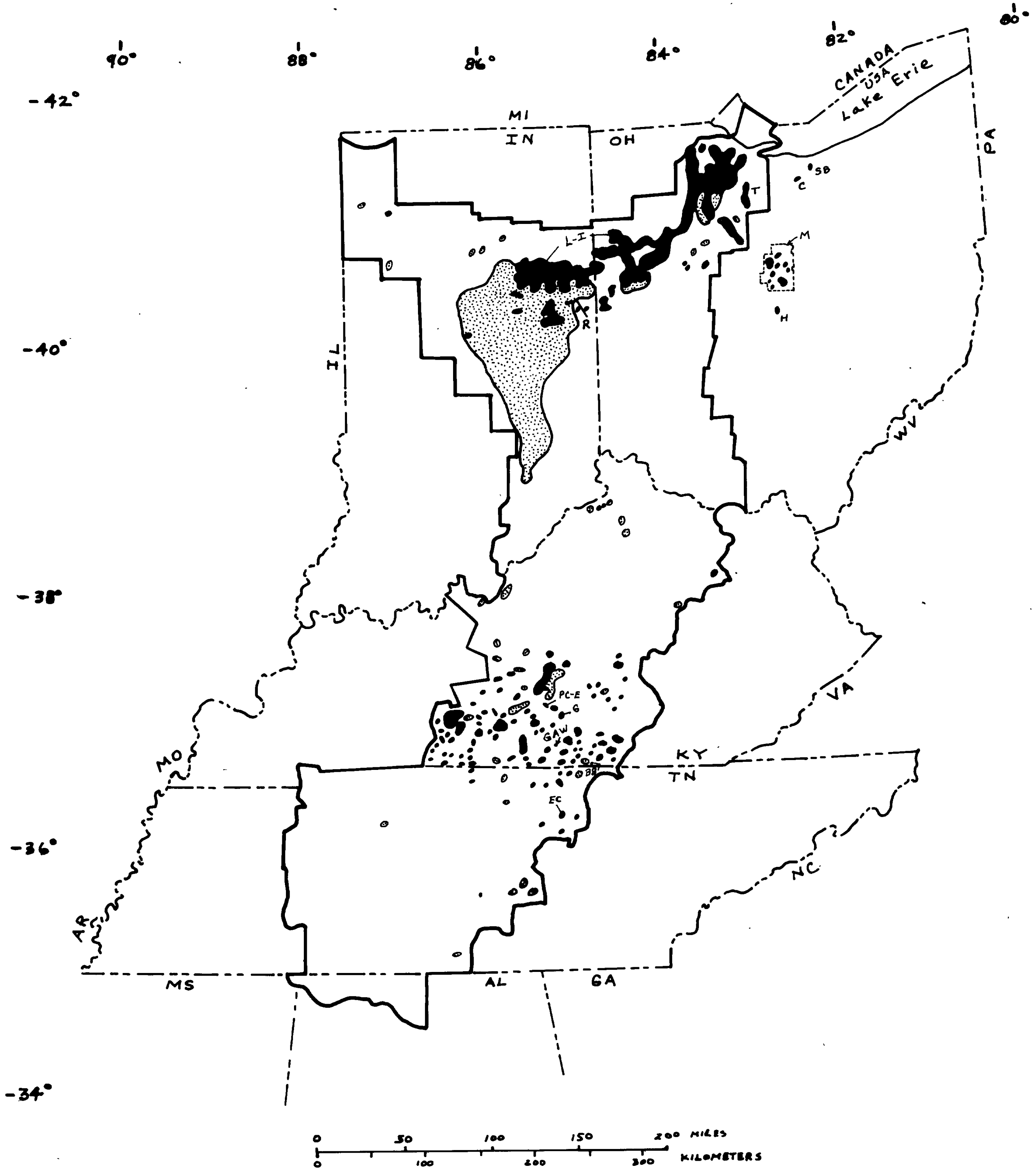
Oil and gas in the Cumberland saddle is distributed among numerous small fields that generally contain less than one million barrels (fig. 4). These fields produce oil and gas from a wide variety of limestone and dolomite reservoirs ranging from Early Ordovician to Late Mississippian in age (figs. 3 and 4). Many of the fields produce from multiple reservoirs. The Lower Ordovician part of the Knox Group produces modest quantities of oil from paleotopographic highs formed by pre-Middle Ordovician erosion (Perkins, 1972; Norris, 1981; Gooding, 1987). Entrapment of the Knox oil is also in part controlled by anticlinal noses that reflect the structure of the underlying Precambrian basement. Modest quantities of oil are also produced from Middle and Upper Ordovician limestones in the Stones River Group and Lexington Limestone. This oil occurs in stratigraphically trapped accumulations characterized by thin, discontinuous buildups of bioclastic limestone encased in micrite (Bond and others, 1971; Pryor and Sullivan, 1985). The largest oil fields in the Cumberland saddle produce from truncation-type stratigraphic traps beneath the pre-Middle and pre-Upper Devonian unconformities (Bond and others, 1971). Most of the reservoirs are vuggy dolomite of Early Silurian and Middle Devonian age commonly known to drillers as the "Corniferous" (Freeman, 1951) (fig. 3). A modest amount of oil and gas has been produced from the Mississippian sequence in the Cumberland saddle and all of it is stratigraphically trapped. Mississippian reservoirs range from locally fractured, cherty crinoidal buildups in the Fort Payne Formation (Bond and others, 1971; Wilson, 1971) to oolitic calcarenite and bioclastic limestone in the Warsaw, Salem, and Monteagle Limestones (Bond and others, 1971; fig. 3).

PRINCIPAL PLAYS

Play identification

According to Proctor and others (1982) a play consists of a group of prospects, with or without nearby discovered fields, having common geologic characteristics such as source rock, trapping mechanism, and structural history which may contain oil and(or) gas. In the recent U.S. Geological

Figure 4. Map of Ohio, Indiana, Kentucky, Tennessee and adjacent states showing the U.S.A. part of the Cincinnati arch (heavy black line) and its oil (black) and gas (stippled) fields. The distribution of oil and gas fields is based on publications by Born (1943), De Brosse and Vohwinkel (1974), Wilson and Sutton (1973, 1976), Carpenter and Sullivan (1976) Schwalb and others (1972), Tennessee Division of Geology (1971, 1981), Lindou (1980). Selected oil and gas fields are: BB, Beech Bottom field; C, Collins pool; EC, Eagle Creek field; G, Gradyville east; GAW, Great American well; H, Harlem field; L-I, Lima-Indiana field; M. Morrow County fields; PC-e, Pickett Chapel-Exie field; R, Redkey field; SB, South Birmingham field; T, Tiffin field.


90°
88°
86°
84°
82°
80°
-42°
-40°
-38°
-36°
-34°
MI
IN
OH
CANADA
USA
Lake Erie
PA
SB
C
T
M
H
L-I
R
IL
WV
VA
KY
TN
MO
AR
MS
AL
GA
NC
PC-E
G
GAW
BB
EC
0 50 100 150 200 MILES
0 100 200 300 KILOMETERS

Survey assessment of undiscovered oil and gas resources only those plays that are believed to have at least one undiscovered accumulation equal to or greater than 1 million barrels of oil (BO) or 6 billion cubic feet (BCF) of gas are evaluated.

Two plays, the Upper Cambrian and Lower Ordovician dolomite play and the Middle and Upper Ordovician carbonate play, are identified on the Cincinnati arch. The Upper Cambrian and Lower Ordovician dolomite play involves the upper part of the Knox Group beneath the pre-Middle Ordovician unconformity whereas the Middle and Upper Ordovician carbonate play involves the Trenton and Black River Limestones and equivalent strata (fig. 3). Attributes of these plays are 1. one or two source rocks that are thermally mature on the arch or in adjacent basins, 2. potential stratigraphic and structural traps, 3. favorable timing regarding the age of trap formation and hydrocarbon migration, 4. adequate limestone and dolomite reservoirs, and 5. known commercial oil and gas accumulations. A moderate number of holes drilled through the Middle Ordovician sequence to at least the top part of the Knox Group provide a reasonable data base.

Additional prospective stratigraphic intervals on the arch not considered to be plays, are the Lower Silurian and Middle Devonian dolomites ("Corniferous") and Lower and Upper Mississippian limestones. Although oil and gas are presently produced from these intervals, the existing fields are generally located on the flanks of the arch at very shallow depths. These factors, in addition to the high density of drill holes, suggest that very little potential remains for undiscovered oil and gas in the Lower Silurian, Middle Devonian, and Mississippian rocks of the arch.

Shale oil from the Chattanooga Shale and equivalent strata has been identified as an unconventional resource in parts of the Cincinnati arch (Smith and Stanfield, 1964; Becker and Keller, 1976). In several areas, the Chattanooga Shale and equivalent strata are being investigated as a source of oil using advanced retorting technology.

Upper Cambrian and Lower Ordovician dolomite play

The Upper Cambrian and Lower Ordovician dolomite play involves oil trapped in the upper part of the Knox Group at or near the overlying pre-Middle Ordovician unconformity (fig. 3). Along most of the Cincinnati arch the pre-Middle Ordovician unconformity overlies the Lower Ordovician part of the Knox Group, except on the Findlay arch where the Lower Ordovician rocks are absent and the unconformity overlies the Upper Cambrian part of the Knox Group (fig. 3). The main exploration target in this play is oil stratigraphically trapped in porous, erosional remnants (buried hills) of karstic origin at the top of the Knox. Analogous oil accumulations occur in Morrow County, Ohio, less than 50 mi (80 km) east of the Findlay arch (fig. 4; Dolly and Busch, 1972; Janssens, 1973), and in the Cumberland saddle (Perkins, 1972; Norris, 1981; Gooding, 1987). At present, exploration for oil in the Knox Group is most active in the Cumberland saddle; however, the entire Knox Group on the Cincinnati arch is prospective and thus the limits of the play coincide with the boundary of the arch (figs. 1 and 4).

The primary reservoir in the Upper Cambrian and Lower Ordovician play is vuggy dolomite. In the Morrow County oil fields, the reservoir consists of medium to coarsely crystalline, vuggy dolomite with an average porosity of 15 percent and an average permeability of about 100 millidarcies (md) (Dolly and Busch, 1972; Petrie, 1982; Gray, 1983). Commonly, the porosity and permeability of the reservoirs are enhanced by solution-enlarged fractures and caverns. Oil saturated zones as much as 110 ft (34 m) thick are present in the buried hills (Dolly and Busch, 1972).

As many as four 30- to 40-ft- (9- to 12-m-) thick, finely crystalline dolomite reservoirs are identified in the Knox Group at the Pickett Chapel-Exie South and Gradyville East fields (fig. 4; Perkins, 1972; Norris, 1981). The porosity in one of these reservoirs in the Gradyville East field ranges from 6.4 to 14.2 percent (Norris, 1981). Corresponding permeability values from this reservoir are between 0.7 and 1.7 md and therefore suggested to Norris (1981) that the most productive wells in the field were drilled into vertically fractured reservoirs.

By analogy to the Morrow County and Cumberland saddle oil fields, erosional remnants of porous Knox dolomite overlain by impermeable shale and argillaceous carbonate of the Wells Creek (Glenwood Formation) Formation provide the primary mode of entrapment for the play. Erosional remnants commonly are aligned along pre-existing anticlines and faults which in turn may aid in the entrapment of the oil. Additional trapping mechanisms in the play include 1. truncated porous dolomite and local porous sandstone beneath the Middle Ordovician unconformity without topographic expression, and 2. anticlinal closure such as displayed at the South Birmingham field in northern Ohio east of the Findlay arch (fig. 4; Janssens, 1973).

The source of the oil in the reservoirs of the Knox Group in Morrow County was considered by Dolly and Busch (1972) and Petrie (1982) to be the shale beds in the Wells Creek Formation (Glenwood Formation). However, their suggestion is unlikely because the TOC of this shale is generally less than 0.5 weight percent (J. R. Hatch, personal commun., April 1985). A more likely source for the Morrow County oil and the Knox oil field on the Findlay arch seems to be the Ordovician Utica Shale and equivalent units in the Appalachian basin. Cole and others (1987) indicated that the Morrow County oil is geochemically similar to oil extracts from the Point Pleasant Formation and to oil from the Lima-Indiana field. Although this proposed source bed is located 600 to 750 ft (183-229 m) stratigraphically above the Knox Group, hydrocarbons generated from it could have been driven shelfward and downsection by gravity, along with discharging saline groundwater, into porous carrier beds associated with the Middle Ordovician unconformity (Bethke and others, 1988). The source of the Knox oil field on the Kankakee arch may have been the Utica Shale in the Michigan basin.

The Chattanooga Shale probably was the source for the oil and gas in the Cumberland saddle, including the oil in the Knox reservoirs (Daley, A. R., personal commun. to Wallace de Witt, Jr., March 1988). Oil in the Lower Silurian, Middle Devonian, and Mississippian reservoirs of the Cumberland saddle could have been derived locally because maturation indices (Harris and others, 1978; Stearns and Reesman, 1986) indicate that there the Chattanooga Shale is in the zone of oil generation. However, for Chattanooga-derived oil to migrate 1400 to 1600 ft (427-488m) downsection into the top of the Knox Group in the Cumberland saddle requires a gravity-drive mechanism identical to that proposed for the Utica-derived oil on the Findlay arch. The topographic relief required in the Appalachian basin for this mechanism to operate is similar to that reconstructed by Stearns and Reesman (1986).

According to Cole and others (1987), the Utica Shale , the Point Pleasant Formation of their paper, began to generate oil in late Paleozoic time in eastern Ohio. A late Paleozoic time of oil generation is also inferred for the Chattanooga Shale of east-central Tennessee based on a hypothetical burial model by Stearns and Reesman (1986). Therefore, the majority of the permeability barriers and structures in the Knox Group in the play area, in place since early Middle Ordovician time, were available to trap the migrating oil and gas.

Drilling in this play is concentrated in the Cumberland saddle where the depth to the top of the Knox Group ranges from 1,500 to 3,000 ft (457 - 914m), and to a lesser extent on the Findlay arch where the depth to the top of the Knox ranges from 1,700 to 2,400 ft (518 - 732m). The drilling depth to the top of the Knox Group on the Jessamine dome, Nashville dome, and Kankakee arch ranges from about 700 to 1500 ft (213 - 457m).

The first commercial Knox oil production on the Cincinnati arch was discovered in Seneca County, Ohio (near drill hole no. 1, fig. 1) in 1909 (Sitler and Wehmeyer, 1962). This oil was found in the existing Tiffin field by Sun Oil Company at a depth of about 2,200 ft (671 m) during exploration of sub-Trenton rocks (fig. 4). Additional Knox oil was discovered in the Tiffin field on 1938 (Janssens, 1973). In 1961, Knox oil was discovered in Morrow County (fig. 4) and initiated a drilling boom throughout this county and adjacent counties (Oil and Gas Journal, 1961, 1965). Although drilling activity peaked in Morrow County between 1961 and 1964, it continues today (Maslowski, 1985). North of Morrow County, Knox oil was discovered in the Collins pool in 1965 and in the South Birmingham field in 1966 (Janssens, 1973, fig. 4).

The first commercial Knox oil in the Kentucky part of the Cumberland saddle was discovered in the now-abandoned Beech Bottom field in 1915 (Perkins, 1972; fig. 4). According to Born (1943), oil was produced from the Knox and the overlying Stones River Group in the Tennessee part of the Cumberland saddle as early as 1892. The Gradyville East field discovered in 1969 (Perkins, 1972) and the Pickett Chapel-Exie south field discovered in 1974 (Norris, 1981) are among the largest of the Knox oil fields found to date in the Cumberland saddle (fig. 4).

Oil is the dominant type of hydrocarbon in the Upper Cambrian and Lower Ordovician play. Cumulative production statistics for Knox oil on the Cincinnati arch generally are not available. Exceptions are the Pickett Chapel - Exie south field where 116,056 barrels of oil were produced from December 1974 to March 1, 1976 (Norris, 1981) and the Gradyville East field where 67,039 barrels of oil were produced from July 1969 to May 1970 (Perkins, 1972). Both of these fields are presently producing oil. Janssens (1973) reported that one well in the Tiffin field produced 21,284 barrels of oil from the Knox in 10 years. One reason why oil production statistics are unavailable for the Knox in the Cumberland saddle is because much of this oil is comingled with oil from the Stones River Group and Lexington Limestone (Wilson and Sutton, 1973).

Based on qualitative resource assessment techniques developed by Miller (1983) and Taylor and Steven (1983), the potential for undiscovered oil and gas resources in the Upper Cambrian and Lower Ordovician play is rated high. The level of certainty of the estimated resource is D, meaning that the available information clearly defines the level of resource potential (Taylor and Steven, 1983).

A factor which may limit the undiscovered resources in this play is the downsection migration that is presumably required to move the oil from the source to the reservoir. Effective dispersal of oil into the Knox requires good fracture communication between it and the source rock and the absence of intervening porous stratigraphic horizons that could act as carrier beds. If an extensive fracture network was lacking and(or) laterally persistent carrier beds existed between the source beds and the Knox, only a small amount of the Utica- and Chattanooga-derived oil may have reached the Knox. An unlikely possibility exists that little Utica-derived oil from the Appalachian basin reached the Knox by the carrier zone associated with the pre-Middle Ordovician unconformity, and all the oil that did was trapped in the Morrow County fields. Unproductive, water-wet erosional remnants situated updip and west of the Morrow County fields (Dolly and Busch, 1972) tend to support this possibility.

Another factor which may limit the undiscovered resources in the Upper Cambrian and Lower Ordovician dolomite play is its reservoir quality. The Cambrian age Knox reservoirs in Morrow County are very porous, medium to coarsely crystalline, vuggy, stromatolitic dolomite. Many such high-quality reservoirs are not present on the Findlay arch because of truncation and facies changes. In the Cumberland saddle, the reservoir consists of dolomite in the Lower Ordovician part of the Knox Group. These dolomite reservoirs are commonly argillaceous, cherty, and finely crystalline and rarely attain the high-quality of the Knox reservoirs in Morrow County, Ohio.

Field and model investigations by Kim (1975) and Unruh (1987) have indicated that some buried-hill traps in the Knox Group are detectable on seismic profiles. If seismic techniques could be used routinely to detect traps and(or) porous intervals in the Knox, many more exploration targets would be identified in the play.

Middle and Upper Ordovician carbonate play

The Middle and Upper Ordovician carbonate play involves oil and gas trapped in the Middle and Upper Ordovician Trenton Limestone, Lexington Limestone, and Nashville Group and in the Middle Ordovician Black River Limestone, High Bridge Group, and Stones River Group (fig. 3). Exploration targets in this play consist of stratigraphically and structurally trapped oil and gas in bioclastic limestone (Bond and others, 1971; Pryor and Sullivan, 1985), depositional facies-controlled dolomite (Coogan and Parker, 1984; Keith, 1981b), and fault-controlled vuggy dolomite (Wickstrom and others, 1984; Wickstrom and Gray, 1985; Black, 1986b; Maslowski, 1986). Except in parts of the Jessamine and Nashville domes, where uppermost Middle Ordovician strata are exposed, the play covers the entire Cincinnati arch (fig. 1). At present, the most active drilling for oil and gas in the play is in the Cumberland saddle and the Findlay arch.

The bioclastic limestone reservoirs in the play are concentrated in the Lexington Limestone of the Cumberland saddle. These reservoirs were deposited as linear beach ridges and elongate, discontinuous mollusc buildups that range in thickness from 5 to 35 ft (1.5 - 11m) (Pryor and Sullivan, 1985). Vuggy and biomoldic porosity was formed in the bioclastic limestone units where they were exposed to subaerial conditions along local positive tectonic features (Pryor and Sullivan, 1985).

Depositional facies-controlled vuggy dolomite reservoirs are concentrated in the upper 50 ft (15m) of the Trenton Limestone on the Findlay and Kankakee arches (Keith, 1981b; Gray, 1983; Coogan and Parker, 1984). Porosity in the vuggy dolomite ranges from 0.1 md to several darcies (Gray, 1983). Locally, large cavities are present in the Trenton Limestone reservoirs which Rooney (1966) attributed to subaerial exposure and erosion at the top of the Trenton.

Fault-controlled vuggy dolomite reservoirs are present on the Findlay arch and Cumberland saddle. Along the Bowling Green fault, much of the Trenton and Black River Limestone sequence has been dolomitized (Wickstrom and others, 1984). Vugs are larger and more numerous near the fault and large cavities are present locally (Gray, 1983). Bond and others (1971) reported small lenses of porous dolomite in the Black River Limestone of the Findlay arch but did speculate on their origin. Dolomite in the Trenton and Black River Limestones in the Harlem field, about 50 mi (80 km) east of the Findlay arch (fig. 4), appears to be the result of fluid migration along fault and fracture zones (Wickstrom and Gray, 1985; Maslowski, 1986). Black (1986b) has identified similar zones of dolomitized Middle and Upper Ordovician limestone along the Kentucky River fault and the Glasgow lineament (fig. 1). Several narrow oil fields along the Glasgow lineament have yielded oil from the dolomitized Leipers Limestone (fig. 3; Black, 1986b).

Throughout the Cincinnati arch, the primary stratigraphic traps in the Middle and Upper Ordovician carbonate play have resulted from the updip pinchout of porous dolomite into nonporous limestone (Bond and others, 1971; Gray, 1983). Coogan and Parker (1984) suggested that the updip pinchout of porous dolomite into laterally equivalent shale also may have trapped oil and gas. Additional stratigraphic traps in the Cumberland saddle consist of lenses of porous bioclastic limestone encased in impermeable fine-grained limestone (Bond and others, 1971; Pryor and Sullivan, 1985). Other oil and gas accumulations in the play have been trapped by anticlines, faulted anticlines, structural terraces, and porosity changes in combination with anticlinal noses (Coogan and Parker, 1984; Black, 1986b).

Based on oil to source rock correlations, Cole and others (1987) suggested that the oil in the Ohio part of the Lima-Indiana field was derived from the black shale in the Point Pleasant Formation, a Utica Shale equivalent. Moreover, based on maturation indices in the Point Pleasant Formation, they concluded that the oil was generated in the eastern Ohio and western Pennsylvania part of the Appalachian basin and migrated to the Findlay arch. Oil (and gas) generated from the Point Pleasant Formation in eastern Ohio and the Utica Shale in western Pennsylvania was easily accessible to the underlying Trenton Limestone. Utica-derived oil also may have been driven shelfward and downsection by gravity, in association with discharging saline groundwater (Bethke and others, 1988) into the underlying Black River Limestone. Fractures in the Black River and Trenton Limestones facilitate the migration process. Oil in the Indiana part of the Lima-Indiana field probably was derived from the Utica Shale in the Michigan basin.

The Chattanooga Shale was probably the source of the oil and gas in the Middle and Upper Ordovician carbonate reservoirs in the Cumberland saddle and Nashville dome. Some of the oil in Middle and Upper Ordovician carbonate reservoirs in the Cumberland saddle could have been derived locally from the Chattanooga Shale because: 1) maturation indices (Harris and others, 1978; Stearns and Reesman, 1986) indicate that the Chattanooga in the Cumberland saddle is in the zone of oil generation and 2) the Chattanooga locally rests on Upper Ordovician strata in the Cumberland saddle as a result of pre-Middle and pre-Upper Devonian erosion (fig. 2). However, most of the Chattanooga-derived oil and gas in Middle and Upper Ordovician rocks in the Cumberland saddle and adjacent Nashville dome was probably generated in the Appalachian basin. This oil and gas was driven laterally and downsection by gravity flow , along with discharging saline groundwater (Bethke and others, 1988), into the Middle and Upper Ordovician carbonate reservoirs. The topographic relief in the Appalachian basin, a requirement for the gravity-flow mechanism to operate, was reconstructed by Stearns and Reesman (1986).

According to Cole and others (1987), the black shale in the Point Pleasant Formation (Utica Shale) of eastern Ohio began to generate oil and gas in late Paleozoic time. A late Paleozoic time of oil and gas generation is also inferred for the Chattanooga Shale of east-central Tennessee based on a hypothetical burial model by Stearns and Reesman (1986). Consequently, the majority of the permeability barriers and structures in the Middle and Upper Ordovician carbonate sequence of the play area, in place since Late Devonian time, were available to trap the migrating oil and gas.

Drilling in this play is concentrated in the Cumberland saddle where the depth to the top of the Lexington Limestone ranges from about 200 to 1800 ft (61-549m) and in the Findlay arch where the depth to the top of the Trenton Limestone ranges from about 1100 to 1800 ft (335-549 m). On the Kankakee arch, the top of the Trenton Limestone is located between about 800 and 1200 ft (244-366m) below the surface. The drilling depth to the top of the Lexington Limestone on the Jessamine and Nashville domes ranges from 0 to 700 ft (0-213m).

On March 11, 1829 (Jillson, 1947, p. 6) the Great American well in Cumberland County, Kentucky (fig. 4) produced the first commercial oil from Middle and Upper Ordovician strata on the Cincinnati arch. This oil was produced from the Sunnybrook limestone (Lexington Limestone) at a depth of about 171 ft (52 m) (Wilson and Sutton, 1973). In adjacent Tennessee, the first commercial oil from Middle and Upper Ordovician strata was discovered in 1866 at the Eagle Creek field, Overton County (fig. 4: Born, 1943). Two zones in the Sunnybrook limestone (Lexington Limestone), located at about 700 ft and 900 ft (213 and 274 m) below the surface, yielded the oil. Since these early oil discoveries, drilling for oil and gas in Middle and Upper Ordovician carbonate reservoirs has continued in the Cumberland saddle and on the adjacent Nashville and Jessamine domes to the present day (Born, 1943; Wilson and Sutton, 1973; International Oil Scouts Association, 1984 a,b). At least 120 small oil and gas fields and(or) pools were discovered between 1900 and 1988 as a result of this drilling. However, many of the discoveries were one-well fields that are now abandoned.

Commercial oil and gas in the giant Lima-Indiana field was discovered between 1884 and 1886 (Keith, 1981a,b: Gray, 1983). The 1884 discovery well near Findlay, Ohio (fig. 1) encountered gas in the Trenton Limestone at a depth of 1,092 ft (333 m). This gas flowed at a rate of about 200 thousand cubic feet of gas per day (MCFPD) (Gray, 1983). Between 1885 and about 1905 as many as 100,000 wells were drilled into the Trenton Limestone in the Ohio part of the field (Gray, 1983). Drilling for Trenton oil continues on the Findlay arch where Gray (1983) reported that 58 wells were drilled between 1981 and 1982. Drilling for oil and gas in the Indiana part of the Lima-Indiana field also peaked between the late 1880's and the early 1900's (Keith, 1981a). Keith (1981a) reported that 11 wells were drilled for Trenton oil and gas on the Kankakee arch in 1980.

Although abundant associated and nonassociated gas has been produced from Middle and Upper Ordovician carbonate units on the Cincinnati arch, the dominant type of hydrocarbon in this play is oil. Bond and others (1971) estimated that, through 1968, 6.3 million barrels of recoverable oil had been identified in the Middle and Upper Ordovician carbonate sequence in the Cumberland saddle. The Ohio part of the Lima-Indiana field is estimated to have originally contained about 378 million barrels of recoverable oil whereas the Indiana part of the field is estimated to have originally contained about 105 million barrels of recoverable oil (Bond and others, 1971). Based on an estimated 392 million barrels of cumulative production from the Ohio part of the Lima-Indiana field through 1950 (Cottingham, 1951), the original amount of recoverable oil from the Ohio part of the field may have been as much as 400 million barrels. Bond and others (1971) estimated that the Lima-Indiana field originally contained about 1.8 billion barrels of oil in place. Moody and others (1970) estimated that the Lima-Indiana field originally contained 514 million barrels of recoverable oil of which 482 million barrels have been produced as of January 1967. About 1 trillion cubic feet of gas has been produced from the Indiana part of the field (Keith, 1981a). The amount of gas produced from the Ohio part of the Lima-Indiana field has not been estimated because few gas production records exist (Wickstrom and others, 1984).

Based on qualitative resource assessment techniques developed by Miller (1983) and Taylor and Steven (1983), the potential for undiscovered oil and gas resources in the Middle and Upper Ordovician carbonate play is rated high. The level of certainty of the estimated resource is D, meaning that the available information clearly defines the level of resource potential (Taylor and Steven, 1983).

Field and model investigations by Johnson (1987) and Clark and White (1987) have indicated that some porosity zones in the Trenton and Black River Limestones are detectable on seismic profiles. If seismic techniques could be used routinely to detect traps and(or) porous intervals in the Trenton and Black River sequence, many more exploration targets would be identified in the play.

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