# *Petroleum geology and geochemistry of the Council Run gas field, north central Pennsylvania*

**Christopher D. Laughrey, Dan A. Billman, and Michael R. Canich**

## ABSTRACT

The Council Run field of north central Pennsylvania is one of the most productive natural gas fields in the central Appalachian basin. The field is enigmatic because of its position near the eastern edge of the Appalachian Plateau, where strata with reservoir potential elsewhere have low porosities and permeabilities or are poorly sealed. Council Run has four principal reservoir sandstones. The lower three occur in a distinct fourth-order type 1 stratigraphic sequence. The stacking pattern of sandstones in this sequence defines lowstand, transgressive, and highstand systems tracts.

Core, well-log, and map interpretations reveal that the lowest interval consists of multiple coarsening-upward parasequences deposited in deltaic and nearshore environments of the lowstand systems tract during a forced regression. Most of these sandstones are lithic, and some are highly feldspathic. Productive sandstones display hybrid void textures that consist of reduced primary intergranular pores preserved, in part, by relatively early petroleum emplacement and secondary oversized fabric-selective pores.

The generative potential of the organic matter in the potential source rocks is exhausted, but geochemical and petrographic evidences indicate that these black shales originally contained oil-prone kerogens and generated liquid hydrocarbons. Stable isotope geochemistry suggests that gases were generated by primary cracking of kerogens and/or by secondary cracking of oil between 320 and 290 Ma. Dispersive migration paths were both lateral and vertical because of compression associated with Alleghanian orogenesis. Most of the oil in the Devonian section was cracked to gas during deeper burial between 270 and 240 Ma.



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## INTRODUCTION

Council Run field is the easternmost significant natural gas field in Pennsylvania (Figure 1). It is also one of the most prolific fields in the entire Appalachian basin (Donaldson et al., 1996). Eastern States Exploration Company (a former Statoil subsidiary now owned by Equitable Resources) discovered Council Run field in 1982. To date, about 700 wells, with an average spacing of 40 ac (0.16 $km^2$), have been drilled in the Upper Devonian sandstone reservoirs of the field. It is now developed across a 751-$km^2$ (290-$mi^2$) area in Centre and Clinton Counties in north central Pennsylvania (Figure 1). Cumulative production through December 2001 is 56.4 bcf. Estimated ultimate recoverable (EUR) reserves per well range from less than 100 mmcf to more than 1.0 bcf; the average EUR in the field is approximately 200 mmcf of gas. Ryder (1995) estimates the ultimate recovery in Council Run field as about 250 bcf of gas.

The Council Run field is located near the eastern edge of the Appalachian Plateau, a gently folded upland northwest of the more intensely deformed central Appalachian Ridge and Valley. The field is developed adjacent to the Allegheny structural front, which separates the Appalachian Plateau from the ridge and valley. Production at Council Run is from Upper Devonian sandstones. Minor oil and gas production from Upper Devonian rocks in the eastern plateau has occurred sporadically since at least 1903, and deeper reservoirs in Ordovician, Silurian, and Lower Devonian rocks of the region were discovered in the late 1970s and early 1980s (Harper et al., 1982; Laughrey and Harper, 1996). Nevertheless, before Council Run's discovery, petroleum exploration and development of Paleozoic rocks in Pennsylvania, especially Upper Devonian sandstones, was largely constrained to its western and central regions. Reasons for avoiding exploration in the eastern plateau included high drilling and finding costs (Cornell, 1971) and the supposed probability of poor seals because of structural complexity in rocks close to the structural front (Bayer, 1982). More importantly, potential source rocks are postmature in the eastern Appalachian Plateau, and very low porosities and permeabilities were anticipated in possible reservoir rocks because of advanced diagenesis associated with high burial temperatures in the geologic past (Harris, 1979; Streib, 1981; Beaumont et al., 1987).

In 1982, Eastern States Exploration Company drilled the No. 1 Commonwealth of Pennsylvania Tract 231 well on a state forestlands lease. The well was completed in an 11-m (36-ft)-thick sandstone (the "Fifth Elk" sandstone) at a depth of 1413–1424 m (4636–4672 ft) in the Upper Devonian Lock Haven Formation (Figure 2). The after-fracture open flow was 1.96 mmcf gas/day, and the reported reservoir pressure was 1740 psi ($1.20 \times 10^7$ Pa) after 7 days. This discovery well established the Council Run field. Porosities in the pay zone, calculated from the neutron and density logs, ranged from 6.9 to 16%, and calculated gas saturations were as high as 83.2%. The gas was relatively dry ($C_1/\sum C_n = 0.97$), but analyses of the stable carbon and hydrogen isotopes of the methane

($\delta^{13}CH_4 = -50‰$ and $\delta D_{CH_4} = -210‰$) revealed that it was an oil-associated gas originally generated, with liquid hydrocarbons in the early oil window (Laughrey and Baldassare, 1998). These data suggested that gas emplacement occurred relatively early in the burial history of the Upper Devonian rocks and that the integrity of the traps and seals remained intact throughout the complex tectonic history of the reservoirs.

Natural gas is produced at Council Run from various stacked, lenticular sandstones in the Upper Devonian Catskill and Lock Haven formations (Figures 2, 3). Entrapment is stratigraphic. Producing sandstones occur at depths ranging from 762 to 1524 m (2500 to 5000 ft). The Third Bradford, basal Bradford, and various Elk sandstones, particularly the Fifth Elk, are the most prolific reservoir rocks in the field; these particular sandstones are in the Lock Haven Formation. The reservoir rocks at Council Run comprise a variety of marine and nonmarine facies (Rahmanian, 1979; Slingerland and Loule, 1988; Warne and McGhee, 1991; Cotter and Driese, 1998; Castle, 2000). Selected aspects of the petroleum geology of some of these reservoirs were discussed by Billman et al. (1991), Kelleher and Johnson (1991), Bruner and Smosna (1994), Humphrey et al. 1994, Donaldson et al. (1996), and Smosna and Bruner (1997).

Eastern State's success at Council Run initiated a surge of exploration in Upper Devonian rocks along and near the structural front (Harper and Cozart, 1982). Gas production like that at Council Run field, however, has yet to be duplicated elsewhere in the eastern plateaus of the central Appalachian basin.

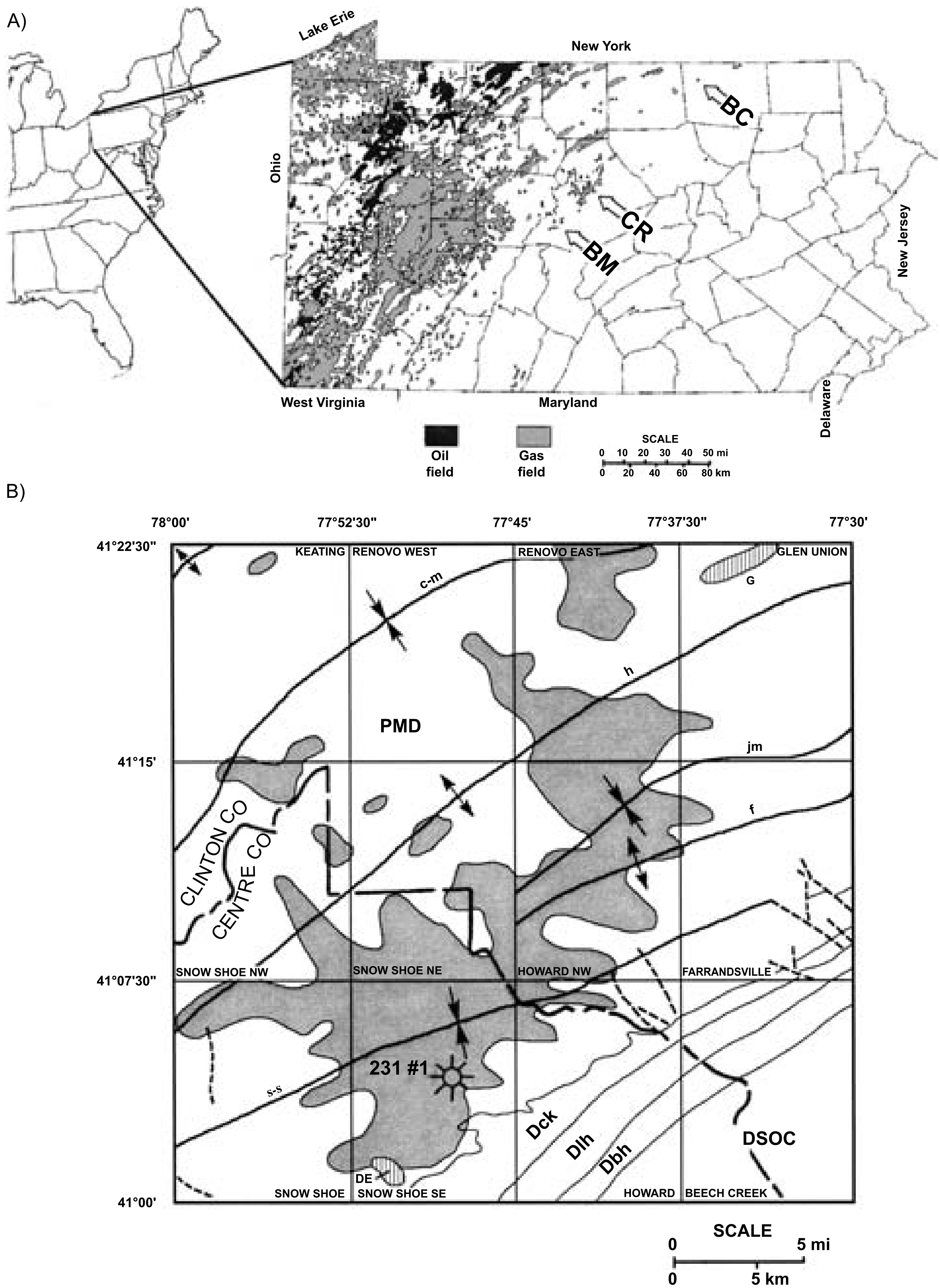
The purpose of this paper is to describe the stratigraphy of the major producing sandstones in the Council Run field, interpret the reservoir geology of the principal producing sandstone, the Fifth Elk sandstone, and to document the petroleum geochemistry of the source rocks and produced natural gases at the field. We demonstrate the utility of sequence stratigraphy for understanding the distribution of important reservoir rocks at Council Run. We propose a burial history and petroleum migration model that is applicable to exploring for other Upper Devonian gas accumulations near the Allegheny Front in the central Appalachian basin.

## STRATIGRAPHIC FRAMEWORK

Faill et al. (1977) defined the Lock Haven Formation as the gray, brown, and green interbedded shales, siltstones, and sandstones that overlie the Brallier Formation and underlie the red beds of the Catskill Formation (Figure 2). The Lock Haven Formation also contains a few thin-bedded quartz pebble conglomerates. The Lock Haven Formation is recognized throughout central and north-central Pennsylvania (Faill et al., 1977; Faill et al., 1989; Taylor, 1997). It is 600–1180 m (1970–3876 ft) thick where exposed (Faill et al., 1977). Lock Haven strata crop out along the Allegheny Front just 3.2 km (2 mi) southeast of the Council Run field.

Warne and McGhee (1991) informally subdivided the Lock Haven Formation along its outcrop at the Allegheny Front into a lower shaly member and an upper sandy member (Figure 3). They correlated the transition between these two members with a late Frasnian eustatic sea level fall. This drop in sea level is one of two (the second occurs at the base of the Third Bradford sandstone in Figure 3) that occurred in a distinct Late Devonian third-order transgressive-regressive (T-R) cycle. Johnson et al. (1985) designated this particular cycle as cycle IId (Figure 3). T-R cycle IId comprises a pair of transgressions and two short-lived but pronounced regressions (Warne and McGhee, 1991).

These two Late Devonian regressions identified in the outcrop of the upper sandy member of the Lock Haven Formation resulted in unconformable surfaces that we interpret as sequence boundaries. The lower sequence boundary occurs at the base of the upper sandy member of the Lock Haven Formation and is marked by a basinward shift of facies (Figure 3). The lower shaly member of the Lock Haven Formation contains fine-grained turbidites interpreted to have been deposited on a low-angle, slope apron environment (Warne and McGhee, 1991, p. 103–104). The upper sandy member sandstones are very fine to fine grained, calcitic, hematitic, and fossiliferous. They exhibit abundant evidence of shallow-water deposition, including wave ripple marks, flaser lamination and bedding, and hummocky cross-stratification (Warne and McGhee, 1991). The upper sequence boundary occurs at the top of cycle IId (Figure 3). This boundary corresponds to the pronounced sea level drop that occurred in the latest Frasnian and it, too, marks a basinward shift in facies. Widespread fluvial and paralic sandstones overlie rocks deposited in a sublittoral shelf depositional environment during a eustatic sea level highstand (Dennison, 1985; Warne and McGhee, 1991). Both unconformities are type 1 sequence boundaries, and they bound a fourth-order type 1 sequence (Van Wagoner et al., 1988, 1990). The lowstand, transgressive, and highstand systems tracts of this sequence can be


A)
Lake Erie
New York
Ohio
BC
CR
BM
New Jersey
West Virginia
Maryland
Delaware
Oil field
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0 10 20 30 40 50 mi
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B)
78°00'
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77°45'
77°37'30"
77°30'
41°22'30"
41°15'
41°07'30"
41°00'
KEATING
RENOVO WEST
RENOVO EAST
GLEN UNION
G
c-m
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jm
f
PMD
CLINTON CO
CENTRE CO
SNOW SHOE NW
SNOW SHOE NE
HOWARD NW
FARRANDSVILLE
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recognized by the stacking patterns of the sandstones exposed along the Allegheny Front in central Pennsylvania (Figure 3).

This fourth-order sequence in the upper part of Devonian cycle IId can also be recognized in the subsurface at Council Run field (Figure 4). There, Lock Haven strata below the Fifth Elk sandstone consist of marine mudrocks and fine-grained, argillaceous sandstones that were deposited in relatively deep water. The Sixth Elk sandstone, for example, occurs approximately 3–6 m (10–20 ft) below the base of the Fifth Elk sandstone. An isopach map of 50% shale-free Sixth Elk sandstone (Figure 5) reveals an elongate radial geometry. Core samples of these rocks consist of argillaceous, micaceous siltstone and very fine-grained lithic wackes. Detrital grains are angular. Matrix consists of illite and sericite. We interpret the Sixth Elk interval as slope deposits correlative to the turbidite deposits in the lower shaly member of the Lock Haven Formation described by Warne and McGhee (1991). This is consistent with our interpretation of the base of the Fifth Elk sandstone as an unconformity and sequence boundary.

The interpreted lower sequence boundary at the base of the Fifth Elk sandstone is marked by a basinward shift in facies and a vertical change in parasequence stacking pattern (Figure 4). The Fifth Elk sandstone is interpreted as a lowstand clastic wedge deposited during a forced regression (Al-Mugheiry, 1995 and this study). The Fifth Elk sandstone consists of isolated pods of relatively coarse-grained deltaic shoreface and foreshore deposits encased in fine-grained marine shales (Figures 5, 6). The Fifth Elk interval offlaps the subjacent marine mudrocks. A distinct marine flooding surface (described in detail below) separates the Fifth Elk sandstone from the overlying transgressive systems tract (TST).

We can correlate the Fifth Elk sandstone in the Council Run field with the sandstone that crops out at the base of the upper sandy member of the Lock Haven Formation on the basis of position in the stratigraphic section and palynology. Both the Fifth Elk sandstone in the gas field and the sandstone at the base of the upper sandy member at the Milesburg outcrop occur approximately 396 m (1300 ft) above the top of the Brallier Formation. Palynomorphs collected from core samples of the Fifth Elk sandstone at Council Run by Al-Mugheiry (1995, p. 27–30) all come from the *Archeoperisaccus ovali–Verrucosisporites buliferus* assemblage zone, which correlates with the middle *Polygnathus assymetricus–Palmatolepis gigas* conodont zone. The middle *P. gigas* zone includes the sequence defined by the base of the Fifth Elk sandstone and the base of the Third Bradford sandstone.

The Fourth Elk C sandstones above the Fifth Elk interval occur in the lower portion of the TST. These reservoir sandstones consist of paralic, fining-upward parasequences exhibiting coastal onlap (Figures 5, 6). Marine siltstones and shales are the principal lithologies in the TST, reflecting the predominance of shelf sediments and processes. Core samples reveal that thin fossiliferous limestone beds also occur in the TST. This fourth-order tract also contains two fifth-order retrogradational sandstones that produce gas in the northwest portion of the Council Run field (Fourth Elk B and A in Figures 5, 6).

The basal Bradford sandstone is the principal reservoir in the highstand systems tract (Figure 4). It consists of a relatively thick, progradational coarsening-upward parasequence.

The tripartite vertical succession of predominantly coarse-fine-coarse lithologies observed in the respective lowstand, transgressive, and highstand systems tracts of this sequence is a characteristic signature for incised-valley-fill sediments (Cotter and Driese, 1998 and references therein). Note in Figure 7 how the thin sandstones of the Fourth Elk interval stack laterally along strike to the southwest. These sandstones dip northeast and are centered on remnant channel and

**Figure 1.** (A) Oil and gas fields map of Pennsylvania showing the location of Council Run field (CR). Brace Creek (BC) and Black Moshannon (BM) are two other fields discussed in the text. (B) Council Run field outline (shaded area), U.S. Geological Survey 7.5-min quadrangles, bedrock geology, and principal structural features of the study area. PMD = Pennsylvanian, Mississippian, and Devonian bedrock; Dck = Catskill Formation; Dlh = Lock Haven Formation; Dbh = Brallier and Harrell Formations; DSOC = Devonian, Silurian, Ordovician, and Cambrian bedrock; s-s = Snow Shoe syncline; f = Ferney anticline; jm = Jersey Mills syncline; h = Hyner anticline; c-m = Clearfield-McIntyre syncline. Dashed lines represent strike-slip faults. The Allegheny Front, a major topographic escarpment, follows the trend of the Catskill Formation (Dck) in the Council Run field area. Surface rocks exposed along the structural front dip gently northwestward into the Snow Shoe syncline. Two deep gas fields adjacent to the Council Run field, the Devils Elbow field (DE ), and the Grugan field (G) produce from anticlinal traps in Lower Silurian and Upper Ordovician rocks, respectively. The 231 1 well is the discovery well in the field.

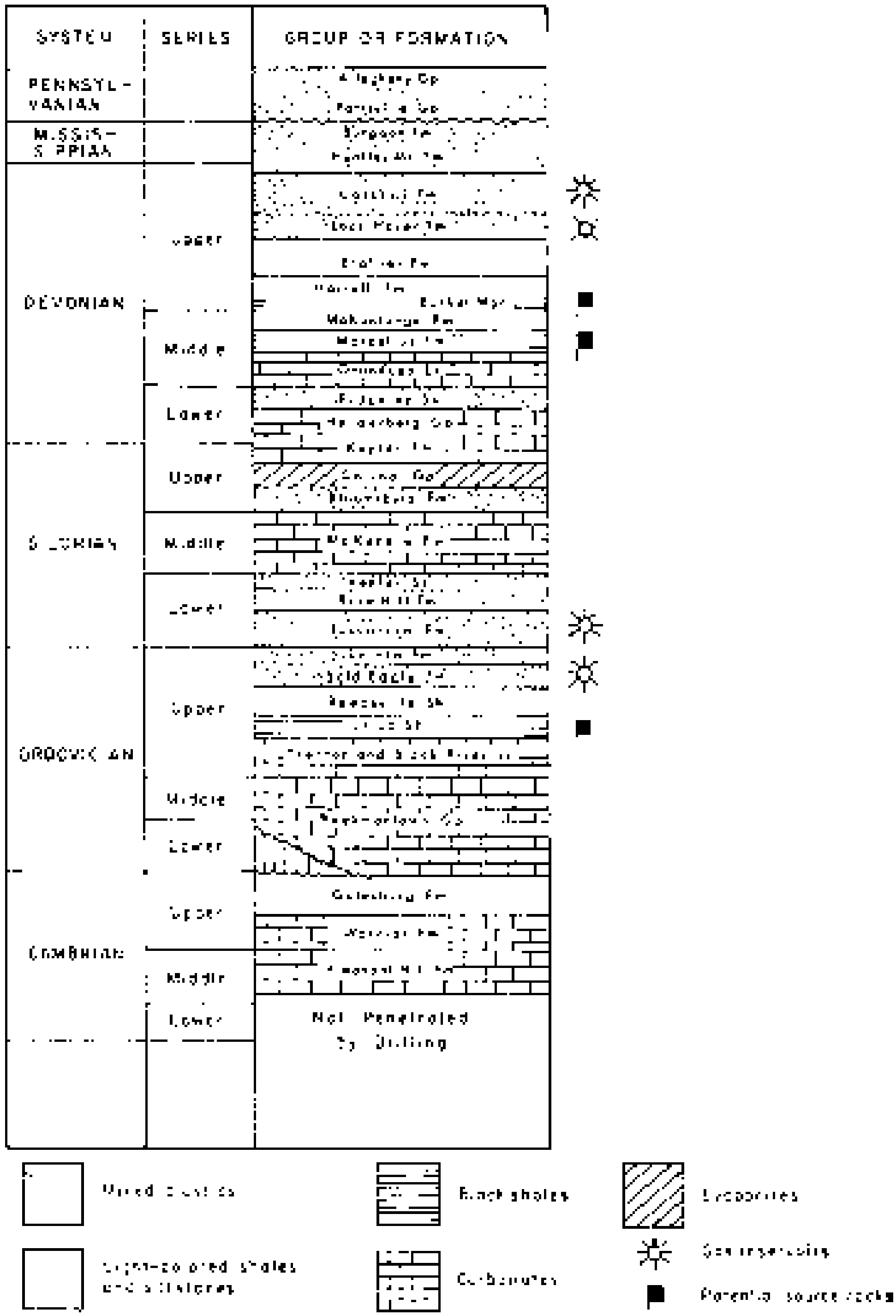



**Figure 2.** Stratigraphic column for the Council Run field vicinity.

delta-front facies in the Fifth Elk sandstone (discussed in detail below). These same sandstones onlap shoreward to the southeast (Figure 6). This geometry may reflect incised-valley filling during marine transgression.

The top of the sequence occurs at the base of the Third Bradford sandstone (Figure 4). The Third Bradford interval comprises a complex fluvial system developed from northeast to southwest between the Hyner anticline and the Allegheny Front (Humphrey et al., 1994). Production is predominantly from point-bar facies in this fluvial system. The Third Bradford sandstone is part of the lowstand systems tract developed at the base of another fourth-order sequence in the upper Lock Haven Formation.

The fourth-order sequence developed between the bases of the Fifth Elk sandstone and the Third Bradford sandstone, along with the Third Bradford itself, contains the most productive reservoir rocks at Council Run (Figure 4). Most producing wells in the Council Run field are multizone completions. Historically, the Fifth Elk sandstone is the most important reservoir in the field, and for this paper, we discuss the reservoir geology of the Fifth Elk in detail. The other reservoir horizons have become increasingly important since the early 1990s. The Fourth Elk sandstones are proving to be important in extending production to the east, northeast, and northwest. The basal Bradford sandstones are relatively thick and widespread in the field area. The Third Bradford sandstones are also extensive in the field area and contribute to higher than average reserves in certain portions of the field. Space limitations preclude a detailed discussion of all these reservoir sandstones. Data for all of the principal reservoir rocks at Council Run are available at the Pittsburgh, Pennsylvania offices of the Pennsylvania Geological Survey.

## FIFTH ELK SANDSTONE

### Sandstone Geometry

An isopach map of 50% shale-free sandstone (Figure 8) reveals that the geometry of the Fifth Elk reservoirs at Council Run field is best described as ''diverse small pods'' (terminology of Pettijohn et al., 1987, p. 345). The pods extend for about 38.4 km (24 mi) along strike. They are ovate, irregular, or elongate. Individual pods are 3.2–11.2 km (2–7 mi) long and 1.3–6.4 km (0.8–4 mi) wide. Cross section AA′ constructed along strike shows that Fifth Elk sandstones in these pods largely consist of coarsening-upward multistory sandstone lenses (Figure 7). A few isolated fining-upward sandstones occur in some pods.

Dip-oriented cross sections at Council Run field, such as that shown in Figure 6, reveal that the subsurface Fifth Elk sandstone mostly consists of stacked coarsening-upward parasequences that prograde from southeast to northwest over a distance of at least 8.5–16 km (5–10 mi). Gaps of 1.6–4.8 km (1–3 mi) separate individual pods of Fifth Elk sandstone along the dip direction. Although rocks equivalent to the Fifth Elk interval crop out only 3.2 km (2 mi) southeast of the field, drilling and seismic surveys failed to find Fifth Elk sandstone reservoir rocks between the southeast border of the field and the outcrop.

### Core Analyses

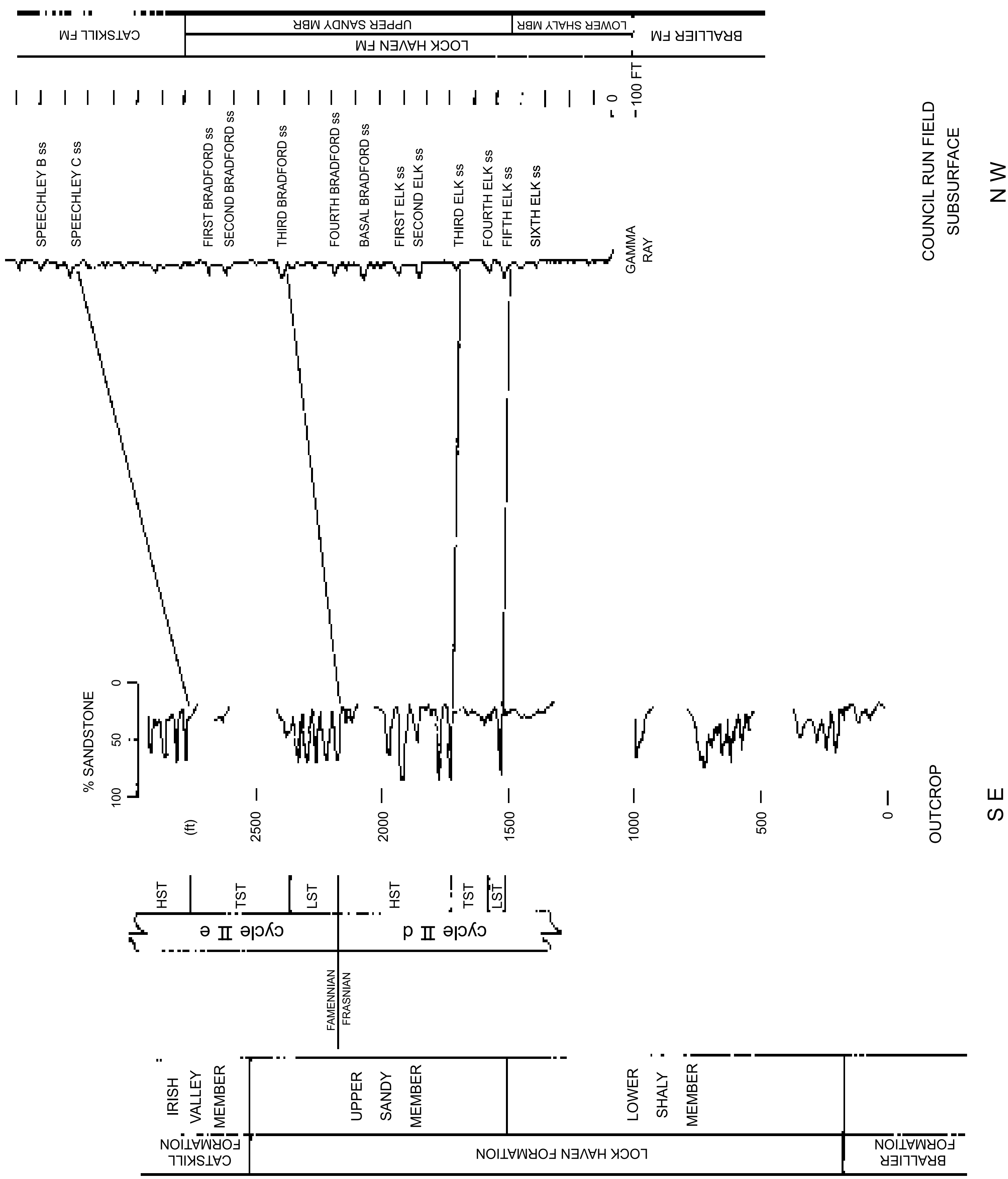
The Eastern States Exploration Company recovered cores of the Fifth Elk sandstone from nine wells in the Council Run field (Figure 8). Two of these are whole-diameter cores. The other seven are rotary sidewall cores. We described the two whole-diameter cores for parasequence recognition, environmental interpretation, wire-line-log calibration, and stratigraphic correlation. We prepared samples from all of the cores for thin-section, x-ray diffraction, and scanning electron microscopy analyses. We used this petrologic data to compliment environmental interpretations based on log signatures, to recognize porosity types, and to identify potential problems related to drilling, log interpretation, and well stimulation.

### Eastern States Exploration Company 5 Commonwealth of Pennsylvania Tract 709 Well Core

The No. 5 Tract 709 well (035-20673) is in the northeast part of the field. The entire thickness of the Fifth Elk sandstone was recovered in this whole-diameter core. The Fifth Elk interval consists of two stacked coarsening-upward parasequences separated by a marine flooding surface at 1322.8–1323.4 m (4340–4342 ft) (Figure 9). This surface is defined by an abrupt change in lithology from sandstone below to mudrock above, shale rip-up clasts, and calcite and siderite nodules. Another marine flooding surface is at the top of the Fifth Elk sandstone at 1315.2 m (4315 ft). This surface also is defined by an abrupt change in lithology from sandstone below to mudrock above and by a horizon of strong bioturbation; the burrowing intensity decreases downward into the sandstone.

The lower parasequence extends from 1331 to 1322.8 m (4367 to 4340 ft) in the core. Its base begins with medium dark gray and brownish gray mudstones that contain very thin to thick laminae of light olive gray siltstone and very fine-grained sandstone. The former are massive or display parallel discontinuous lamination, indicating continuous to episodic sedimentation from suspension with some bottom currents (Potter et al., 1980). The latter exhibit ripple cross-laminations, minor parallel laminations, basal scour surfaces, and small load structures. These rocks have a bioturbated texture and contain distinct burrows, including *Rhizocorallium*. We interpret these rocks (1331–1327.4 m; 4367–4355 ft) as marine shelf deposits.

The lower parasequence becomes sandier upward as it grades from the lithologies described above into


CATSKILL FM
LOCK HAVEN FM
UPPER SANDY MBR
LOWER SHALY MBR
BRALLIER FM
0
100 FT
SPEECHLEY B ss
SPEECHLEY C ss
FIRST BRADFORD ss
SECOND BRADFORD ss
THIRD BRADFORD ss
FOURTH BRADFORD ss
BASAL BRADFORD ss
FIRST ELK ss
SECOND ELK ss
THIRD ELK ss
FOURTH ELK ss
FIFTH ELK ss
SIXTH ELK ss
GAMMA RAY
COUNCIL RUN FIELD SUBSURFACE
N W
% SANDSTONE
0
50
100
(ft)
2500
2000
1500
1000
500
0
OUTCROP
S E
HST
TST
LST
HST
TST
LST
cycle II e
cycle II d
FAMENNIAN
FRASNIAN
IRISH VALLEY MEMBER
UPPER SANDY MEMBER
LOWER SHALY MEMBER
CATSKILL FORMATION
LOCK HAVEN FORMATION
BRALLIER FORMATION

interbedded mudstones and sandstones. The latter are thin- to medium-bedded, light olive gray, very fine-grained rocks. They are bioturbated, but do contain some parallel and ripple cross-laminations, slump structures, and convolute bedding. This mixed heterolithic association of mudstone and lenticular to wavy bedded sandstone shows a repeated alternation between physical and biological sedimentary processes related to storm and fair-weather periods (Elliott, 1978). We interpret this interval from 1327.4 to 1324.7 m (4355 to 4346 ft) as muddy lower shoreface deposits.

The upper portion of this first parasequence, from 1323.7 m to its top at 1322.8 m (4343 to 4340 ft), consists of medium gray to light greenish gray, very fine-grained sublitharenite. The sandstone displays burrows and low-angle planar cross-laminations near its base, but sedimentary structures become obscure upward. Much of the sandstone is mottled because of intercalated organic matter. Shale rip-up clasts occur at 1323 and 1323.4 m (4341 and 4342 ft). Small calcite nodules are scattered throughout the sandstone between 1323 and 1323.4 m (4341 and 4342 ft). A large siderite nodule crosses the core at 1323 m (4340.4 ft). The siderite and calcite indicate moderate reducing conditions; the organic matter intercalated in the sandstones probably contributed to reducing conditions in the original sediment (Pettijohn et al., 1987). We interpret this upper portion of the parasequence as upper shoreface to foreshore sandstones capped by a transgressive lag that marks the marine flooding surface at 1322.8–1323.4 m (Figure 9).

The upper parasequence in the No. 5 Tract 709 well core contains a similar vertical facies distribution. It extends from 1322.8 to 1315.2 m (4340 to 4315 ft). The parasequence begins with interbedded mudstone and sandstone (1322.8–1321.6 m; 4340–4336 ft), which we interpret as marine shelf deposits above the marine flooding surface. The mudstones of this interval are medium dark gray and bioturbated. They contain abundant small horizontal burrows filled with sand and clay. Pyrite is common in these burrows. The sandstones of this interval are very light gray to medium dark gray, very fine grained, and largely bioturbated. Sedimentary structures include ripples, low-angle cross-lamination, wavy bedding, convolute bedding, scour surfaces, and small load structures.

Interpreted lower shoreface deposits occur from 1321.6 to 1318 m (4336 to 4324 ft). Light to medium dark gray, very fine-grained sandstones dominate this interval, although it also contains thin interbeds of dark gray mudrock. The sandstones are sublitharenites and subarkoses. They mostly occur in medium-sized, bioturbated, wavy or lenticular beds, although a few of the sandstones contain low-angle parallel laminations. The core contains brachiopods between 1320 and 1320.7 m (4331 and 4333 ft).

The upper part of this parasequence, from 1318 to 1315 m (4324 to 4315 ft), consists of very light gray, very fine- and fine-grained sublitharenites and subarkoses. Sedimentary structures include trough and planar cross-bedding, parallel lamination, ripple cross-laminations, minor wavy and lenticular bedding, and some scour surfaces. Shale rip-up clasts are concentrated at the base of the trough cross-beds, and a few are scattered throughout the interval. A few brachiopods and burrows also occur in this section. We interpret this uppermost interval as upper shoreface and foreshore deposits based on published depositional models of Elliott (1978), Reinson (1979), and Reineck and Singh (1980).

### Litke 30 Well Core

The Litke 30 well (027-20283) is in the center of the field. Coring operations in this well recovered sandstone and shale samples from the Fourth Elk interval and sandstone from the uppermost Fifth Elk interval (Figure 10). Only the top 0.64 m (2.1 ft) of the Fifth Elk sandstone were recovered in the core, but it is significant because the samples from directly above the sandstone reveal evidence of the same marine flooding surface identified at the top of the reservoir in the No. 5 Tract 709 core. This marine flooding surface in the Litke core is at 1418.3–1418.8 m (4653.1–4654.8 ft). It is defined by an abrupt change in lithology from

**Figure 3.** Correlation of the Lock Haven Formation outcrop with the subsurface Lock Haven rocks encountered in the Council Run field. The outcrop and well are 3.2 km (2 mi) apart. Percent sandstone in the outcrop section and terminology are from Warne and McGhee (1991). The Frasnian and Famennian cycles are from Johnson et al. (1985). LST = lowstand systems tract. TST = transgressive systems tract. HST = highstand systems tract. The gamma-ray log shows driller's names for specific reservoir sandstones in the Catskill and Lock Haven formations at Council Run field.

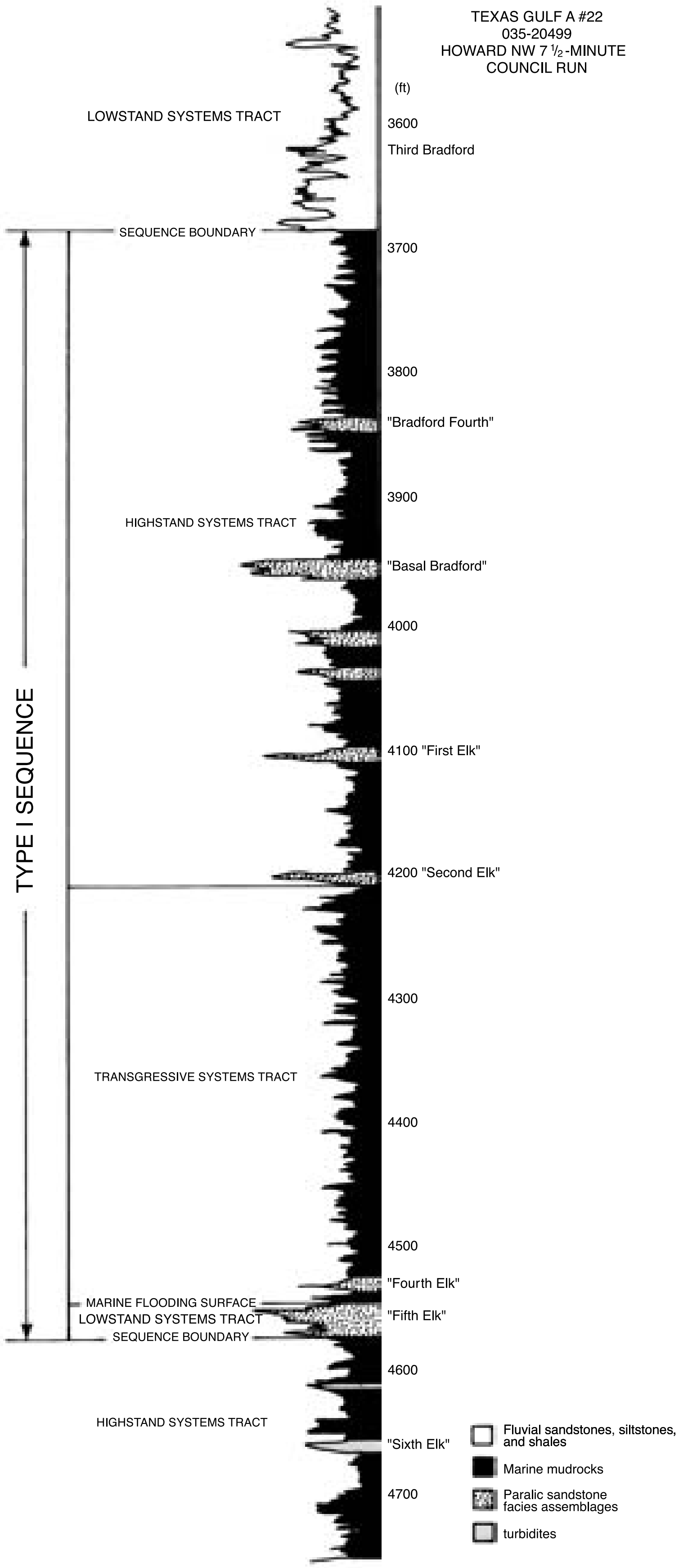



**Figure 4.** Gamma-ray log of the Texas Gulf A22 well in Council Run field showing the interpreted type I sequence preserved between the base of the Fifth Elk and Bradford Third reservoir sandstones.

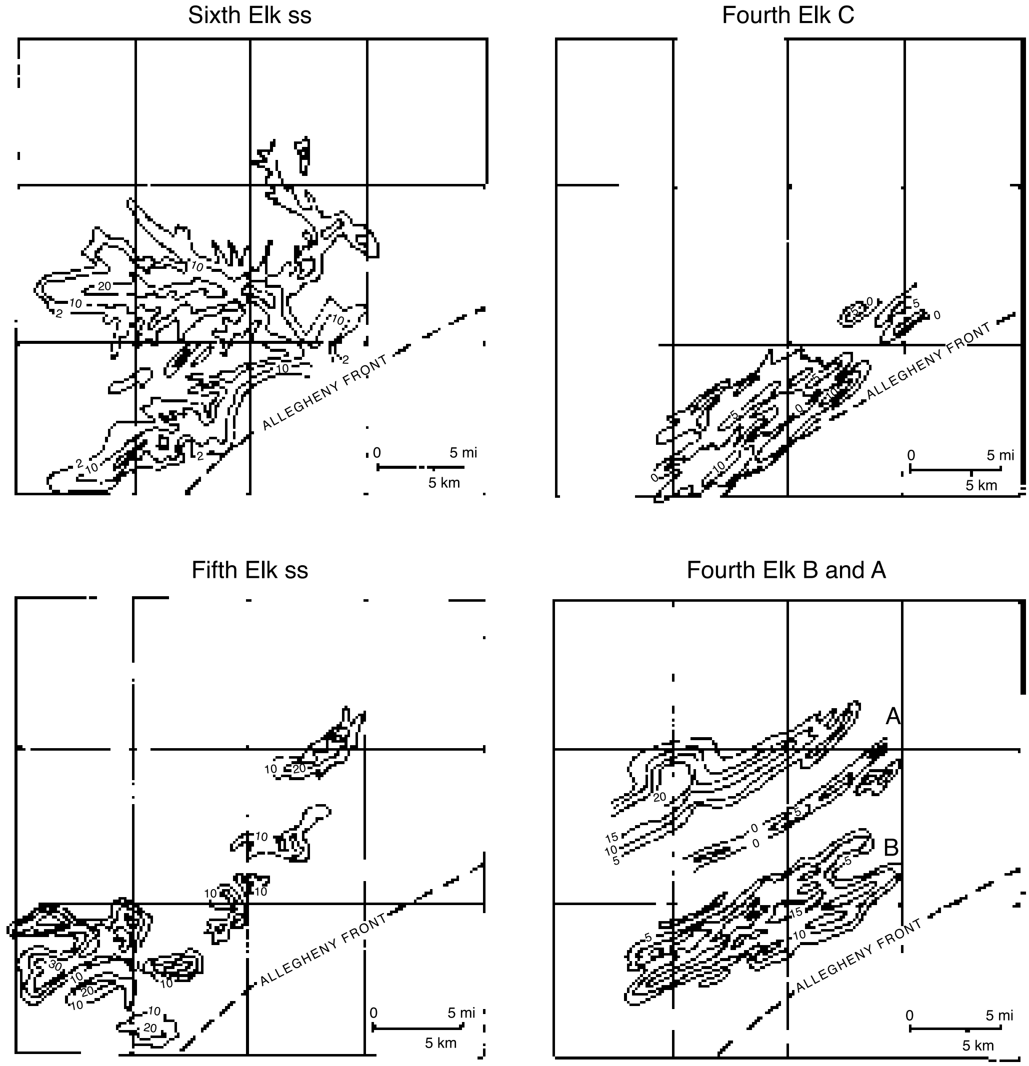



**Figure 5.** Isopach maps of 50% shale-free sandstone for the Sixth Elk, Fifth Elk, Fourth Elk C, Fourth Elk B, and Fourth Elk A reservoirs at Council Run field. Contour thickness is in feet. The map patterns are discussed in the text.

sandstone below to mudrock above, very thin lenses of lithic, micaceous, rounded quartz pebble conglomerate, shale rip-up clasts, and strong bioturbation (Figure 10). Most of the core contains rocks of the TST that overlie the Fifth Elk sandstone.

Fifth Elk sandstone recovered from 1418.8 to 1419.4 m (4654.8 to 4656.9 ft) in the core consists of light gray to very light gray, well-sorted, very fine- to fine-grained arkosic arenite. The sandstone coarsens upward, and it exhibits low-angle to horizontal laminations. The gamma-ray log of the entire Fifth Elk interval reveals that the cored portion is the top of a clean 4.3-m (14-ft)-thick coarsening-upward parasequence (Figure 10).

## Depositional Setting

The specific sedimentary characteristics of the parasequences in the No. 5 Tract 709 and Litke 30 cores suggest that the rocks originated in a paralic depositional environment. Lithologies, fossils, trace fossils, and sedimentary structures all suggest a vertical transition from marine shelf muds to muddy and increasingly sandy shoreface sediments to foreshore deposits. Palynomorphs from various intervals in the No. 5 Tract 709 well core and others indicate a nearshore marine environment (Al-Mugheiry, 1995). The ratio of sandstone to shale increases upward in all of the parasequences. Grain size increases upward in the sandstones. The sandstone bedsets and beds thicken upward.

All of these features record a gradual decrease in water depth. Van Wagoner et al. (1990) suggest that such coarsening-upward parasequences formed as associations of beach or deltaic facies. The ovate lens geometry of the Fifth Elk pods suggests that the reservoirs were deposited as lobate to arcuate/cuspate delta lobes in a delta-front environment (Elliott, 1978; Brown, 1979; Coleman and Prior, 1982). The vertical

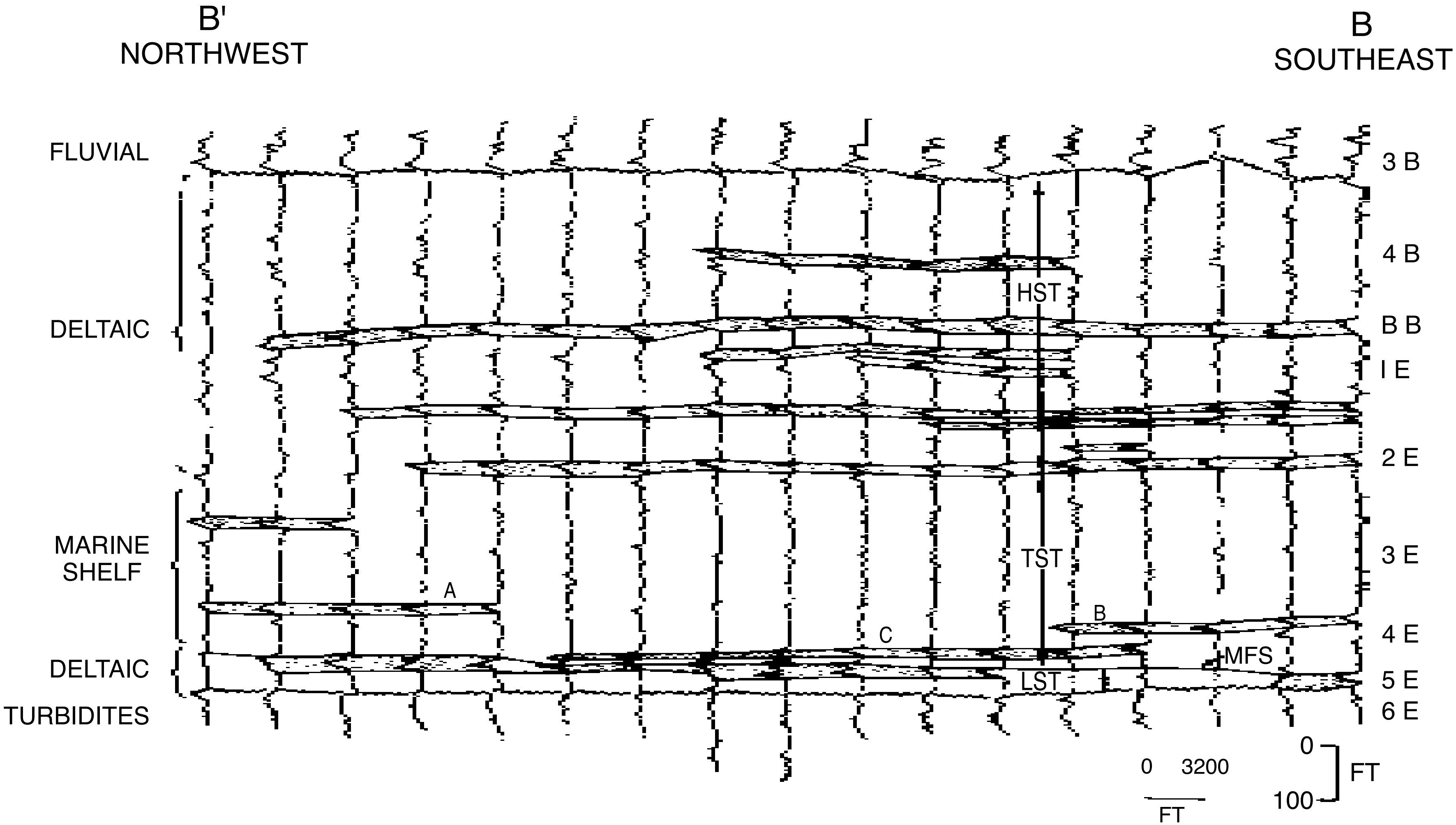



**Figure 6.** Northwest-southeast subsurface stratigraphic cross section BB′ of the principal producing sandstones between the Fifth Elk and Third Bradford intervals at Council Run field showing interpreted systems tracts. See Figure 8 for the line of section.

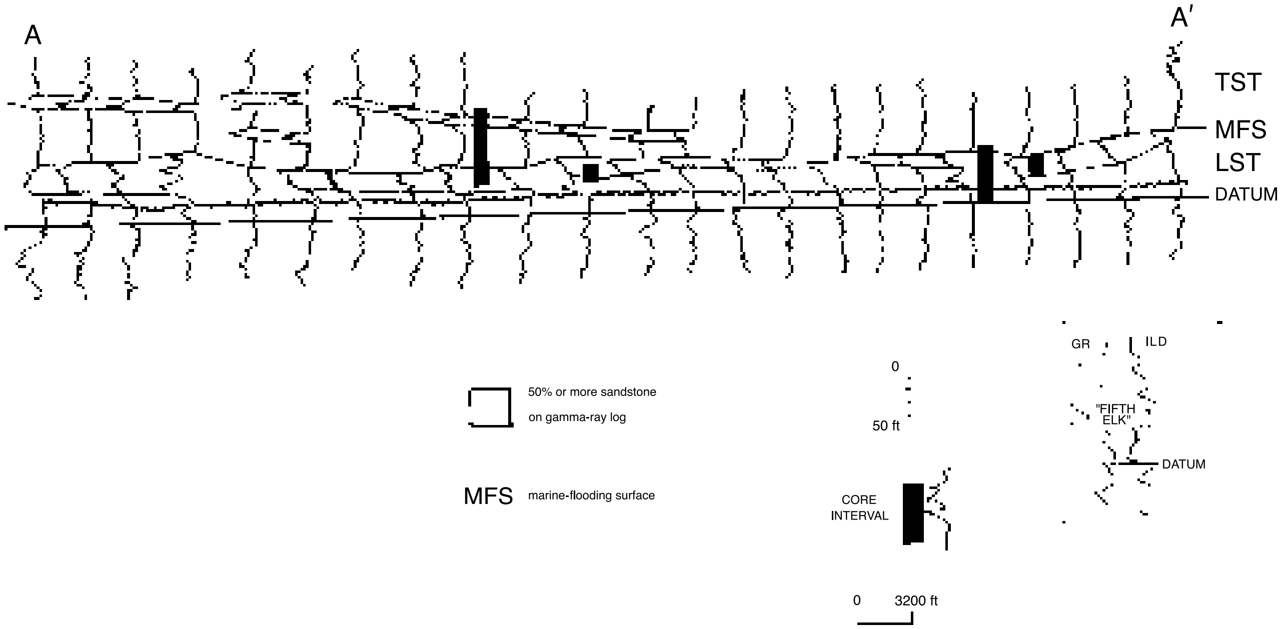



**Figure 7.** Stratigraphic cross section AA′ constructed along strike showing sandstone geometry of the Fifth Elk sandstone across the Council Run field. See Figure 8 for the line of section.

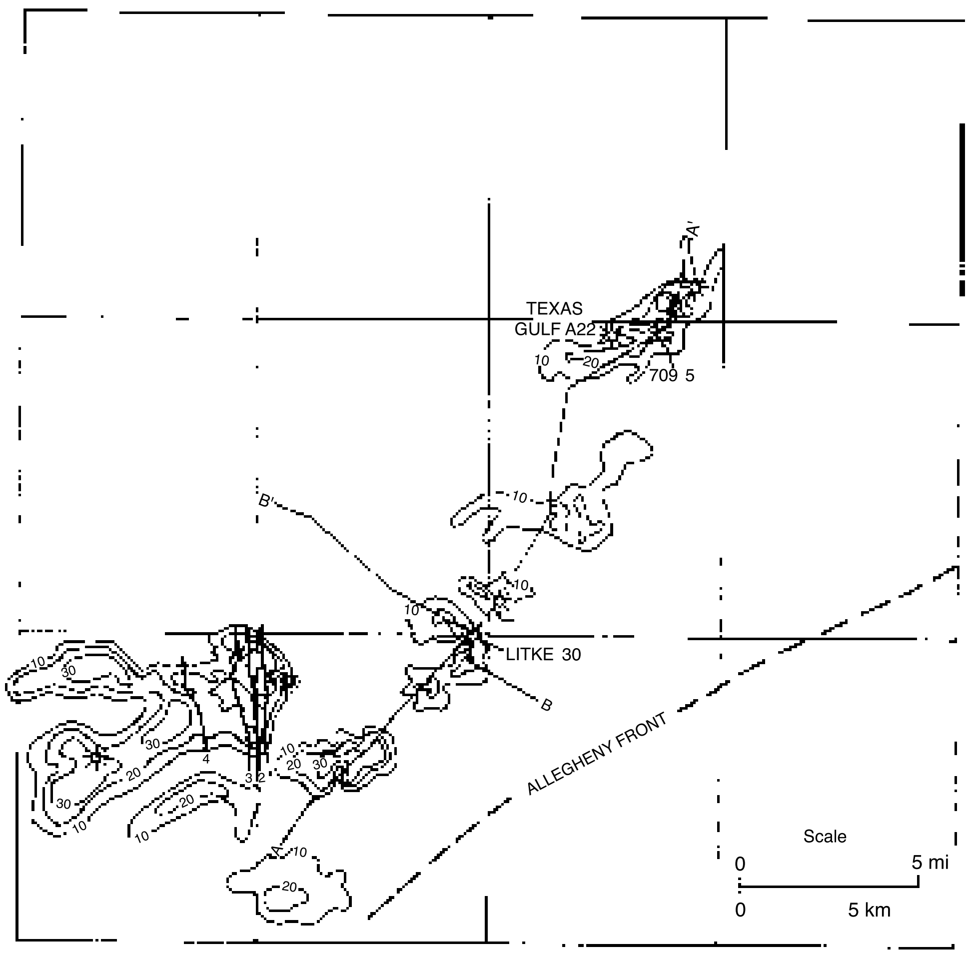



**Figure 8.** Enlargement of the isopach map of 50% shale-free Fifth Elk sandstone at Council Run field shown in Figure 5. Contour thickness is in feet. The different cross section lines are discussed in the text. Well symbols represent locations of cored wells.

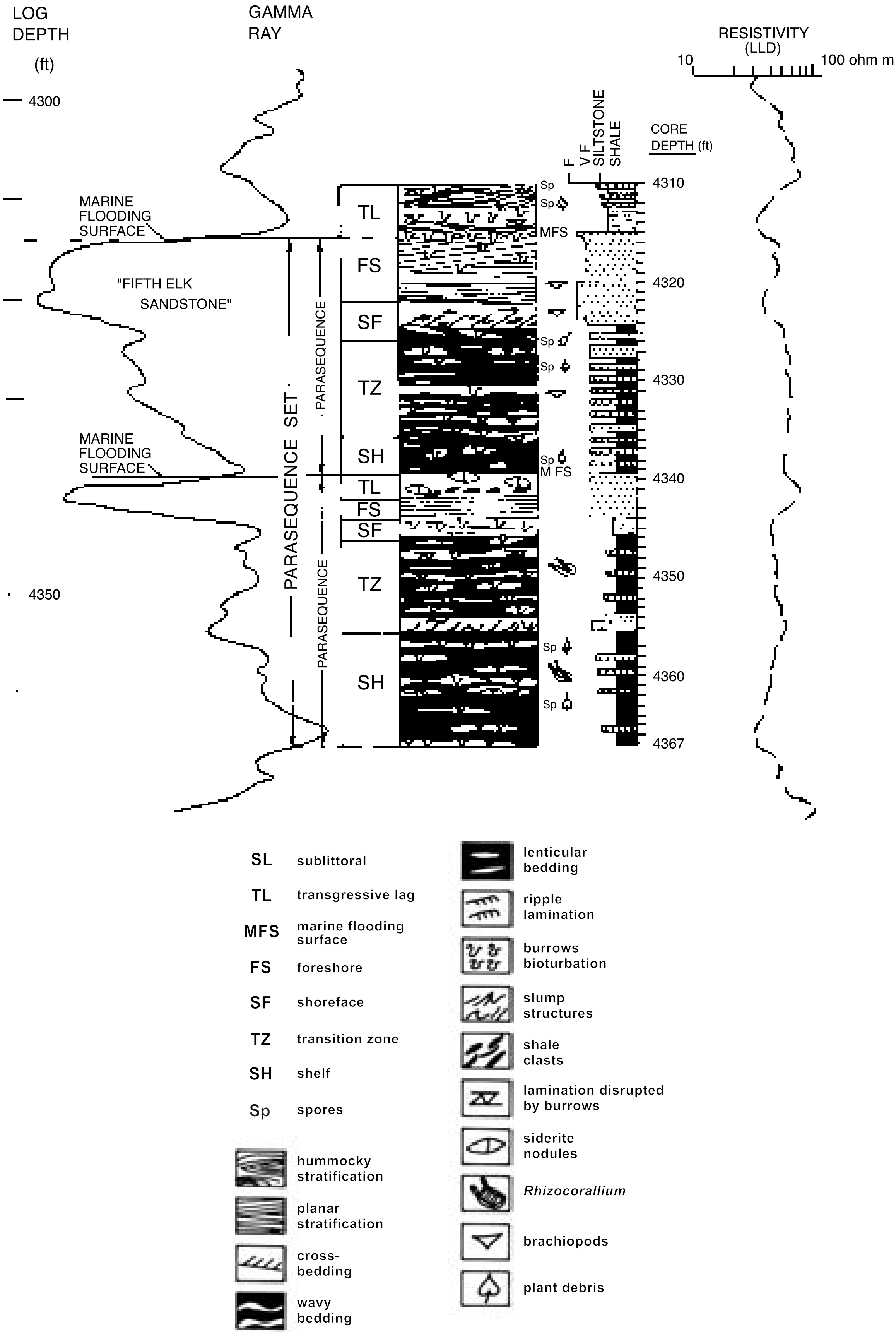



**Figure 9.** Graphical core description of the Fifth Elk sandstone recovered from the No. 5 Tract 709 well at Council Run field.

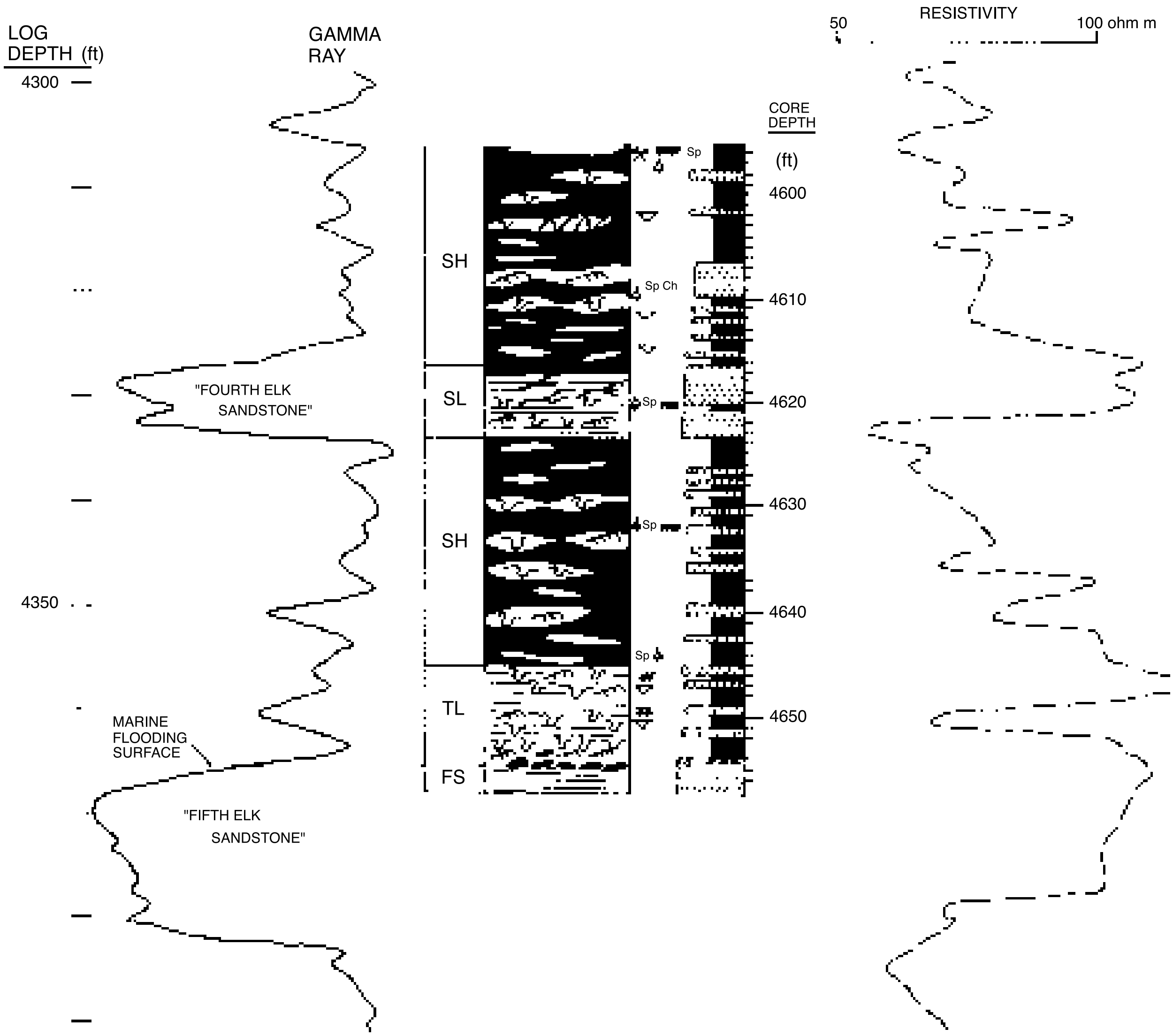



**Figure 10.** Graphical core description of the uppermost Fifth Elk sandstone and overlying mudrocks and sandstones of the transgressive systems tract recovered in the Litke 30 well core. See legend in Figure 9.

facies arrangement of shelf to shoreface to foreshore deposits interpreted in the Fifth Elk cores bears a similarity to the vertical facies associations in the offlap sequence of the Brazos River delta of the Texas coast described by Bernard et al. (1970). Closely spaced gamma-ray log cross sections through the largest lobe in the southwest part of the Council Run field (Figure 11) show the prevalence of coarsening-upward sandstones throughout the reservoir body. A serrate funnel-shaped pattern is the dominant gamma-ray log signature in the Fifth Elk sandstone at Council Run as it is in the Brazos River delta. Restricted blocky and fining-upward log patterns running through portions of the east end of the largest Fifth Elk sandstone pod might represent remnants of the original distributary channel fill (Figure 11, lines 1 and 2).

Equivalent strata exposed along the Allegheny Front southeast, or landward, of the Council Run field were deposited in marine to beach environments (Warne, 1986; Warne and McGhee, 1991). There is no evidence for coeval delta-plain facies, Fifth Elk distributary channels, or any other significant sandy facies between Council Run and the structural front. Posamentier et al. (1992) suggest that direct evidence of feeder systems to paralic sandstones of lowstand systems tracts deposited during a forced regression is commonly lacking, as is the case of the Fifth Elk sandstone at Council Run field. This is because the coeval alluvial plain deposits landward of the lowstand shorelines were thin because of sedimentary bypass, or they were removed because of ravinement during a subsequent transgression (Posamentier et al., 1992, p. 1705; Posamentier and Allen, 1993).

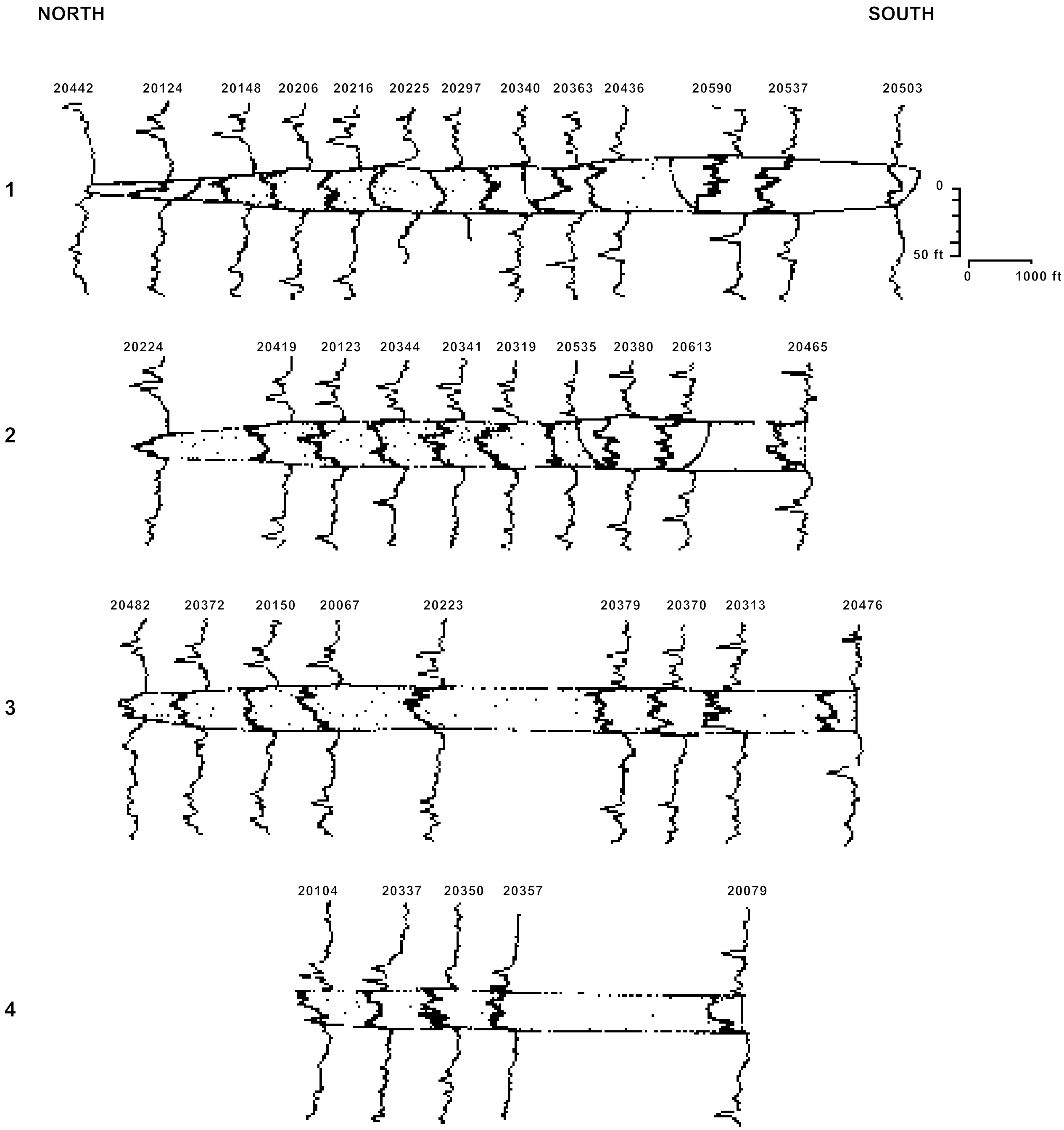



**Figure 11.** Closely spaced north-south gamma-ray log cross sections of the Fifth Elk sandstone interval in the southwest portion of the Council Run field. See Figure 8 for the locations of the lines of section. Most logs reveal coarsening-upward sandstone (fine stippling), although a few (coarse stippling, lines 1 and 2) do exhibit blocky and fining-upward patterns. The latter might be distributary channel remnants.

## Petrography

We examined 42 thin sections of the Fifth Elk sandstone from cores recovered in the Council Run field. All of the sandstone samples were pressure impregnated with clear, blue-dyed epoxy, and the thin-section billets were ground past the disturbed surfaces where grain plucking might have occurred to assure accurate identification of secondary pore fabrics. We also tabulated petrographic data generated by consultants and service companies for Eastern States Exploration Company over the years of Council Run development.

Some of the latter information was published by Billman et al. (1991), Bruner and Smosna (1994), and Smosna and Bruner (1997). The purpose of our petrographic analysis was to document the nature of porosity in the Fifth Elk sandstone and to determine the potential for formation damage that could be caused by completion and stimulation procedures.

Two-thirds of the Fifth Elk sandstone samples are sublitharenites. The remainder consists of arkosic arenites, subarkoses, and lithic arenites. The sandstones are very fine to fine grained and moderately to well sorted. Detrital grains comprise an average 70.6% of the bulk mineral composition of the rocks and contain an average of 44.6% monocrystalline quartz, 4.3% polycrystalline quartz, and 1.0% chert. Lithic grains include abundant metamorphic rock fragments (mean = 9.0%) and lesser amounts of igneous and sedimentary fragments. Feldspars make up between 2 and 27% of the bulk mineralogy. The mean feldspar content of the sandstones is 10%. Albite is the most common feldspar in the sandstones, whereas potassium feldspars comprise only traces to a few percent of the total. Accessories include muscovite, biotite, and various heavy minerals, along with small quantities of recrystallized fossils, phosphate and dolomite pellets, and disseminated organic material.

Clay minerals occur in the Fifth Elk sandstones as matrix and authigenic cement. Clay matrix accounts for an average of 8.5% of the bulk mineral composition of the sandstones. It occurs as pseudomatrix, laminar shale, and dispersed shale. Pseudomatrix formed through the deformation of ductile rock fragments during compaction of the sandstones. Some of the dispersed shales were also deformed by compaction. Authigenic clay minerals constitute 5–9% of the Fifth Elk's bulk mineralogy and average 6% in the sandstones. Iron-rich chlorite is the most abundant authigenic clay. It occurs as pore-lining and pore-filling euhedral, pseudohexagonal crystals. Authigenic kaolinite occurs in the sandstones as pore-filling stacks of pseudohexagonal plates or books. Minor amounts of authigenic illite occur as thin fibrous flakes or wispy laths that coat detrital grains and partially fill intergranular pores.

Authigenic quartz and carbonate cements make up an average 20.4% of the bulk mineral composition of the Fifth Elk samples. Silica cement ranges from 8 to 30% and averages 17%. It occurs as (1) syntaxial overgrowths on framework quartz grains, (2) pore-bridging crystals, and (3) large interlocking euhedral crystals that partially occlude intergranular pore spaces and throats. Carbonate cements in the sandstones include ferroan dolomite, siderite, and calcite. These carbonate cements occur in scattered clusters of small crystals or patches of sparry cement. Ferroan dolomite (ankerite) occurs as rhombic or sparry pore-filling cement. Calcite is present in trace amounts as isolated patches of sparry cement. Siderite occurs as microcrystalline mosaics of pore-filling cement.

Minor cements present in trace quantities in the Fifth Elk sandstones include feldspar overgrowths, pyrite, and anhydrite.

Porosities of the Fifth Elk sandstone, measured in thin sections, range from 1 to 14%. Porosities measured by core and geophysical log analyses are as high as 16%. Good porosities in the pay zones (>6%) exhibit two principal textures: reduced primary intergranular porosity and secondary oversized fabric-selective porosity (terminology of Schmidt and McDonald, 1979). In most instances, sandstones with the highest porosities (10–14%) have void spaces that are combinations of these two pore textures. Microporosity in the sandstones is associated with pore-lining clay cements.

Reduced primary pores account for one-fourth to one-half of the total porosity of most of the sandstones with 6% or more porosity. Preservation of primary porosity occurred through incomplete cementation and chlorite grain coats that inhibited the nucleation of silica cements on detrital grains. In a few samples, the emplacement of hydrocarbons, which are now present as bitumen, preserved original primary pores. This mechanism of porosity preservation in the Lock Haven Formation sandstones was first noted by Billman et al. (1991) and Bruner and Smosna (1994) and appears to be regional phenomena in these rocks along the length of the Allegheny structural front.

Secondary oversized fabric-selective porosity accounts for as much as three-fourths of the total porosity in Fifth Elk sandstones with more than 6% porosity. It formed principally through the leaching of chemically labile lithic fragments and feldspars. Most of these pores contain clay mineral residues. The dissolution of carbonate cement and recrystallized fossils also contributed to this secondary pore texture. The largest oversized fabric-selective voids formed where plastically deformed lithics were dissolved, leaving what Bruner and Smosna (1994) called elongate "channel" pores.

The generally low porosities and permeabilities of the Fifth Elk sandstone are typical of Upper Devonian sandstones in the central Appalachian basin and are the reason that hydraulic fracture stimulation is routinely required to complete wells drilled in the Council

Run field. Depositional porosity and permeability of the Fifth Elk sandstones were substantially reduced by compaction and cementation. Secondary dissolution porosity enhances the productivity of the Fifth Elk sandstones locally in the field. The sandstones are devoid of expandable clay minerals and are not susceptible to damage from contact with freshwater-based fluids. Pore-filling kaolinite and fibrous, pore-lining illite pose a potential problem with particle migration; formation/wellbore-pressure differentials should be limited during well completion and production, and the Fifth Elk should be treated with polymers designed to stabilize silt- and clay-sized minerals. The rocks contain minor amounts of acid-soluble carbonate. Acid solubility of the reservoir is insignificant, and acidization will not improve reservoir performance. The Fifth Elk sandstones contain notable amounts of iron-bearing chlorite and small amounts of siderite and pyrite, rendering the rocks susceptible to formation damage from contact with HCl or oxygenated fluids. Damage can be limited by using weak acid when removing drilling mud and cement debris from perforation tunnels, by blending an iron chelating agent into the acid, and by recovering the acid from the reservoir as quickly as possible.

## GEOCHEMISTRY OF PETROLEUM SOURCE ROCKS AND NATURAL GASES AT COUNCIL RUN FIELD

### Petroleum Source Rocks

Potential source rocks in the study area include the Burket Member of the Upper Devonian Harrell Formation, the Middle Devonian Marcellus Formation, and the Upper Ordovician Utica Shale (Figure 2). These are the only rocks in the region with sufficient total organic carbon to have generated commercial quantities of hydrocarbons (Figure 12). Black shales of the Burket and Marcellus (Devonian) are the likely source of the hydrocarbons produced from the Upper Devonian sandstones at Council Run field. The Utica Shale (Ordovician) is the probable source rock for gas produced from the deeper reservoirs at Devil's Elbow and Grugan fields (Donaldson et al., 1996; Laughrey and Harper, 1996; Laughrey and Baldassare, 1998).

Source rocks in the Burket Member and Marcellus Formation at Council Run field are postmature. Vitrinite reflectance ($R_o$) of kerogen samples from these stratigraphic intervals ranges from 2.81 to 3.0%. The thermal alteration index of the samples is 4.0. None of the kerogen samples fluoresce under ultraviolet light. Rock-Eval pyrolysis of Burket and Marcellus shales shows that the rocks have poor petroleum potential because of advanced thermal maturation: $S_1$ in these rocks ranges from 0.17 to 0.39 mg HC/g rock, and $S_2$ is less than 0.1 mg HC/g rock; the production index is 0.61.

The kerogens in the Burket and Marcellus shales are 90–100% amorphous, with traces to 5% each of vitrinite and inertinite. Amorphous kerogens are generally presumed to be hydrogen rich and oil prone (Peters and Casa, 1994, p. 98), but the postmature character of our samples makes it difficult to interpret the type of organic matter on the basis of petrography. Gas chromatograms of bitumen extracts from the Burket and Marcellus shales display an odd-carbon predominance of midchain normal alkanes ($C_{15}$–$C_{19}$) and a relatively low abundance of higher molecular weight compounds. Such normal alkane distributions are typical of organic matter deposited in shaly marine source rocks (Peters and Moldowan, 1993). The dominance of smaller molecules in these samples, however, probably reflects the postmature nature of the source rocks (Hunt, 1996, p. 134). The carbon preference index values (1.13–1.53), pristane/phytane ratios (1.18–1.36), and isoprenoid-to-normal-alkane ratios (pristane/n-$C_{17}$ = 0.43–0.56 and phytane/n-$C_{18}$ = 0.43–0.49) most likely reflect maturation effects instead of source organic matter composition.

Several other lines of evidence do suggest that the spent source rocks in the Burket Member and Marcellus Formation originally contained oil-prone kerogens and generated liquid hydrocarbons in the geologic past. First, type II organic matter occurs in the Marcellus Formation black shales analyzed in less mature sample suites west and northwest of the Allegheny Front in Pennsylvania (Milici, 1993; Laughrey, 1997). Second, oil produced from the Lock Haven Formation at Brace Creek field in Bradford County, northeast of Council Run field (Figure 1A), also originated in the Burket Member and Marcellus Formation (Laughrey, 1997). The source rocks are also postmature at this location. The oil produced at Brace Creek field exhibits characteristics typical of oil that was subjected to high thermal stress, i.e., high API gravity (45.8°), a normal alkane maximum at $C_9$, and no biomarkers. Near-surface rocks at Brace Creek field are on the borderline between oil preservation and gas-only preservation. The oil escaped complete thermal destruction because of extensive vertical migration and was subsequently

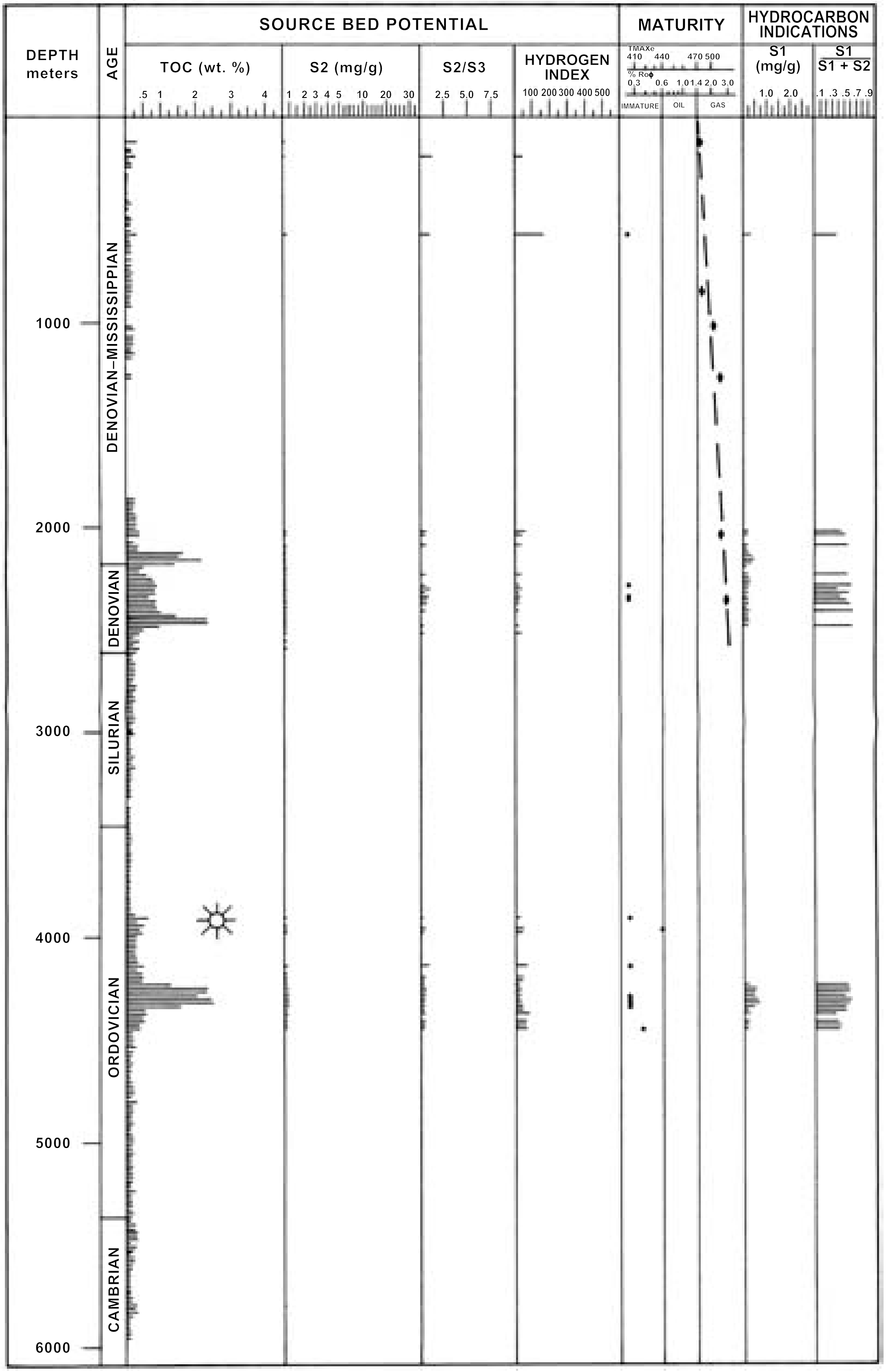



**Figure 12.** Geochemical log from the Texaco-Marathon Pennsylvania State Tract 285 well in the Grugan field developed immediately northeast of the Council Run field.

preserved under relatively cooler conditions in the reservoir. Third, Bruner and Smosna (1994) documented the presence of dead oil or bitumen in the pore spaces of the Lock Haven reservoir sandstones at Council Run field. Fourth, methane produced from the Upper Devonian sandstones at Council Run field is isotopically light relative to the postmature kerogens found in the probable source rocks (Laughrey and Baldassare, 1998). Gas produced today at Council Run field was originally associated with oil and was generated, in part, when the source rocks were in the oil window.

## Natural Gas Geochemistry

For this study, we sampled gases from eight wells and a compressor station to determine the chemical and stable isotopic composition of the hydrocarbons produced from Upper Devonian reservoirs at Council Run field as well as the adjacent gas fields that produce from different stratigraphic intervals (Table 1). Seven of the samples are gases from Upper Devonian Lock Haven and Catskill Formation rocks at Council Run. One of the samples is gas from the Black Moshannon field located southwest of the Council Run field. This gas is produced from very thin, relatively porous and permeable beds in the Brallier Formation, just above the source rocks of the Burket Member. One gas sample is from the Lower Silurian Tuscarora Formation at Devil's Elbow field south of Council Run.

Figure 13 shows the gas samples on a plot of methane $\delta^{13}C$ vs. $\delta D$. The plot shows the nine samples from Table 1 along with three additional samples from Laughrey and Baldassare (1998); these include gases from the Fifth Elk sandstone at Council Run, the Brallier Formation at Black Moshannon field, and the Upper Ordovician Bald Eagle Formation at Grugan field (Figure 2). The gases produced from Upper Devonian sandstones at Council Run all plot in the field labeled, "thermogenic gas, with oil." We interpret these methane samples as mixtures of gases generated with oil as the source rocks passed through the oil window and gases later cracked from oil in the reservoir rocks. The gases produced from the Brallier Formation are more mature, plotting in the field for methane associated with condensate. The Silurian and Ordovician gas samples are distinctly postmature and plot near the upper limits of the condensate-associated gas field, near its border with the dry thermogenic gas field.

In addition to methane $\delta^{13}C$ and $\delta D$, we measured $\delta^{13}C$ for ethane and propane in most of our samples (Table 1). The cracking of complex organic compounds to light hydrocarbon gases commonly yields an isotopic distribution in which methane $\delta^{13}C$ < ethane $\delta^{13}C$ < propane $\delta^{13}C$. Several of the Council Run samples, however, exhibit isotopic reversals with methane $\delta^{13}C$ > ethane $\delta^{13}C$ and ethane $\delta^{13}C$ > propane $\delta^{13}C$ (Figure 14A). Even the samples with normal isotopic distributions display very little carbon isotope separation between the $C_1$ to $C_3$ hydrocarbons. Isotopic reversals and distributions such as these indicate a mix of different thermogenic gases or postgenetic isotope fractionation of the gases (Jenden et al., 1993; Prinzhofer and Huc, 1995). A plot of ethane $\delta^{13}C$ minus propane $\delta^{13}C$ ($\delta^{13}C_2 - \delta^{13}C_3$) vs. $\ln(C_2/C_3)$ (Figure 14B) shows that there is not much variation in the relative proportion of $C_2/C_3$, whereas there is significant variation in $\delta^{13}C$; the plot is relatively steep with a positive slope, suggesting higher fractionation in the $\delta^{13}C$ than in $C_2/C_3$. Prinzhofer and Huc (1995) suggested that gases generated by primary cracking of kerogens typically show a subvertical trend with negative slope on such $\delta^{13}C_2 - \delta^{13}C_3$ vs. $\ln(C_2/C_3)$ plots. Gases generated by secondary cracking of oils typically show a subhorizontal trend with positive slope. Our Upper Devonian gas samples plotted in Figure 14B exhibit an intermediate trend between these two extremes. Because the Council Run gases show less fractionation for the $C_2/C_3$ than the $\delta^{13}C_2 - \delta^{13}C_3$, secondary cracking of oil was the most likely source of the gas. The trend is not strong, however, probably indicating that the secondary gases are mixed with earlier formed gases that were cracked from kerogens along with oils. We suggest that the gases produced from Upper Devonian reservoirs at Council Run field are mixtures of hydrocarbons generated by primary cracking of kerogens when the source rocks resided in the oil window and hydrocarbons generated by secondary cracking of oil during deeper burial of both reservoir and source rocks.

## Burial History and Petroleum Migration

We used data collected from the Texaco-Marathon Pennsylvania State Tract 285 well in the nearby Grugan field (Figure 1) to construct a burial and thermal history for the rocks of the Council Run field area. This well is adjacent to Council Run field, and it penetrated to the Upper Cambrian Warrior Formation. Geochemical data were available for the entire borehole (Figure 12).

Figure 15 is a graphical representation of the burial and thermal history of the rocks penetrated in the

**Table 1.** Gas Geochemistry Data from the Council Run Field*

| Sample Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Reservoir | Brallier Formation | Fifth Elk | Fifth Elk | Fourth Elk | Basal Bradford | Third Bradford | Commingled Elk | Commingled Speechley/Bradford | Tuscarora Formation |
| Well | Compressor Station | 035-20673 | 027-20297 | 035-20197-R | 035-20562 | 035-20876 | 027-20555 | 035-20806 | 027-20008 |
| **Chemical Composition (vol.%)** | | | | | | | | | |
| Methane | 96.17 | 97.35 | 96.13 | 96.11 | 94.91 | 96.74 | 94.66 | 96.30 | 80.68 |
| Ethane | 2.85 | 2.02 | 2.74 | 2.70 | 2.72 | 2.47 | 3.07 | 2.90 | 2.75 |
| Propane | 0.16 | 0.10 | 0.19 | 0.19 | 0.28 | 0.13 | 0.42 | 0.19 | 0.20 |
| Isobutane | 0.012 | 0.0068 | 0.020 | 0.026 | 0.045 | 0.0093 | 0.13 | 0.018 | 0.019 |
| n-Butane | 0.020 | 0.0082 | 0.038 | 0.032 | 0.081 | 0.019 | 0.13 | 0.033 | 0.024 |
| Isopentane | 0.0052 | nd | 0.016 | 0.015 | 0.049 | 0.0049 | 0.088 | 0.0085 | 0.0092 |
| n-Pentane | nd | nd | 0.0068 | 0.0065 | 0.041 | nd | 0.052 | 0.0050 | 0.0020 |
| Hexanes+ | 0.010 | 0.0011 | 0.030 | 0.029 | 0.16 | 0.0098 | 0.15 | 0.015 | 0.0075 |
| $C_2$+ (%) | 3.08 | 2.15 | 3.07 | 3.03 | 3.43 | 2.66 | 4.09 | 3.19 | 3.6 |
| Oxygen + argon | 0.010 | nd | 0.020 | 0.010 | 0.010 | 0.010 | 0.010 | nd | 0.030 |
| Nitrogen | 0.69 | 0.51 | 0.77 | 0.86 | 1.67 | 0.60 | 1.26 | 0.53 | 16.19 |
| Carbon dioxide | 0.07 | nd | 0.04 | 0.02 | 0.03 | 0.01 | 0.03 | nd | 0.09 |
| **Carbon Isotopic Composition (‰)** | | | | | | | | | |
| Methane | −39.87 | −42.90 | −40.00 | −43.59 | −44.73 | −40.48 | −44.16 | −41.83 | −32.72 |
| Ethane | −42.12 | −41.84 | −41.17 | −42.76 | −43.35 | −41.69 | −42.19 | −42.30 | −40.04 |
| Propane | −42.99 | −42.48 | −40.84 | −40.33 | −39.57 | −42.35 | −35.23 | −38.88 | −41.49 |
| **Hydrogen Isotopic Composition (‰)** | | | | | | | | | |
| Methane | −177.4 | −204.9 | −186.4 | −193.0 | −203.7 | −201.1 | −189.9 | −202.5 | −164.6 |

*Well identification numbers are state county codes and permit numbers.

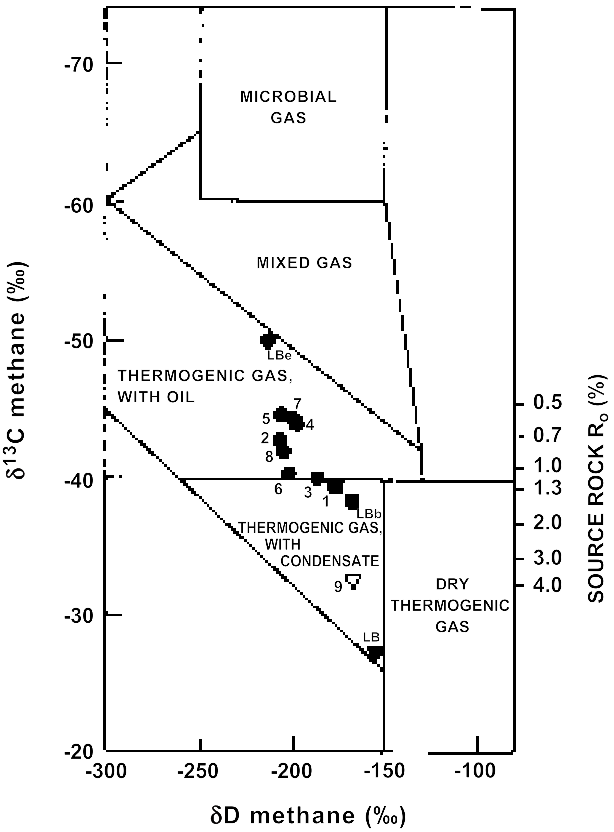



**Figure 13.** Plot of methane $\delta^{13}$C vs. methane $\delta$D for the gas samples in Table 1. Numbers correspond to sample numbers in Table 1. LBe is a Fifth Elk sample, LBb is a Brallier sample, and LB is a Bald Eagle Formation sample; all three are from Laughrey and Baldassare (1998). Compositional fields for various genetic types of gases are modified from Schoell (1983). $R_o$ scale is from Jenden et al. (1993).

State Tract 285 well. The burial curve was constructed using software available from Platte River Associates and Waples (1985). The amount of overburden removed from the sedimentary section was determined from sonic traveltime data using techniques described by Magara (1976) and from vitrinite reflectance data using a technique described by Price (1983). Our estimate of 3.8 km (2.36 mi) removed overburden agrees with an estimate by Lacazette (1991) based on fluid-inclusion data. Burial and erosion rates were taken from Beaumont et al. (1987) and Slingerland and Furlong (1989). We based our thermal maturation model (Figure 15; Table 2) on kerogen type IIc and oil-to-gas kinetics published by Hunt and Hennet (1992) and Hunt (1996).

Oil generation in the Devonian source rocks (Burket Member and Marcellus Formation) started when the rocks reached burial temperatures of 100° C about 320 Ma and ended about 290 Ma, before maximum burial to depths of approximately 6 km (3.73 mi). As the shales were buried beyond the oil window, liquid hydrocarbons remaining in the source rocks were cracked to gas. Cracking began about 290 Ma and was completed about 270 Ma. Approximately 98% of any oil remaining in the source rocks was cracked to gas by 270 Ma (Table 2).

Petroleum expelled from the Devonian source rocks migrated through permeable beds in the Upper Devonian Brallier Formation between 320 and 290 Ma and accumulated in the sandstones of the Lock Haven and Catskill formations. Dispersive migration paths were probably both lateral and vertical (Mann et al., 1997). Some accumulation might have continued until 270 Ma, when the reservoirs were buried to depths in the deep gas window. Oil trapped in the Lock Haven and Catskill formations reservoirs was progressively cracked to gas between 270 and 240 Ma during deepest burial and initial uplift. About 87.5% of this oil was cracked to gas before relatively rapid uplift removed the rocks from extreme maturation depths (Table 2).

## IMPLICATIONS FOR PETROLEUM EXPLORATION IN NORTH CENTRAL PENNSYLVANIA

The Council Run field is one of the most productive gas fields in the central Appalachian basin. The petroleum geology and geochemistry of the field provided an exploration and development model useful for searching for similar accumulations in regions deemed nonprospective by conventional wisdom, particularly in terms of reservoir stratigraphy and thermal maturation. The principal reservoir sandstones at Council Run are stratigraphic traps that were deposited during a Late Devonian (late Frasnian–early Famennian) third-order transgressive-regressive cycle, approximately 380 Ma. The most important reservoirs occur in a distinct fourth-order type 1 stratigraphic sequence that begins at the base of the Fifth Elk sandstone and ends at the base of the Third Bradford sandstone. The latter is also an important reservoir in some parts of the field. We interpret the tripartite vertical succession of predominantly coarse (lowstand), fine (transgressive), and coarse (highstand) lithologies observed in the respective systems tracts of this sequence as evidence for incised-valley-fill sediments. The incised valley probably is an integral component of the stratigraphic entrapment observed at Council Run field. Lateral transitions from reservoir rock to seal are gradational in

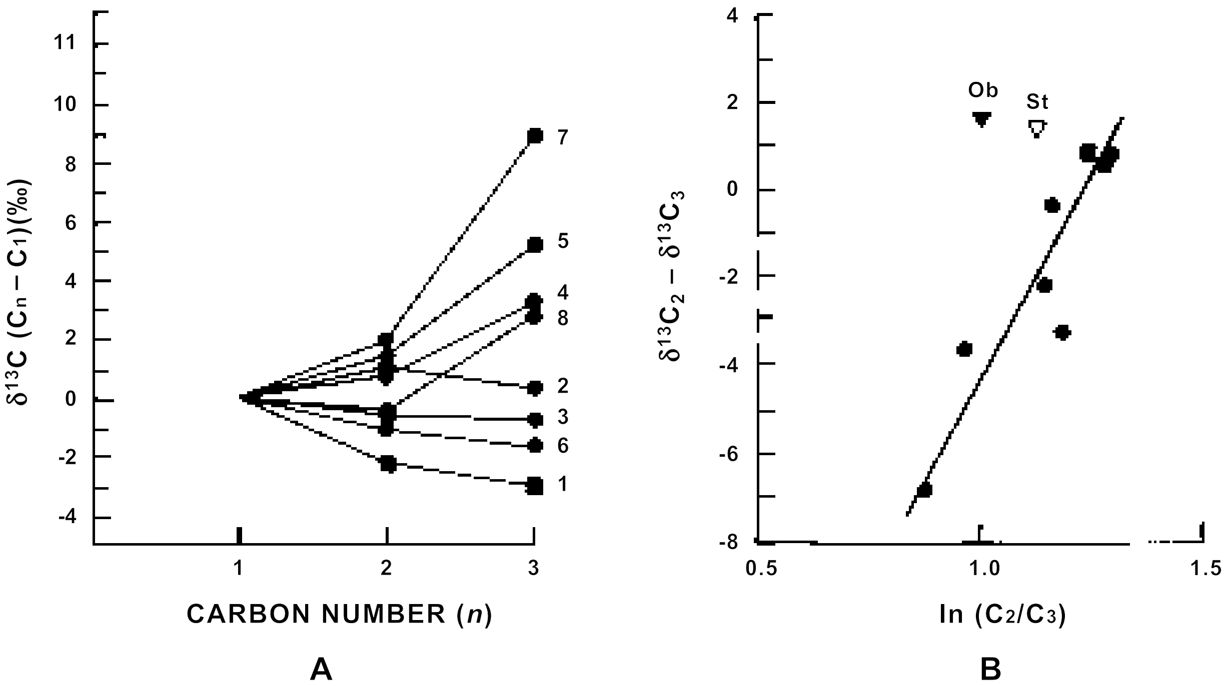



**Figure 14.** (A) $\delta^{13}C$ distribution in $C_1$ to $C_3$ hydrocarbons at Council Run field. (B) Plot of ethane $\delta^{13}C$ minus propane $\delta^{13}C$ vs. the natural logarithm of the ratio of ethane to propane for gas samples in Table 1.

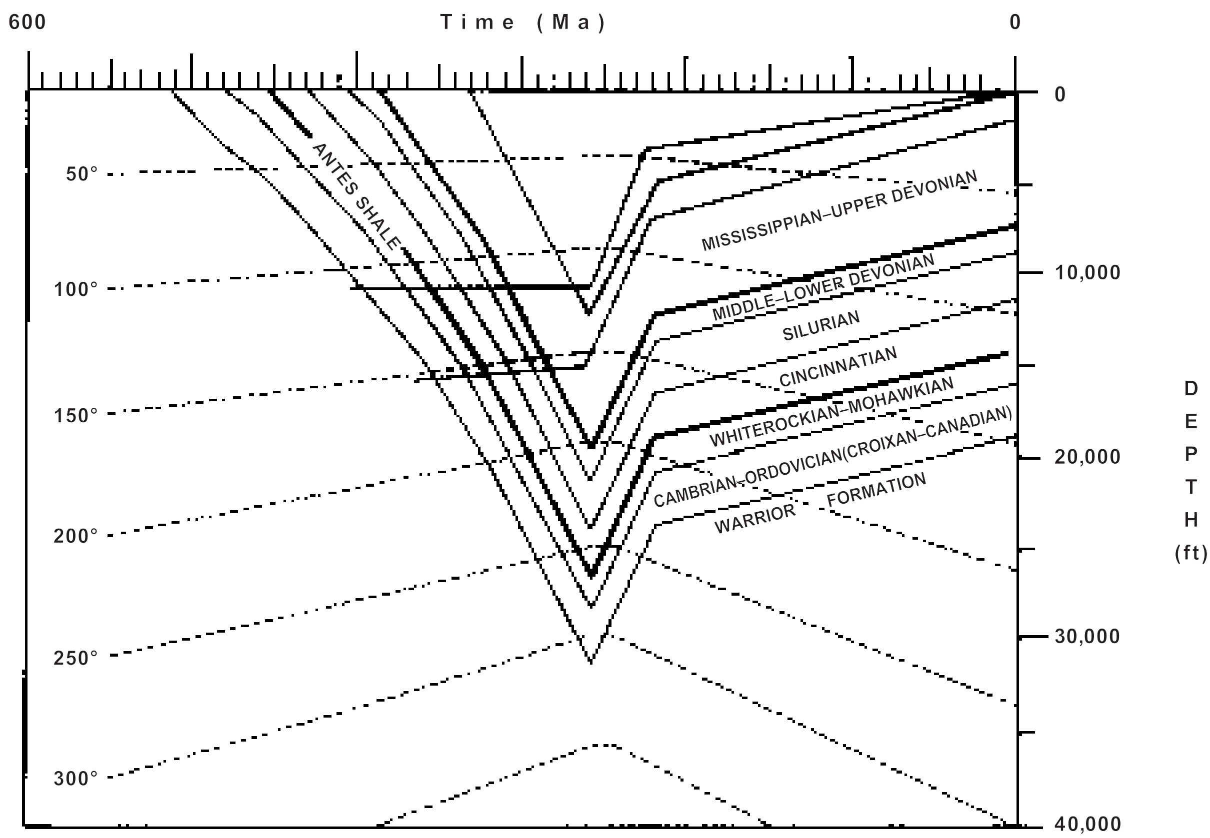



**Figure 15.** Burial and thermal history of the Paleozoic rocks along the Allegheny Front in north central Pennsylvania based on geological and geochemical data from the Pennsylvania State Tract 285 well in the Grugan field. Stippled area depicts the oil window. Heavy lines represent stratigraphic positions of source rocks discussed in the text.

**Table 2.** Arrhenius TTI Values ($TTI_{ARR}$) for Oil and Gas Generation in the Burket Member and Marcellus Formation Source Rocks and Lock Haven Formation Reservoir Using Kerogen Type IIC and Oil-to-Gas Kinetics, Texaco-Marathon Pennsylvania State Tract 285 Well

| Temperature Range (°C) | Exposure Time (m.y.) | $TTI_{ARR}$ | $\sum TTI_{ARR}$ | Oil Window | % Oil Generated | Oil to Gas, $TTI_{ARR}$ | Oil to Gas, $\sum TTI_{ARR}$ | Oil Cracking to Gas | Oil to Gas (%) |
|---|---|---|---|---|---|---|---|---|---|
| **Source Rocks** | | | | | | | | | |
| 90–100 | 10 | | | | | | | | |
| 100–110 | 6 | 1.3 | 1.3 | beginning | 1 | | | | |
| 110–120 | 6 | 8 | 9.3 | | 9 | | | | |
| 120–130 | 6 | 38 | 47.3 | | 38 | | | | |
| 130–140 | 6 | 150 | 197.3 | | ~87 | | | beginning | |
| 140–150 | 8 | 900 | 1097.3 | end | | 4 | 4 | | 3 |
| 150–160 | 4 | | | | | 11 | 15 | | 15 |
| 160–170 | 3 | | | | | 38 | 53 | | 40 |
| 170–180 | 9 | | | | | 430 | 483 | end | 98 |
| 180–190 | 5 | | | | | | | | |
| 190–200 | 16 | | | | | | | | |
| 180–190 | 4 | | | | | | | | |
| 170–180 | 6 | | | | | | | | |
| 160–170 | 2.5 | | | | | | | | |
| 150–160 | 2.5 | | | | | | | | |
| 140–150 | 2.5 | | | | | | | | |
| 130–140 | 6 | | | | | | | | |
| 120–130 | 25 | | | | | | | | |
| 110–120 | 32 | | | | | | | | |
| 100–110 | 28 | | | | | | | | |
| 90–100 | 30 | | | | | | | | |
| **Reservoirs** | | | | | | | | | |
| 140–150 | 5 | | | | | 3 | 3 | beginning | 5 |
| 150–160 | 4 | | | | | 11 | 14 | | 25 |
| 160–170 | 15 | | | | | 175 | 189 | | 85 |
| 150–160 | 5 | | | | | 13 | 202 | | 87 |
| 140–150 | 5 | | | | | 3 | 205 | end | ~87.5 |

the field and are caused by encasement of the sandstones in marine mudrock, internal lithologic heterogeneities, and sandstone diagenesis. These lateral transitions are responsible for less productive wells and noneconomic segments in the reservoirs (Biddle and Wielchowsky, 1994).

The most significant reservoir, the Fifth Elk sandstone, accumulated in marine-dominated delta-front environments of the lowstand systems tract during a forced regression. Reservoir quality in the sandstones was highly modified by diagenesis during burial and subsequent uplift of the rocks. Black shales in the Burket Member of the Upper Devonian Harrell Formation and the Middle Devonian Marcellus Formation are the probable source rocks of the gases produced at Council Run. These gases are a mixture of gas generated in the oil window before maximum burial of the Paleozoic rocks in the region and gas generated by the conversion of oil to gas during deeper burial. The source rocks are now overmature, and their generative potential is exhausted.

Exploration for other Lock Haven Formation and Catskill Formation fields along the Allegheny Front has been unsuccessful to date. Good-quality reservoir rocks equivalent to the Fifth Elk sandstones were encountered southwest of Council Run field in Somerset County, Pennsylvania, and Garret County, Maryland. The sandstones drilled there were similar to those at Council Run in terms of thickness, geometry, interpreted origin, and structural setting (Follador, 1993).

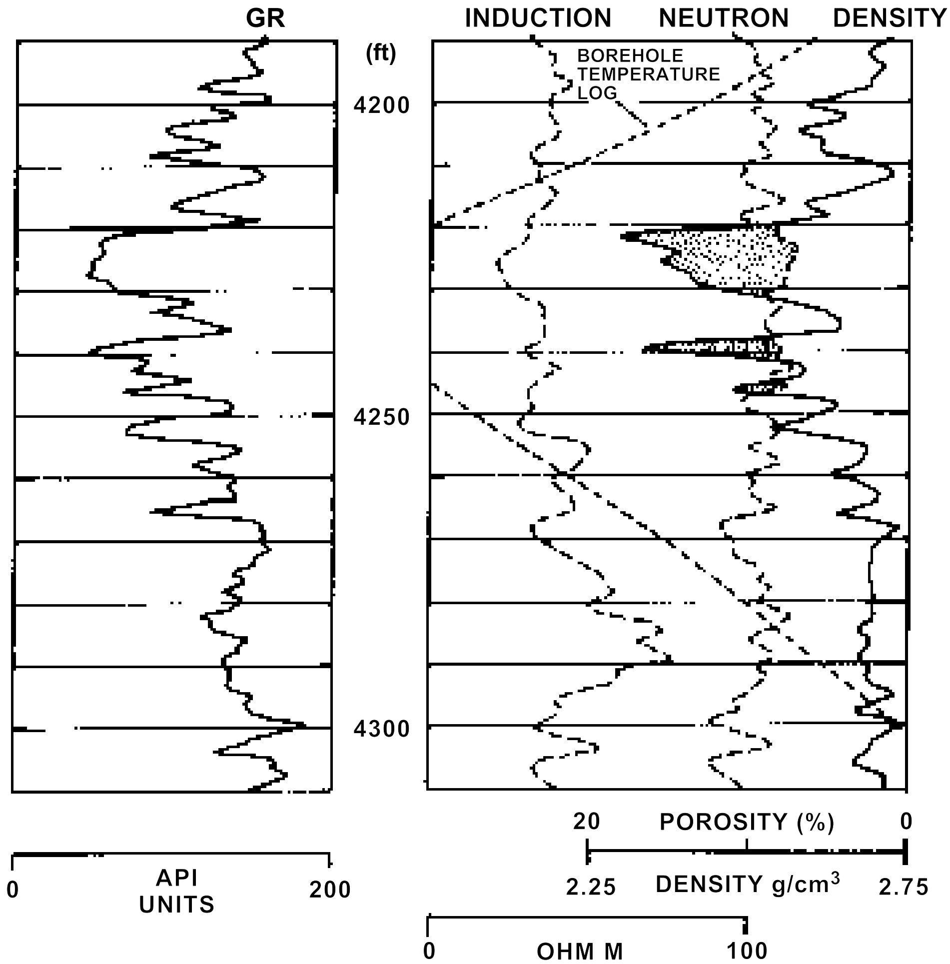



**Figure 16.** Geophysical log of the Beckman 5 well in the recently developed Hepburnia pool, Lumber City field in Clearfield County, Pennsylvania. The pool is 50 km (31.2 mi) west-southwest of the Council Run field and has significant gas production from the Fifth Elk sandstone. Note the similarity of the coarsening-upward parasequences in the Fifth Elk in this well's gamma-ray (GR) log (1286–1300 m [4220–4266 ft]) to those found in the Fifth Elk at Council Run (Figures 9, 10). The left and right borders of track 2 are 60 and 65°F, respectively, for the temperature log scale.

Bruner and Smosna (1994) documented the presence of porosity preserved by dead oil in these sandstones just like that observed at Council Run field. Folladorr (1993) suggested that faulting and fracturing might have allowed previously trapped hydrocarbons to escape, and that source bed intervals in that area are significantly thinner than those present at Council Run. Minor oil production from the Lock Haven Formation occurs at Brace Creek field northeast of Council Run (Figure 1), but no significant petroleum accumulations have been found in that vicinity. Interestingly enough, Lock Haven Formation sandstones southwest and northeast of Council Run field are thicker than those at Council Run and were deposited in open deltaic and ramp environments (Warne and McGhee, 1991; Follador, 1993; Castle, 2000) as opposed to the interpreted incised-valley-fill deposits discussed in this report. Hydrocarbon entrapment in these other regions was not as effective as it was at Council Run field. We attribute this to less structural complexity at Council Run than elsewhere along the Allegheny Front, thicker source rocks and shorter migration routes, relatively lower maturation temperature exposures, and faster uplift rates during the Alleghanian orogeny. We also suspect that the incised valley interpreted at Council Run is a subtle but integral component of the stratigraphic trap there.

We suggest exploration for similar Lock Haven sandstone reservoirs to the west of Council Run field, where additional lowstand deposits might occur, particularly where coarse sediments could have further bypassed the exposed ramp during progressive sea level fall and sandstones might have accumulated in lower shoreface, deltaic, or shelf fan environments (Van Wagoner et al., 1990). Indeed, the relative thinness of the Lock Haven and Catskill strata penetrated at Council Run field and exposed along the nearby Allegheny Front (Warne and McGhee, 1991) may reflect sediment bypass through an efficient incised-valley transport system. Recent discoveries of gas in the Fifth Elk sandstone and associated strata in Clearfield County, Pennsylvania, 50 km (31.2 mi) west-southwest of Council Run field may be in such reservoirs (Figure 16).

We interpret the critical moment at Council Run field, i.e., that point in time when the generation-migration-accumulation of most hydrocarbons in the Marcellus/Burket–Lock Haven/Catskill petroleum system took place, as having occurred between 260 and 240 Ma, when most of the oil in the petroleum system was cracked to gas. Preservation time has been relatively long and was controlled by the rapid rate of uplift and denudation that occurred during Permian time as well as during Mesozoic extension (Slingerland and Furlong, 1989). A petroleum systems approach (Magoon and Dow, 1994) provides the best analytical tools for finding and developing other such accumulations in areas of the central Appalachian basin that are removed from the principal producing fields of the province.

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