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Heavy-Oil and Bitumen Resources of the Western Kentucky Tar Sands

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Abstract

Heavy-oil and bitumen resources in western Kentucky are present in the Upper Mississippian Big Clifty and Hardinsburg Sandstones and Lower Pennsylvanian Kyrock and Bee Spring Sandstone Members of the Caseyville Formation in a belt extending from Logan County on the south to Breckinridge and Hardin Counties on the north.

Net oil-saturated intervals in the tar sands range from 2.5 to 4.7 m thick, largely in downthrown fault blocks in and bounding the Rough Creek Graben. Records from 1,500 wells, analysis of reservoir properties from 3,769 plugs from 135 coreholes, and bulk volume of hydrocarbon calculated in 139 surface samples were evaluated using original quantitative methods, reinterpretation of prior qualitative results, and industry-standard petroleum-engineering principles. Median porosity of the tar-sand reservoirs is 14.8 to 19.8 percent, and median oil saturation is 17.4 to 34 percent. Mobile versus immobile oil in the pore space was calculated for five wells cored in Edmonson County in which permeability and porosity were measured before and after extracting all hydrocarbons in 393 core plugs. Median movable oil saturation in these cores was 40.7 percent of the total oil saturation in the Big Clifty, 26.9 percent in the Hardinsburg, and 61.9 percent in the Caseyville. Unrisked contingent and prospective heavy-oil and bitumen resources in place in the tar sands are estimated to total 3,346 million barrels of oil: 2,247 million barrels in the Big Clifty, 357 million barrels in the Hardinsburg, and 742 million barrels in the Caseyville. There are no demonstrable reserves. Overall, these resources are about 10 percent greater than previous evaluations.

The western Kentucky tar sands developed from microbial degradation of light oil during migration into the reservoir rocks, leaving heavily biodegraded pore-lining bitumen and mobile heavy oil. Pore-lining bitumen causes the reservoirs to be oil-wet, reducing effective permeability and porosity in a reservoir and decreasing oil recovery in enhanced-oil-recovery projects.

Since the collapse of the rock-asphalt industry in 1957, there has been no commercial process developed to date, either for enhanced oil recovery or for bitumen extraction from mined rock asphalt, to produce oil from the western Kentucky tar sands. In 2014, a new project was initiated to recover bitumen from the Big Clifty in northern Logan County; however, results of this project are inconclusive.

Introduction and Previous Work

The western Kentucky heavy-oil– and bitumen-saturated sandstones, historically called tar sands, rock asphalt, and black rock, are found in the southeastern Illinois Basin on the southern and eastern margins of the Western Kentucky Coal Field (Figs. 1–3). They occur in a belt of surface outcrops and subsurface occurrences extending from Logan County on the south to southern Hardin and eastern Breckinridge Counties on the north, an area of about 3,100 km^2 (Eldridge, 1901; Crump, 1913; Jillson, 1924; Russell, 1932, 1933; McGrain, 1976; Williams and others, 1982; Noger, 1984, 1987; Bowersox, 2014a, b). Tar-sand resources are hosted

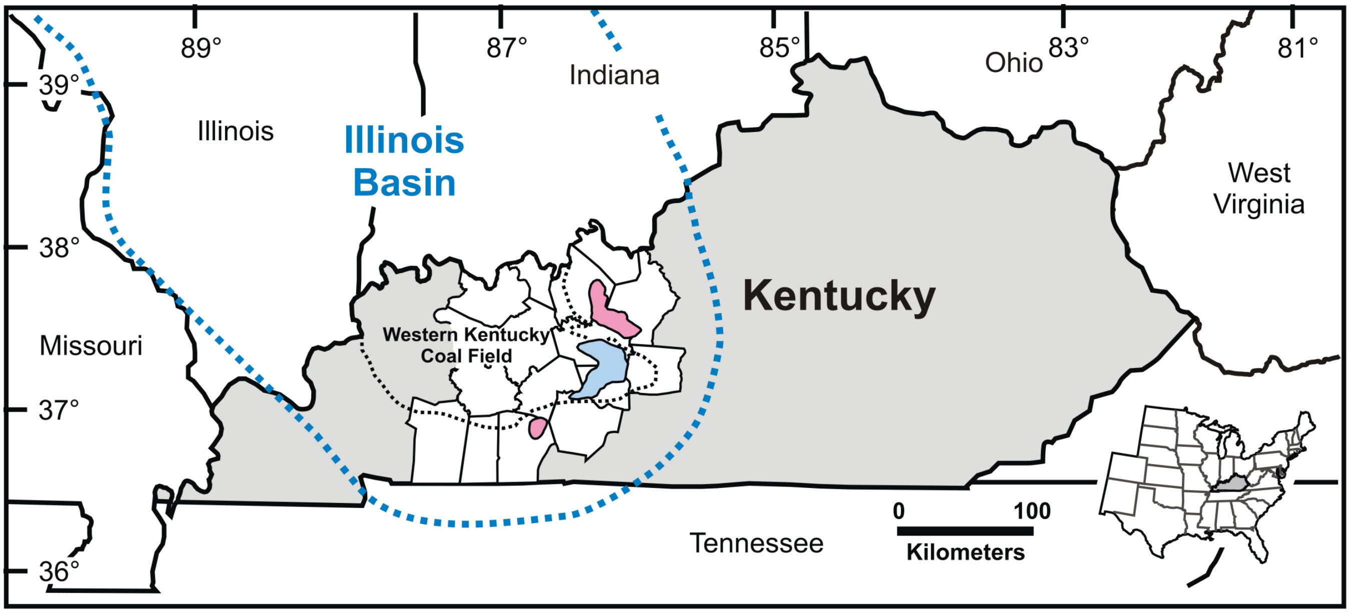

Figure 1. Location of heavy-oil– and bitumen-saturated sandstones in the southeastern Illinois Basin (dashed blue outline), western Kentucky. These resources are exposed in outcrops on the southern and eastern margins of the Western Kentucky Coal Field. Red shading indicates outcrop areas with tar sands hosted in the Upper Mississippian (Chesterian) Big Clifty Sandstone and blue shading indicates deposits hosted in the Lower Pennsylvanian Caseyville Formation and its members.

in Upper Mississippian to Lower Pennsylvanian (Serpukhovian to Bashkirian; Chesterian North American Stage) (Swezey, 2009) Big Clifty and Hardinsburg Sandstones and the Kyrock and Bee Springs Sandstone Members of the Lower Pennsylvanian Caseyville Formation (McGrain, 1976; Williams and others, 1982; Noger, 1984, 1987; Hamilton-Smith, 1994) (Figs. 2–3). Rock asphalt in the Big Clifty is exposed in outcrops on the eastern margin of the Western Kentucky Coal Field (Fig. 1) on the northern and southern flanks of the Rough Creek Graben, whereas Caseyville rock asphalt is exposed at the eastern end of the graben (Fig. 2B). Bituminous sandstone in the Hardinsburg is exposed in a limited area in northern Grayson County (Fig. 2B).

History of Western Kentucky Rock-Asphalt Production

The archeological record of western Kentucky shows use of these bitumen resources by Native Americans predating European colonization (Collins, 1981), and use by American settlers dates to the early 19th century (Owen, 1856). Rock-asphalt–bearing outcrops were described in early geologic reports for the region (Orton, 1891; Eldridge, 1901; Bryant, 1914) and mapped in later studies (Fig. 2B). These surface exposures fostered the development of the rock-asphalt industry in western Kentucky from 1889 to 1957 (McGrain, 1976; Bowersox, 2016b). Commercial value of the Big Clifty rock-asphalt deposits was first recognized in 1881, and its production for road-paving material began in 1889 in Grayson County (Orton, 1891; Parker, 1892; Bowersox, 2014a, 2016b, and sources cited therein). Exploitation of the Caseyville rock-asphalt deposits in Warren County followed in 1900, expanding into Edmonson County by 1904 (Bowersox, 2016b). Estimated volumes of heavy oil and bitumen produced by all methods to date are negligible. The western Kentucky rock-asphalt deposits were mined for use as road surfacing from 1889 to 1957, but after World War II roads thus paved were replaced by modern asphalt roads (Rose, 1992; May, 2013; Bowersox, 2014a, b, 2016b). Total rock-asphalt production is estimated to have been 5.48 million metric tons (tonnes) (Bowersox, 2016b). At an average commercial bitumen content of 7 weight-percent (Weller, 1927), this amounts to 385,560 tonnes of bitumen in the mined rock asphalt. Thus, assuming an average volume of 6.06 barrels of oil per tonne of bitumen (U.S. Energy Information Administration, 2015), an estimated 2.33 million barrels of oil of bitumen was produced with the

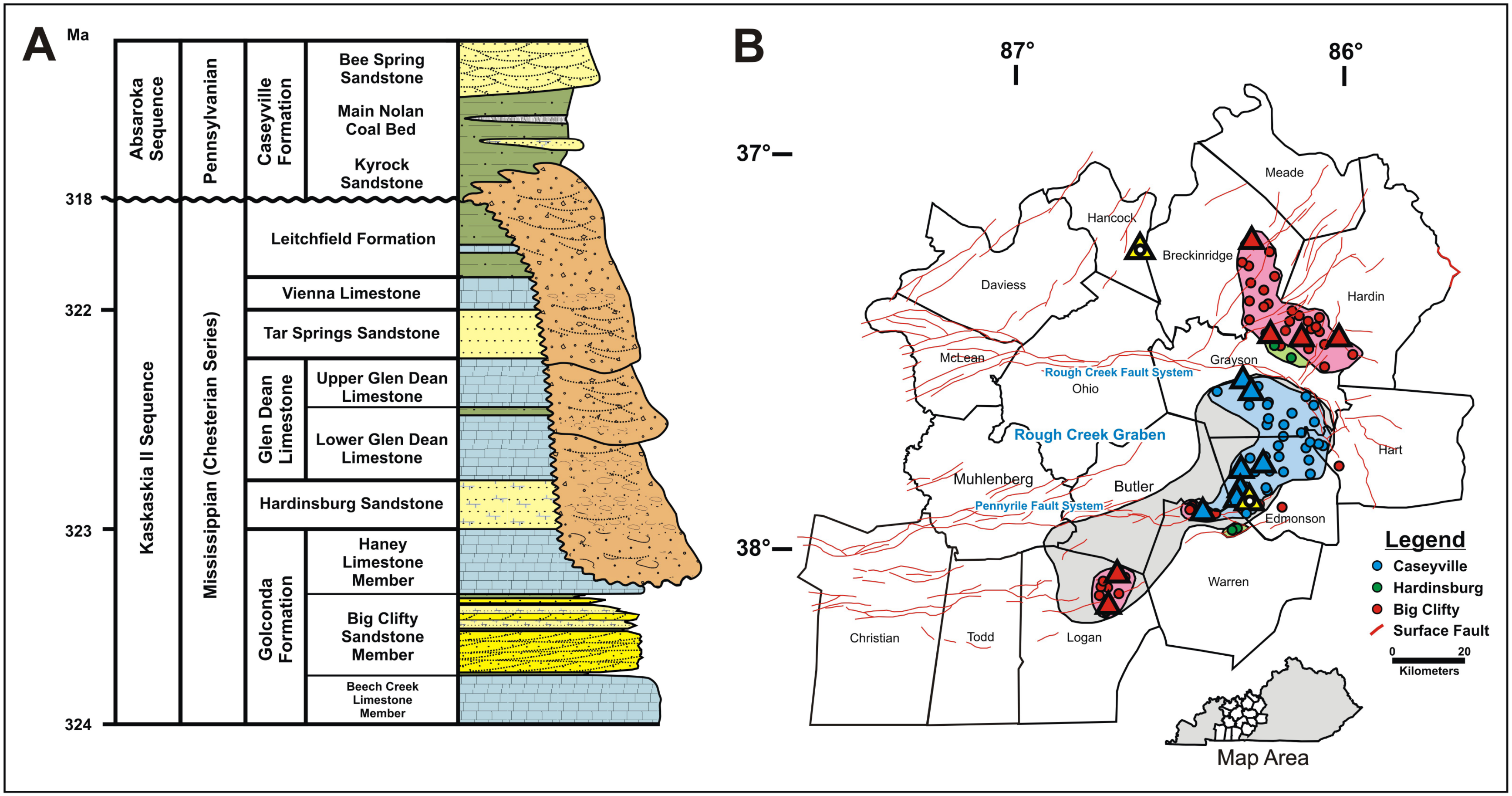

Figure 2. Stratigraphy and distribution of tar-sand resources in western Kentucky. (A) Stratigraphy of the Upper Mississippian–Lower Pennsylvanian section in the study area. Colored circles indicate bitumen-saturated intervals: red, Big Clifty Sandstone; green, Hardinsburg Sandstone; and blue, Caseyville Formation and its members; data from Pryor and Potter (1979). Ages of formation boundaries from Swezey (2009). (B) The tar sands occur in a belt extending from northern Logan County to southern Hardin and eastern Breckinridge Counties; data from Eldridge (1901), Richardson (1924), Clark and Crittenden (1965), Gildersleeve (1966, 1968), and Collins (1981). Red areas are surface tar-sand deposits developed in the Big Clifty, blue area is the surface developed area of the Caseyville, and gray area is the subsurface extent of the combined reservoirs. This color code is also used on remaining figures. The yellow triangle in Edmonson County is the location of the Westken Petroleum well 20 C.L. Vincent well (Fig. 3), and the yellow triangle in Hancock County is the location of the Kentucky Geological Survey 1 Marvin Blan research well.

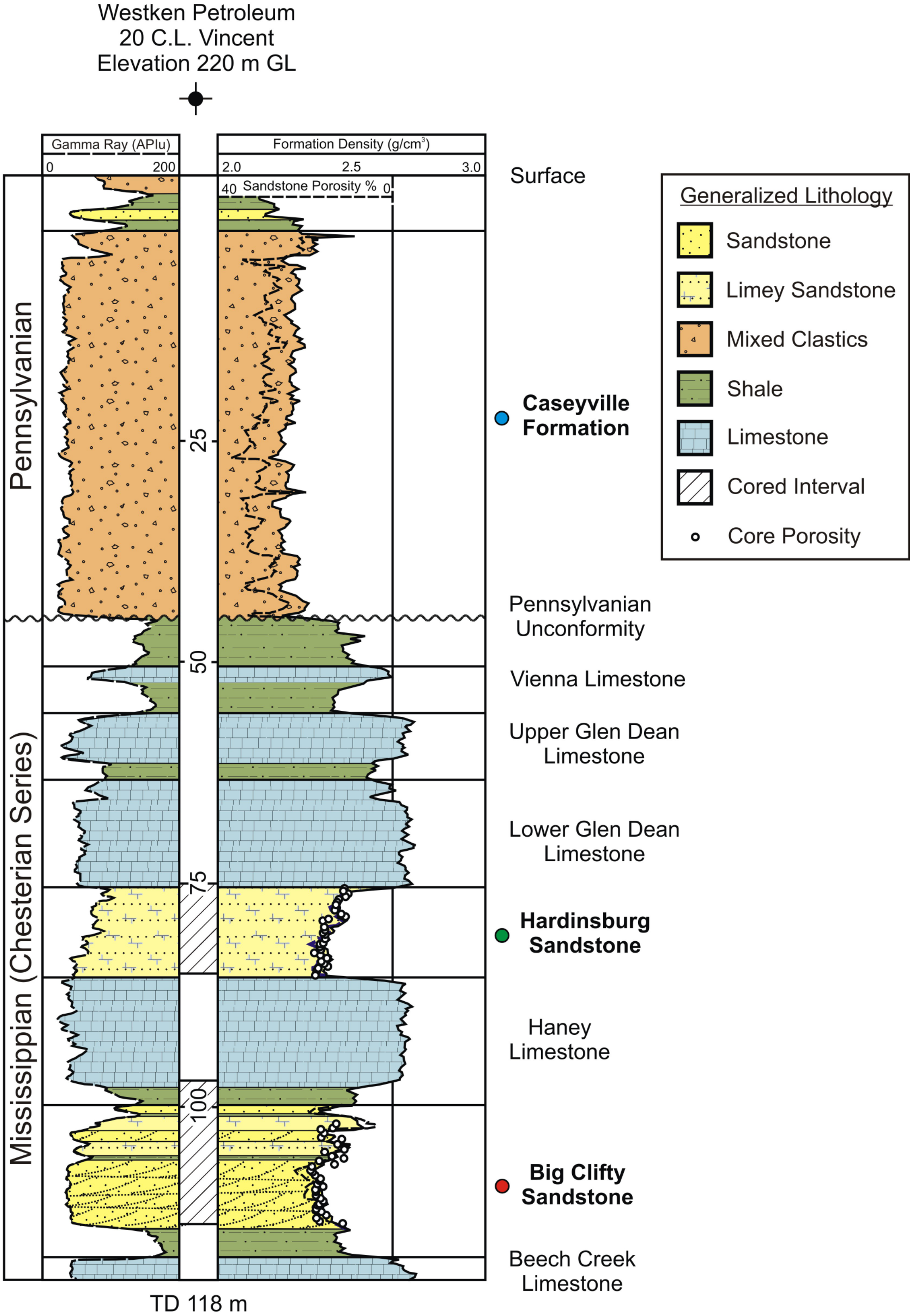

Figure 3. Correlated typical geophysical log suite through the tar-sand section in Westken Petroleum well 20 C.L. Vincent, Edmonson County. The diagonal lines in the depth column are cored intervals. Porosity measured in sample plugs from whole-diameter conventional cores (open circles) are shown for reference. Note the close correspondence of measured porosity with that calculated from the formation-density log (dashed curve).

rock asphalt (Bowersox, 2016b). Minor amounts of petroleum products were refined from the rock asphalt before 1930, but production was insufficient to support commercial development (McCormack, 1925; Weller, 1927; Hagan, 1942).

Previous Resource Evaluations

Resource assessments in the early 20th century were undertaken to determine the value of individual deposits for quarrying rock-asphalt road topping (Bowersox, 2016b, and sources cited therein), but it was Russell (1933) who made the first regional estimate of oil in place in the tar-sand belt of about 1,000 million barrels. Subsequent studies, predicated on surface mining of the resources, did not address subsurface occurrences of heavy oil and bitumen, and instead focused on outcrop areas or in the near surface where overburden was less than 4.5 m thick (Ball, 1951; Ball and Associates Ltd., 1965). McGrain (1976) felt the rock-asphalt resources in the deeper subsurface of western Kentucky, below surface-mining depths, could reasonably be estimated as equal to or greater than the assessments of Ball (1951) and Ball and Associates Ltd. (1965). The Interstate Oil Compact Commission updated and expanded upon earlier evaluations by including subsurface tar-sand resources (Lewin and Associates Inc., 1984a). Their evaluation used the methodology of Lewin and Associates Inc. (1982, 1984b) and distinguished two resource categories: measured (resources identified from well control and core analysis) and speculative (that part of the resource assumed present from bitumen shows reported on drillers' logs and geologic interpretation) (Lewin and Associates Inc., 1984a). Noger (1984, 1987), using a methodology adapted from Lewin and Associates Inc. (1982), revised the IOCC resource estimate. Subsequent reviews of U.S. and world tar-sand resources (Meyer and DeWitt, 1990; Hein, 2006) cited Noger's (1984, 1987) resource estimates for western Kentucky tar sands.

Purpose of This Study

This study refines and updates the work of Noger (1984, 1987); however, resources assigned to the Tar Springs Sandstone were not reassessed in this study because of its extensive conventional oil production from shallow oil fields in the study area and limited outcrop area in Breckinridge County where bitumen-saturated Tar Springs is exposed. The methodology of this study derives, in part, from original quantitative research and reinterpretation of prior qualitative results, but otherwise is based on industry-standard petroleum-engineering principles. With the completion of this evaluation, surface exposures remain on the margins of the defined resource areas (see Bowersox, 2016a); detailed mapping and sampling will be required to fully assess the tar-sand resources in those areas. Resource categories used in this study follow those of the Society of Petroleum Engineers (2001).

Geology

Heavy-oil and bitumen reservoirs are developed in the Big Clifty Sandstone, Hardinsburg Sandstone, and Caseyville Formation. The Lower to Middle Mississippian section in the tar-sand belt consists of about 350 m of limestone and dolomite with interbedded shales and sparse sandstones. The Chesterian strata are part of a 110-m-thick transgressive-regressive sequence from the Beech Creek Limestone at the base through the Leitchfield Formation at the top (Fig. 2A). Chesterian tar sands are unconformably overlain by the Lower Pennsylvanian Caseyville Formation (Bashkirian) (Swezey, 2009). The Caseyville was deposited on the Kaskaskia II–Absaroka cratonic sequence boundary (Sloss, 1963, 1988; Swezey, 2009) in two episodes of coarse to conglomeratic clastic sediments; the lower of these is the Kyrock Sandstone and the upper is the Bee Spring Sandstone (Pryor and Potter, 1979) (Fig. 2A). The post-Caseyville section is described in Greb and others (1992).

Chesterian Section

Transgressive, shallow-water marine Beech Creek and Haney limestones are overlain by regressive, near-shore, fine- to medium-grained tidal-shelf to intertidal-bar quartz sandstones and clay-rich shales of the Big Clifty and Hardinsburg Sandstones (McGrain, 1976; Pryor and others, 1990; Nelson and Treworgy, 1994) (Fig. 3). Tidal channels filled with bioclastic carbonates are present in the upper Big Clifty (Bowersox, 2016a). Correspondence of depositional trends in the Big Clifty and Hardinsburg with the regional fault pattern (Fig. 4) suggests syndepositional influence of fault movement on deposition. Siliciclastic sediments were transported to the Illinois Basin by the

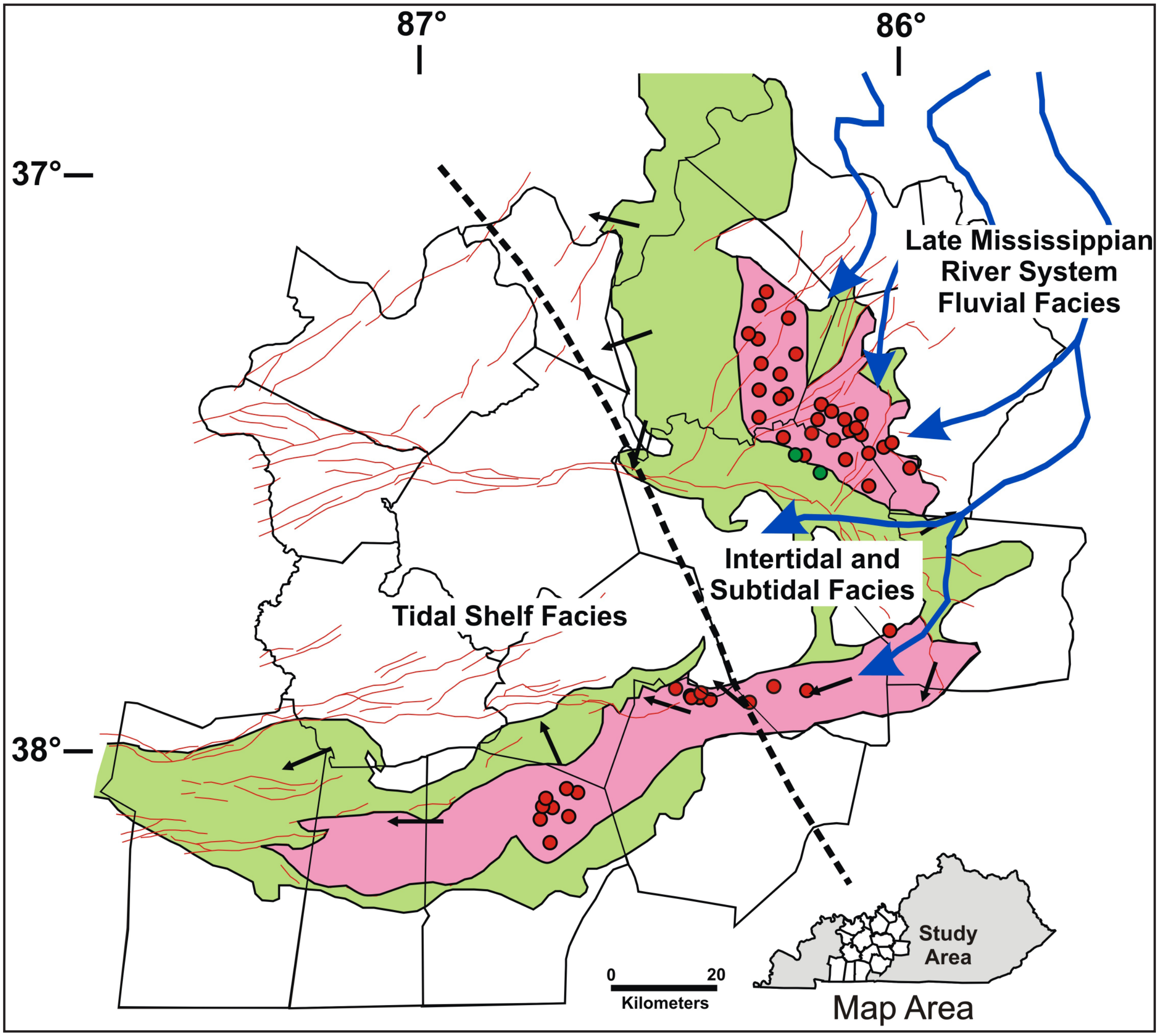

Figure 4. Outcrops and seeps of the Big Clifty (red area and circles) and Hardinsburg (green area and circles) Sandstones in western Kentucky. Data for the generalized distribution and outcrop areas of the Chesterian Series sands and depositional system are from Potter and others (1958), Williams and others (1982), and Noger (1984). Locations of outcrops and seeps are from Figure 2B. Facies of the Late Mississippian river system and direction of sediment transport inferred from crossbeds shown by black arrows (data from Potter and others, 1958; Potter, 1962; and May, 2013).

southwest-flowing Late Mississippian river system (Potter and others, 1958; Potter, 1962; Swann, 1963) (Fig. 4). Crossbeds in the Big Clifty and Hardinsburg Sandstones show that the depositional trend of the sandstones was generally S55°W (Potter and others, 1958) (Fig. 4), a factor that, in part, accounts for the distribution of the oil reservoirs. Net sandstone thicknesses mapped in the Big Clifty between the top of the Beech Creek and base of the Haney Limestone (Figs. 2A, 3, 5) are indicative of deposition in a tide-dominated delta system (e.g., see Dalrymple and others, 2012). Following the model of Dalrymple and others (2012), sandstones in central Edmonson County to central Grayson County are interpreted to have been deposited in river-mouth intertidal bars; there is a broad region of subtidal bars from western Edmonson County to southwestern Grayson County, and tidal-shelf ridges

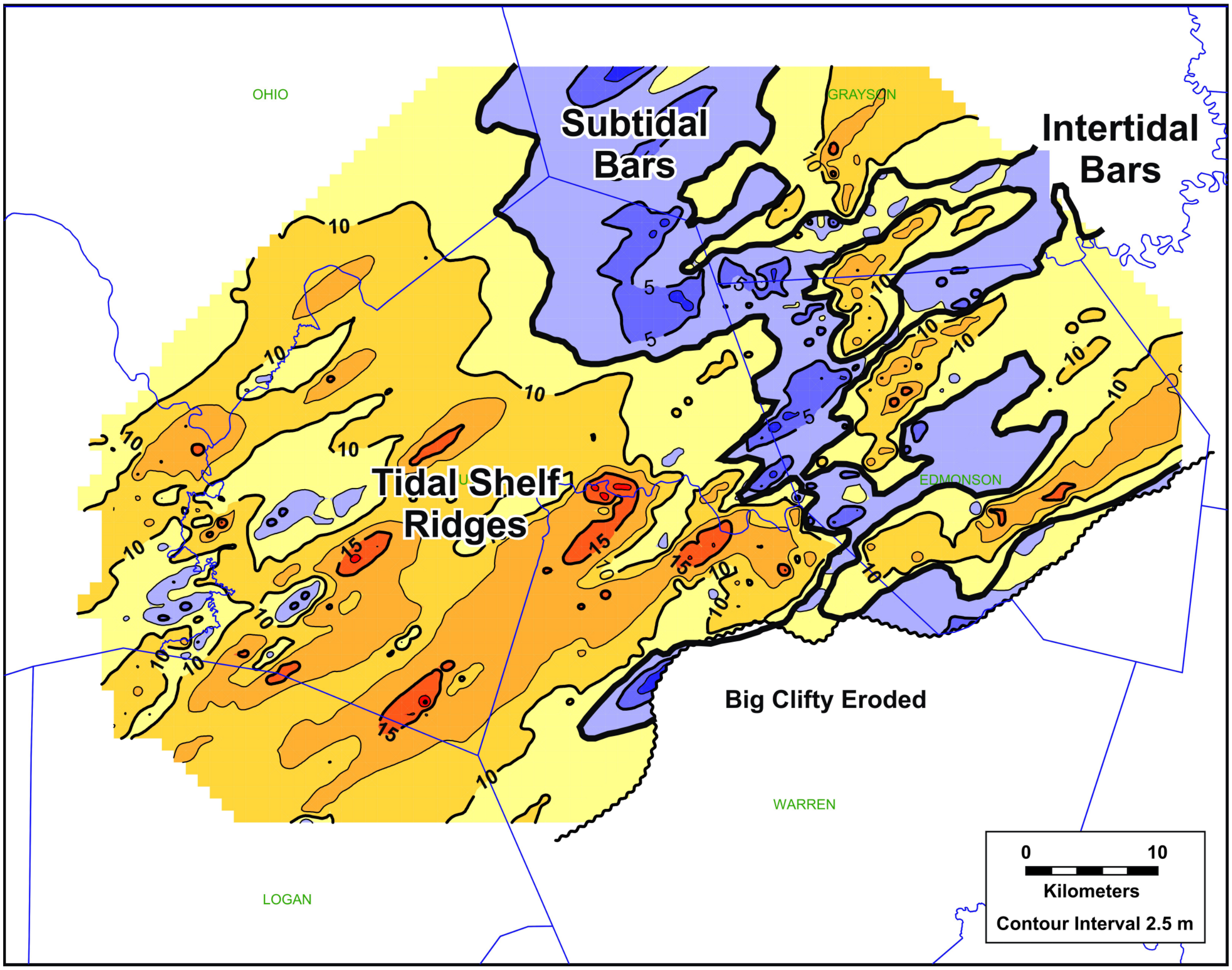

Figure 5. Net sandstone thickness in the Big Clifty interval between the top of the Beech Creek and base of the Haney Limestone. Crossbeds in the Big Clifty and Hardinsburg show a S35°W depositional trend (Fig. 4), a factor that partially accounts for the distribution of the oil reservoirs. Depositional facies are outlined by the heavy black line. This pattern of river-mouth intertidal bars, subtidal bars, and tidal-shelf ridges is indicative of deposition in a tide-dominated delta system (compare with Dalrymple and others, 2012).

were deposited in the region from northwestern Warren County to southeastern Ohio County (Fig. 5). The Big Clifty is capped by the transgressive Haney Limestone, which is overlain by regressive, shallow-water marine, subtidal to tidal-shelf, fine-grained quartz sandstone of the Hardinsburg (Figs. 2A, 3). The upper half of the section includes a more shoreline-distal series of interbedded limestones and shales of the Glen Dean Limestone, overlain by the thin sands of the Tar Springs and the thin Vienna Limestone, capped by the Leitchfield Formation (Fig. 2A).

Caseyville Formation

McFarlan (1943) noted the presence of tar sands in both Kyrock and Bee Spring paleovalley fills, recognizing that the largest resources were in the Kyrock of Edmonson County. This fluvial system of deep paleovalleys eroded as much as 66 m into underlying Chesterian sediments in Edmonson County (Pryor and Potter, 1979; Greb, 1989) (Figs. 2A, 3, 6). Greb (1989) observed that the coincidence of paleodrainage systems with the regional fault systems suggests structural control of the paleovalleys' development and thus a general southwestern depositional trend of the Caseyville.

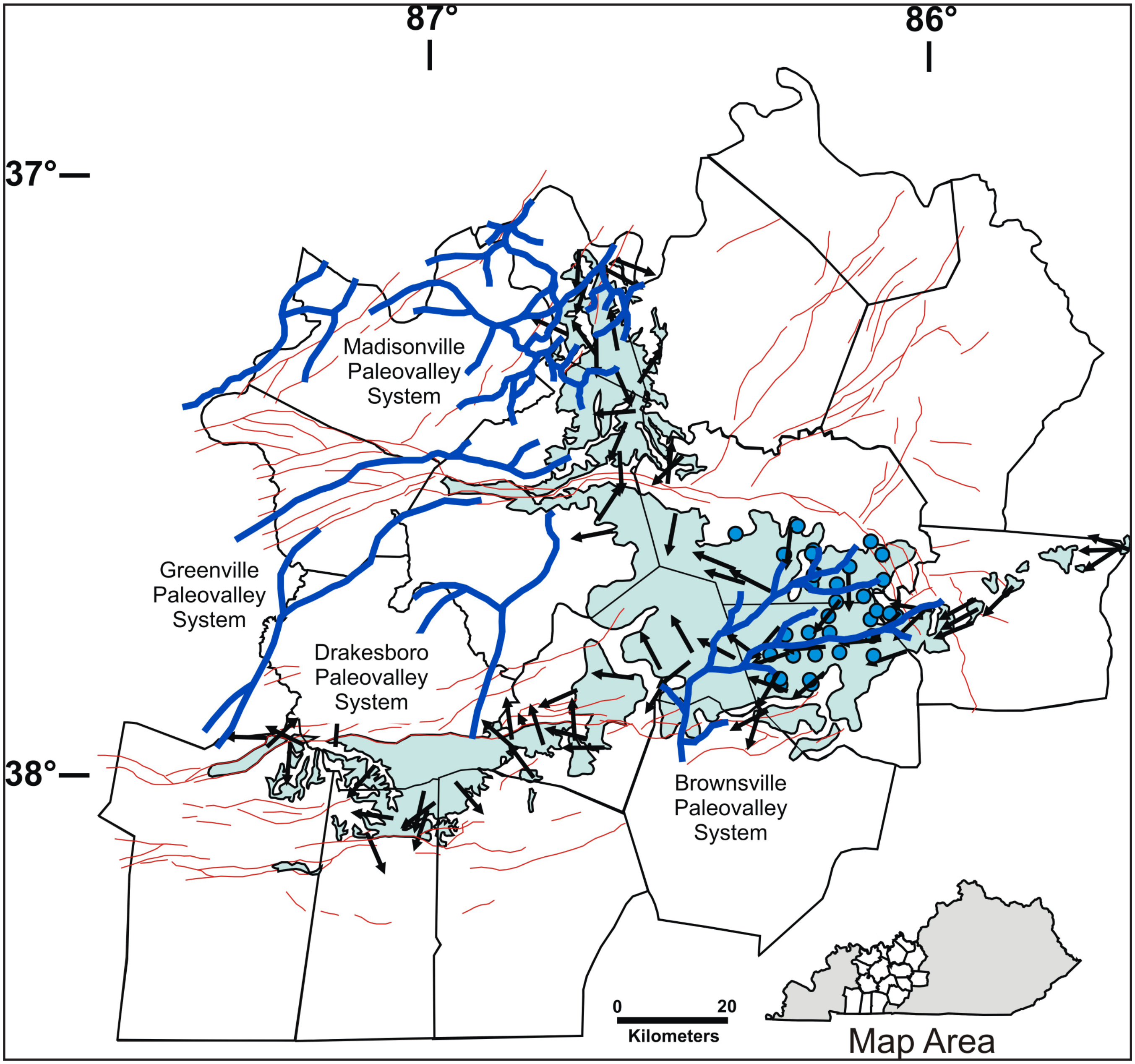

Figure 6. Generalized distribution and outcrop areas of the Caseyville, sediment transport directions (black arrows), and paleovalley systems (blue lines). Data from Potter and Sevier (1956), Bristol and Howard (1971), Pryor and Potter (1979), Noger (1984), Greb (1989), and Greb and others (1992). Deposition of the Caseyville was to the southwest, controlled by the paleovalley system. At its deepest point in central Edmonson County, the Caseyville eroded the Chesterian section to the top of the Big Clifty.

Where the conglomeratic member, the Kyrock Sandstone, is thickest in northeastern Edmonson County (Pryor and Potter, 1979), erosion has reached as deep as the underlying Haney Limestone (Figs. 2A, 7). Indeed, the Caseyville Formation in central Edmonson County has been mapped lying on the Hardinsburg Sandstone and, in very limited exposures, on the uppermost Big Clifty Sandstone (Klemic, 1963; Gildersleeve, 1971).

Post-Caseyville History

Mesozoic uplift of western Kentucky, and subsequent erosion to the present time, removed the Upper Mississippian and younger strata in southern Kentucky and exposed the tar-sand reser-

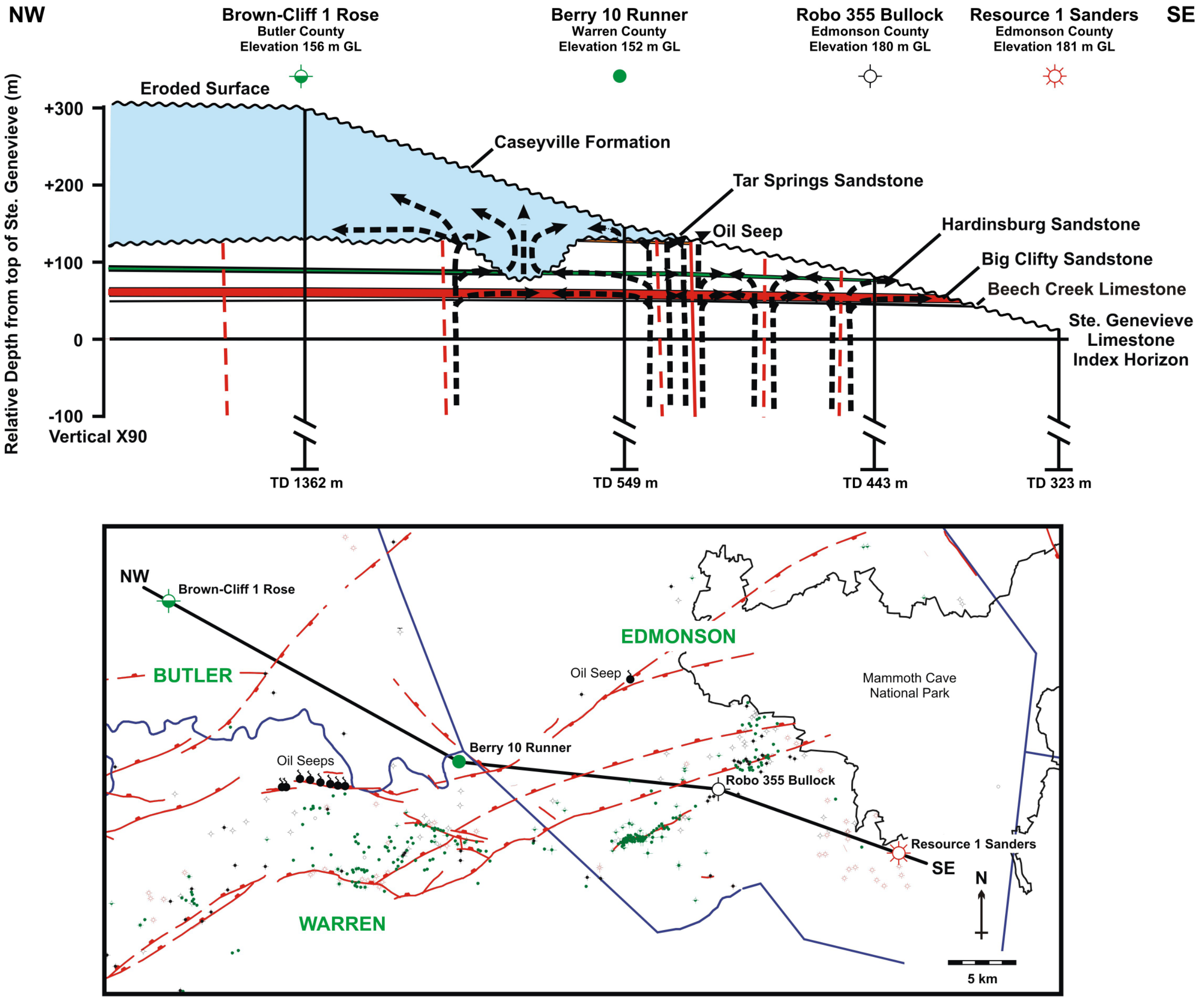

Figure 7. Stratigraphic cross section from central Butler County to central Edmonson County. Oil migrated vertically along fault planes (dashed red lines) from the New Albany Shale to shallower reservoirs, with accumulations developed in the Chesterian sands in downthrown fault blocks (dashed heavy black lines). Secondary migration from the Hardinsburg and Tar Springs Sandstones into the Caseyville occurred in the deepest paleovalleys in central Edmonson County.

voirs at the surface on the margins of the Western Kentucky Coal Field. Thicknesses of post-Mississippian rocks in the Western Kentucky Coal Field (Greb and others, 1992) suggest that more than 1,400 m of strata have been eroded in the tar-sand belt and south-central Kentucky. Timing of exposure is evidenced by the earliest occurrence of locally derived, well-rounded Devonian and Mississippian chert pebble clasts in the Upper Cretaceous (Cenomanian) Tuscaloosa Formation in the Mississippi Embayment fill of western Tennessee and the Jackson Purchase Region of western Kentucky (Marcher and Stearns, 1962; Cushing and others, 1964; Davis and others, 1973; Smath and Chesnut, 2000).

Structure

The structure of western Kentucky is dominated by the Illinois Basin and fault systems bounding the Rough Creek Graben, an east-trending extension of the Mississippi Valley Graben and a major structural feature dominating the geology of western Kentucky west of the Cincinnati Arch (Hickman, 2013) (Figs. 2B, 8A). Near-vertical normal faults bounding the Rough Creek in the

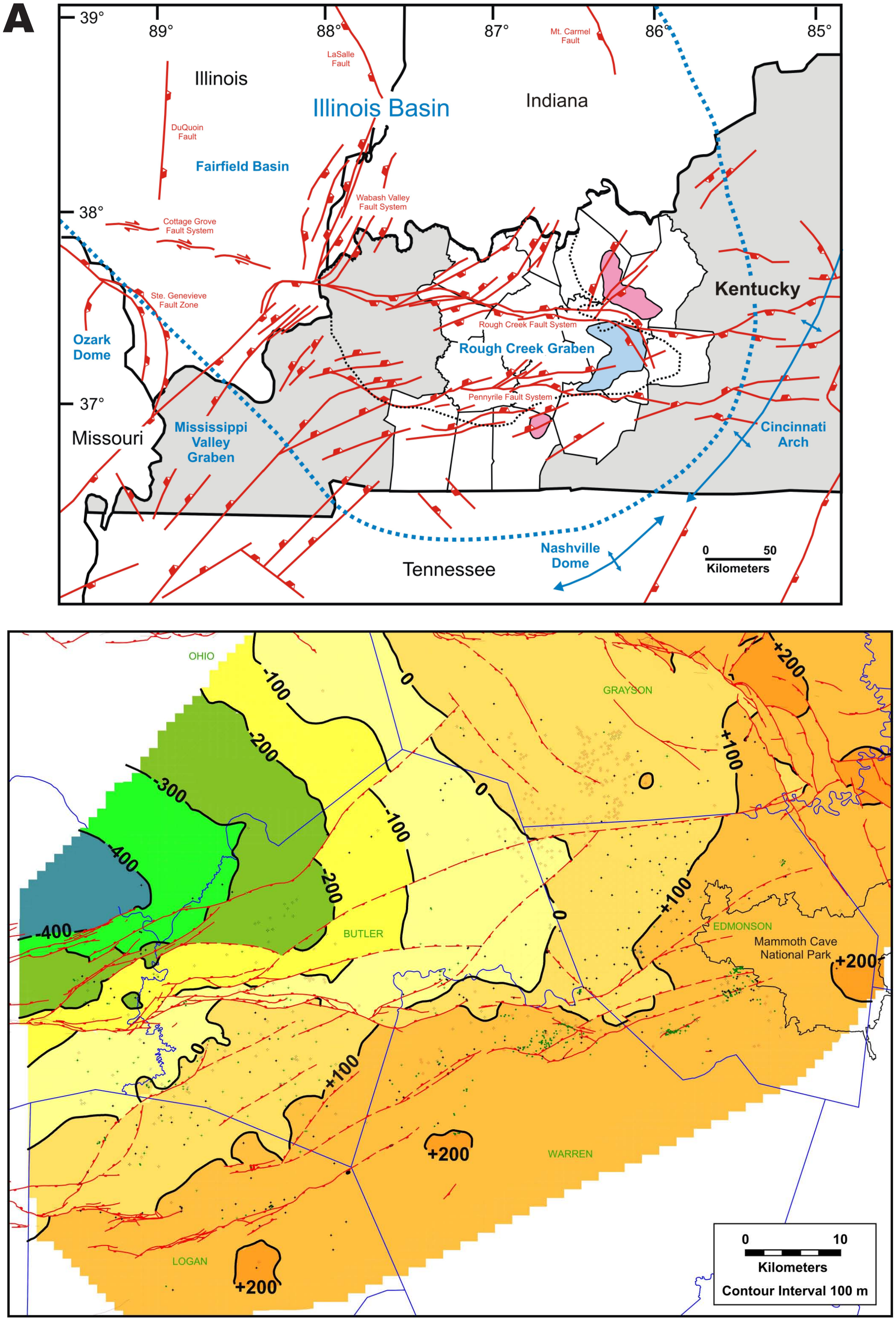

Figure 8. Geologic structure of western Kentucky and southern Illinois Basin is dominated by the Rough Creek Graben and the flanking Rough Creek and Pennyrile Fault Systems (data from Hickman, 2013). (A) The tar-sand belt lies in the eastern Rough Creek Graben and on adjacent shelves. Outcrop areas of Big Clifty tar sands are colored red and the outcrop area of Caseyville tar sands is colored blue. (B) Subsurface contours on top of the Beech Creek show fault offsets ranging from about 5 to 30 m. Inferred subsurface faults (red dashed lines) are from data in Noger (1984).

Pennyrile and Rough Creek Fault Systems dip into the graben. Steeply dipping normal faults inside and flanking the Rough Creek Graben generally trend northeast in a system of horsts, half-grabens, and grabens (Fig. 8A). Structure of the tar-sand belt, contoured on top of the Beech Creek Limestone, is shown in Figure 8B. Fault offsets in the region range from less than 5 m to about 30 m (Figs. 7, 8B). Folds associated with the fault systems are present near the Rough Creek and Pennyrile Fault Systems in Grayson and Warren Counties (Shawe, 1966; Gildersleeve, 1978). The Big Clifty and Hardinsburg Sandstones are exposed in outcrops on the eastern margin of the Western Kentucky Coal Field (Figs. 1, 4, 7) on the northern flank of the Rough Creek Graben in Breckinridge, Grayson, and Hardin Counties and on the southern flank of the graben in Edmonson, Warren, and Logan Counties (Sparks, 2009) (Figs. 2B, 4, 7).

Evaluation Methodology

This study incorporates data from wells available from the Kentucky Geological Survey's Oil and Gas Records Database (kgs.uky.edu/kgsweb/DataSearching/OilGas/OGSearch.asp), the Kentucky Geologic Map Information Service (kgs.uky.edu/kgsmap/kgsgeoserver/viewer.asp), and previously unavailable historical data from W.R. Jillson available from the KGS publications catalog (kgs.uky.edu/kgsweb/pubs/pubsearch.asp). Petra version 3.8.3 software was used for well-data compilation and database management, constructing subsurface correlation cross sections, subsurface geologic mapping, and reservoir volumetric calculations. A data set of 1,500 well records that includes reservoir properties measured in whole cores from 135 coreholes drilled between 1950 and 2007 was reviewed in detail (Table 1). In addition to these data, analyses from 139 surface and quarry rock-asphalt samples from the literature were used, most of which were from the period of rock-asphalt mining between 1910 and 1930, and unpublished data held by KGS (Table 1). Subsurface cross sections, both structural and stratigraphic, were constructed, and formation boundaries were correlated using electric logs, lithologic descriptions, and formation boundary depths from drillers' logs. Net oil-saturated intervals in the reservoir sands from core descriptions and analyses, drillers' logs, and by correlation were compiled by well into the Petra database. Because of the limitations of the hydrocarbon shows in core and drillers'-log descriptions, and because samples were analyzed only for their total bitumen and oil content, this study could not differentiate the presence of oil- versus bitumen-bearing sands in each formation, and only total oil in place was calculated.

Reservoir Properties

Rock and reservoir properties of the western Kentucky tar sands were determined from analysis of plugs from whole-diameter cores from the subsurface, surface samples of bituminous

Table 1. Summary of data sources used in this study.

Reservoir	*Number of Wells*[1]	*Electric Logs*	*Drillers' Logs*	*Reservoir Net Pay*	*Reservoir Data*[2]	*Whole Cores*[3]	*Cores Analyzed*	*Core Samples*[4]	*Surface Samples*[5]	*Quarry Samples*[6]
Study area	1,500	977	523	687	200	146	138	4,053	125	14
Big Clifty	1,072	753	319	423	129	134	99	2,304	50	8
Hardinsburg	682	541	141	133	29	103	35	520	0	0
Caseyville	452	408	44	131	104	115	40	1,229	75	6

[1] Approximately 18,000 wells have been drilled to all depths in the study area.
[2] Number of coreholes plus surface and quarry samples with calculated $S_o\phi$.
[3] Any whole core, including eight cores with descriptions only.
[4] Number of individual core plugs analyzed.
[5] Samples with analyses of weight-percent bitumen content from the literature.
[6] Sample with analyses of weight-percent bitumen content from the literature.

sandstones, and porosity calculated from logs for which bulk-density nuclear survey data were available. Properties of the three tar-sand reservoirs measured in core plugs are summarized in Table 2. These sample analyses measured permeability (k, in milliDarcys), porosity (φ, in percent), and oil saturation (So, as percentage of the pore space) and water saturation (Sw, as percentage of the pore space) in horizontal core plugs, although not all properties were measured in all plugs (Table 2). Bulk volume of hydrocarbons in a reservoir is calculated from fractional values of So and φ, So × φ, and thus Soφ. A small number of core plugs also had vertical permeability measured. Surface sample analyses held by KGS and not available publicly, and analyses of the weight-percent bitumen content of surface samples from reports in the literature (Jillson, 1922a, b, 1923a–c, 1925a–c, 1926a, b, 1927a–c, 1928a, b, 1929), were also used to evaluate reservoir properties (Table 1). Porosity data used in this study are either total porosity measured in core plugs or were calculated from formation-density geophysical logs from 66 wells. Porosity calculated from density logs was generally in good agreement with that measured in cores from the same intervals (Fig. 3).

Core Analysis of Western Kentucky Tar Sands and Undersaturated Petroleum Reservoirs

One aspect of the reservoir properties of the western Kentucky tar sands that is problematic is that total fluid saturations, So + Sw, do not sum to 1 (Table 2). May (2013) attributed this to the loss of lighter-end hydrocarbons from unpreserved cores in storage. Mobile oil produced from the Big Clifty, however, is 10° API gravity (Ward and Ward, 1984) and thus not subject to substantial evaporative loss of hydrocarbons after recovery of cores from the subsurface (see Noble and others, 1997). The apparent problem, when fluid saturations measured in cores from the tar sands do not sum to 1, stems from the tar-sand reservoirs' history of uplift and erosion. Uplift and erosion cause water volume to shrink in the pore space as reservoir temperature is reduced (Barker, 1972), while rock density decreases as pressure reduction expands reservoir pore space and decreases water saturation (Hoffman, 2008, 2013). That is, the absolute volume of water in the reservoir pore space is unchanged, but the pore space becomes greater. The pore volume that was previously occupied by water fills with low-pressure gas that evolved from the pore water and expands to fill the greater pore space (Hoffman, 2008, 2013). Median gas saturation in cores from the tar sands is 35.1 percent in the Big Clifty, 28.2 percent in the Hardinsburg, and 43.6 percent in the Caseyville (Table 2). By comparison, Terwilliger (1976) found 24 percent gas saturation in the Caseyville from the shallow subsurface in northern Edmonson County. Because the relative permeability to gas in the tar-sand reservoirs is far greater than relative permeability to high-viscosity heavy oil and bitumen, pressure release during recovery of a

Table 2. Summary of reservoir properties from 138 coreholes in the study area (Table 1). Bitumen saturation (So_B) and movable oil saturation (So_M) is from a subset of six coreholes by Westken Petroleum and KSA Resources (Table 3).

Reservoir	*Big Clifty*				*Hardinsburg*				*Caseyville*				*All Zones*	
Property	*n*	*Range*	*Average*	*Median*	*n*	*Range*	*Average*	*Median*	*n*	*Range*	*Average*	*Median*	*n*	*Median*
k (mD)	1,904	0.01–2,193	191	97.2	349	0.1–784.0	42	24.2	893	0.10–8,340	648	361	3,146	164
φ (%)	2,100	0.13–29.0	15.4	15.8	493	3.3–25.8	14.4	14.8	1,176	4.00–31.6	19.3	19.8	3,769	16.9
So (%)	1,969	0.40–76.2	33.8	34.0	493	0.3–82.7	28.4	26.6	1,026	0.10–89.8	22.8	17.4	3,488	28.1
Sg (%)	1,961	0.10–93.9	35.2	35.1	451	0.2–85.7	29.9	28.2	1,155	1.50–94.0	44.3	43.6	3,567	39.7
Sw (%)	2,045	1.40–95.5	32.7	28.6	493	10.2–94.9	46.9	46.2	1,152	1.40–97.5	35.7	32.6	3,690	32.2
So_B (%)	204	0.50–56.3	22.1	23.0	68	4.4–41.9	17.7	20.5	121	0.00–24.5	6.6	5.1	393	17.1
So_M (%)	204	4.00–75.7	16.3	15.8	68	1.6–31.3	11.5	7.4	121	0.90–63.6	9.5	8.3	393	15.1

core from the subsurface will release the gas (lost gas) and cause oil to bleed from the core (Ahmed and McKinney, 2011). Indeed, Ward and Ward (1984) observed lost methane gas slowly bubbling through high-viscosity oil on the surface of cores of the Big Clifty from southwestern Edmonson County, causing very slight loss of oil. Thus, for the purposes of this study, fluid saturations measured in cores from the western Kentucky tar sands are accurate.

Data from Coreholes Drilled by MegaWest Energy Corp. Compared to Earlier Core Data

Although the tar-sand reservoirs have free gas in the pore space, core analysts studying the nine MegaWest Energy Corp. coreholes in Butler and Warren Counties drilled in 2007, the most recent core-analysis data, appear to have assumed that total fluids should total 1 and accordingly calculated lower porosities and higher oil saturations in cored intervals. Thus, the MegaWest core analysts, as part of their analytical procedure, in essence applied the technique of Elkins (1972) for normalizing total fluid saturations measured in cores to 1, where So and Sw are proportionally increased and φ is proportionally decreased. Despite this analytical difference, Soφ calculated from MegaWest core-analysis data is comparable to that calculated from core analysis in which φ and So were measured individually. For example, in Butler County, MegaWest corehole 107 was drilled 6 m east of Shell corehole 47. Both wells were cored through the Big Clifty in the interval from 55.2–64.7 m. Soφ calculated for this interval in the two coreholes is virtually identical: 0.046 in MegaWest 107 versus 0.047 in Shell 47. Median oil saturation measured in 21 core plugs from MegaWest 107 is 39.2 percent, however, and median porosity is 11.5 percent, whereas median oil saturation measured from 30 core plugs in Shell 47 is 25.6 percent and median porosity is 18.2 percent. Although the MegaWest porosity and fluid saturations cannot be directly compared to conventional routine core analysis, the data do provide accurate Soφ to be calculated.

Calculation of Bulk Volume of Hydrocarbons from Rock-Asphalt Analysis

The weight-percent bitumen in a rock-asphalt sample was historically measured in laboratories by either or both of two methods: the change in sample weight after removing the bitumen by ignition as described in Crump (1913), or the change in sample weight after extraction of the bitumen by carbon disulfide solvent (e.g., see Jillson, 1925c). Soφ of rock-asphalt samples was calculated from weight-percent bitumen content (B_w) and the density of the bitumen (ρ_B) was calculated from its API gravity. The weight-percent of bitumen in a rock-asphalt sample was derived as the bulk volume of bitumen in the pore space (Soφ) multiplied by its density (ρ_B), then by 100 to determine percentage:

$$B_w = So\varphi \times \rho_B \times 100. \qquad (1)$$

The density of bitumen in Kentucky rock asphalt can be calculated from its API gravity. API gravity is calculated from the specific gravity of oil at 15.5°C (Selley, 1998) by:

$$^\circ\ \text{API gravity} = (141.5/(\text{specific gravity}) - 131.5 \qquad (2)$$

and the specific gravity of the oil of a given API gravity is

$$\text{specific gravity} = 141.5/(\text{API gravity} + 131.5). \qquad (3)$$

Therefore, specific gravity of bitumen is 1.06 to 1.0 g/cm^3 for the range of 2° to 10° API gravity. Because specific gravity is the density of the bitumen measured relative to the density of fresh water, which has a density of 1.0 g/cm^3 at 15.5°C, bitumen specific gravity equals ρ_B. In this study, API gravity of bitumen is assumed to be 6° (Groves and Hastings, 1983), whose calculated density is 1.03 g/cm^3. Calculation of Soφ from the weight-percent bitumen, derived in this study, is

$$So\varphi = (B_w/100)/\rho_B. \qquad (4)$$

Individual values of both porosity and oil saturation are unknown from analysis of rock-asphalt bitumen; however, their calculated product is the value being sought for calculating oil in place.

Estimating Oil Versus Bitumen Content from Tar-Sand Core Analysis

The western Kentucky tar-sand reservoirs are oil-wet (Bowersox, 2014b) (Figs. 9A–C); thus, total oil saturation measured by retort and Dean-Stark analysis cannot distinguish mobile heavy oil in the pore space from immobile pore-lining bitumen. It is possible, however, to estimate the mobile versus immobile oil in the pore space. Westken Petroleum Corp. cored five wells in an enhanced-oil-recov-

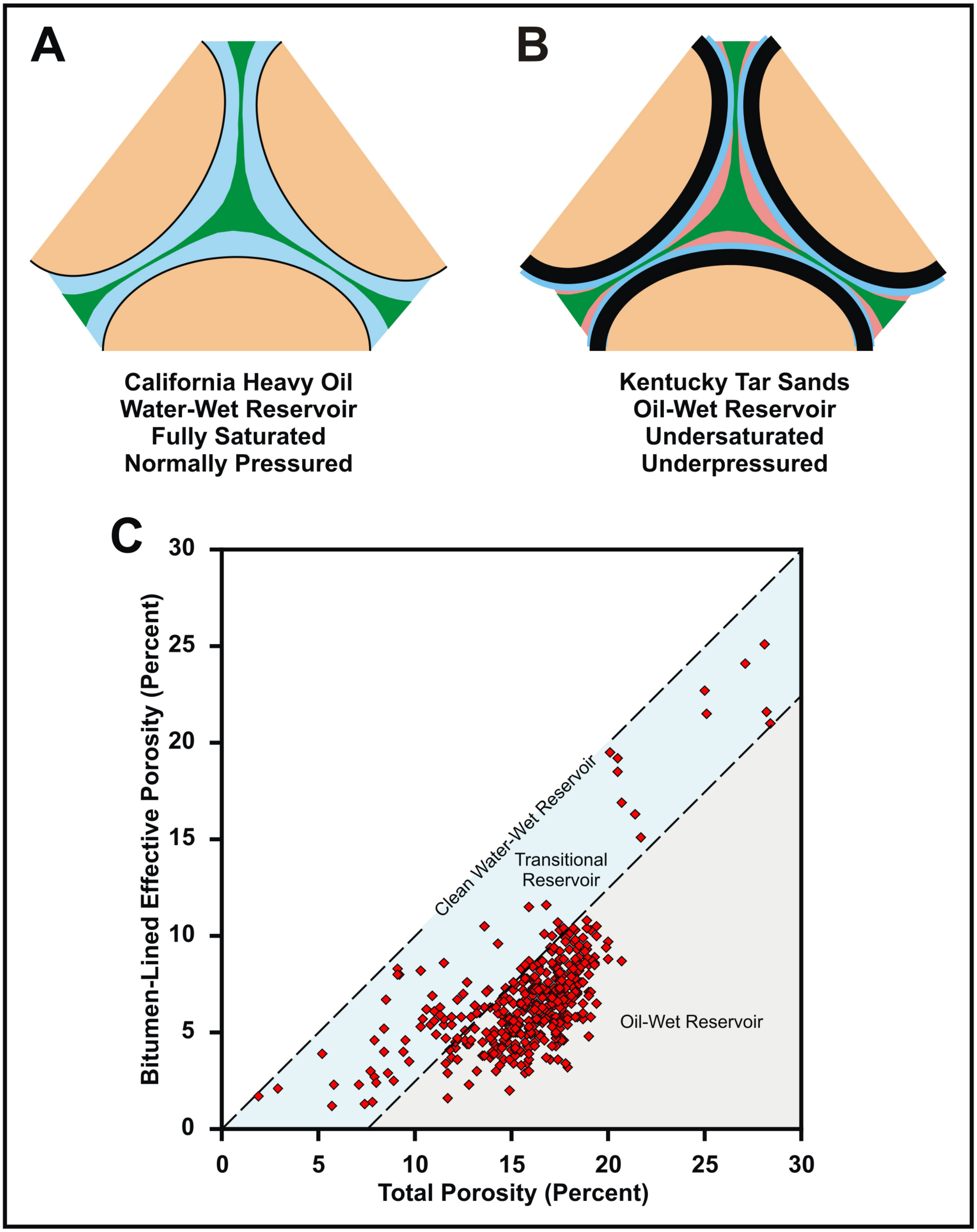

Figure 9. Oil-wet porosity in the western Kentucky tar sands. (A) Porosity system in a typical California heavy-oil reservoir is water-wet, where water (blue) coats sand grains in the reservoir and mobile heavy oil is free in the pore space. (B) Western Kentucky tar sands are both oil-wet and undersaturated in water. Immobile bitumen (black) coats the sand grains, and water, methane (red), and mobile heavy oil fill the pore space. (C) Total porosity and bitumen-lined effective porosity measured in cores from Westken Petroleum wells in Edmonson County. Bitumen in the pore space effectively halves porosity compared to the total porosity. Figure continued on next page.

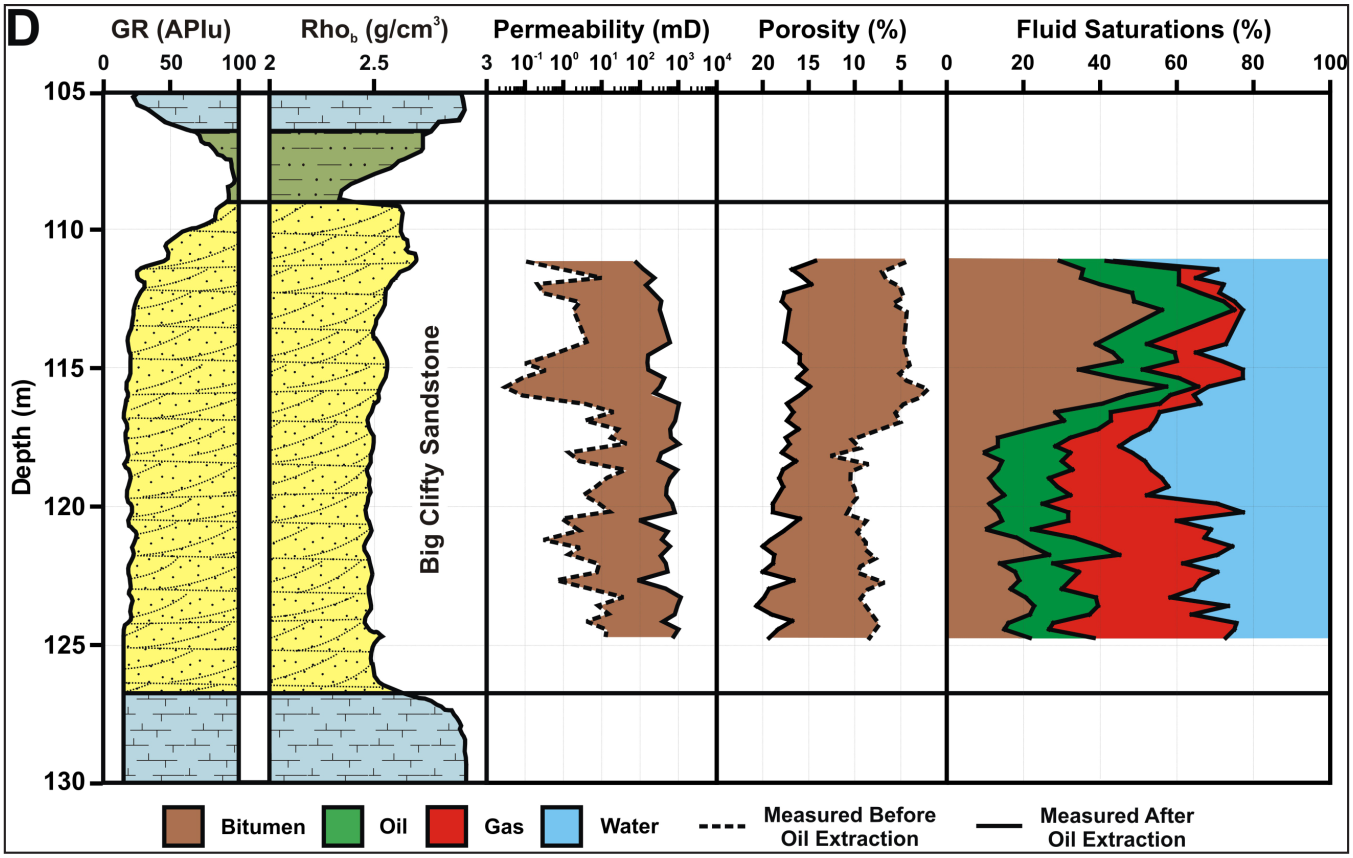

Figure 9. Continued. (D) Electric-log and core analysis from the Big Clifty in Westken Petroleum well No. 18 Vincent, located 450 m south of the 20 Vincent well (Fig. 3). Bitumen lining the pore space reduced permeability by two to four orders of magnitude and porosity by 7 to 10 percent. Fluid saturations calculated from core analysis shows the effect of undersaturation in water on hydrocarbons in the pore space, with the methane volume greatest in the lower half of the core and bitumen greatest in the upper half. The movable oil fraction is about the same throughout the cored section.

ery project in southwestern Edmonson County in which permeability, porosity, and oil saturation were measured before and after extracting all hydrocarbons in 393 core plugs (Table 3, Fig. 9D). Mobile oil (So_M) and water (Sw) were first extracted from the core plugs by flushing with a solvent under low pressure; the samples were dried, and effective porosity (φ_e) and effective permeability (k_e) of the bitumen-lined pore space were then measured. The pore-lining immobile oil and bitumen and any remaining water were extracted by retorting the core plug, and the total sample porosity (φ) and permeability (k_T) were then measured. The sum of So_M and immobile oil saturations (So_B) is the So reported in the core-analysis report. Immobile bitumen-saturated porosity (φ_B) is calculated as the difference between the porosity measured before and after retorting core plugs, where

$$\varphi_{B} = \varphi - \varphi_e. \qquad (5)$$

An estimate of bitumen and immobile heavy saturation of φ_B (So_B), a fraction of So, can then be calculated:

$$So_B = (\varphi_B / \varphi) \times So, \qquad (6)$$

and thus an estimate of movable oil (So_M) can then be calculated:

$$So_M = So - So_B. \qquad (7)$$

Median movable oil saturation calculated in the tar sands in the Westken coreholes (Tables 2–3), the potential fraction of the total oil saturation that can be produced, is 15.8 percent in the Big Clifty (40.7 percent of So), 7.4 percent in the Hardinsburg (26.9 percent of So), and 8.3 percent (61.9 percent of So) in the Caseyville.

Table 3. Summary of core analysis from six coreholes in which porosity and permeability were measured before and after oil and bitumen extraction. This allowed the calculation of So_B and So_M components of total oil saturation (So), an example of which is shown in Figure 9D.

Corehole	n	Avg. H (m)	k_e (md)	k_T (md)	ϕ_e (%)	ϕ_B (%)	ϕ_T (%)	So_B (%)	So_M (%)	So_T (%)	Sg (%)	Sw (%)	Tf (%)
Big Clifty													
KSA 17 Douglas	30	69	1.8	100.8	9.1	8.1	17.2	14.6	16.5	31.2	28.5	40.3	71.5
Westken Vincent 18	43	118	10.1	486.6	7.4	10.1	17.5	24.7	17.9	42.6	22.2	35.1	77.8
Westken Vincent 19	55	103	9.2	401.9	6.1	9.7	15.8	26.2	16.5	42.7	29.0	28.3	71.0
Westken Vincent 20	39	105	3.0	120.3	7.2	8.2	15.4	19.3	16.8	36.1	31.3	32.7	68.7
Westken York 21	37	152	nm	118.3	5.1	8.3	13.4	21.9	13.5	35.5	21.0	43.5	79.0
Weighted Average (n_T = 204)		88	6.6	270.2	6.8	9.0	15.9	22.1	16.3	38.4	26.5	35.1	73.5
Hardinsburg													
Corehole	n	Avg. H (ft)	k_e (md)	k_T (md)	ϕ_e (%)	ϕ_B (%)	ϕ_T (%)	So_B (%)	So_M (%)	So_T (%)	Sg (%)	Sw (%)	Tf (%)
WestKen 6 Bracher	12	44	9.4	44.0	9.2	6.6	15.8	11.7	16.2	27.9	32.5	39.6	67.5
WestKen Vincent 18	12	91	8.3	79.5	7.8	7.5	15.3	16.8	17.6	34.4	21.5	44.1	78.5
WestKen Vincent 19	14	77	60.8	60.8	5.1	9.2	14.2	22.1	12.2	34.3	20.8	44.9	79.2
WestKen Vincent 20	30	81	30.3	30.3	3.9	10.7	14.6	18.5	6.8	25.3	16.0	58.7	84.0
Weighted Average (n_T = 68)		73	29.0	47.7	5.8	9.1	14.8	17.7	11.5	29.2	20.8	49.9	79.2
Caseyville													
Corehole	n	Avg. H (ft)	k_e (md)	k_T (md)	ϕ_e (%)	ϕ_B (%)	ϕ_T (%)	So_B (%)	So_M (%)	So_T (%)	Sg (%)	Sw (%)	Tf (%)
WestKen Vincent 18	47	40	122.7	905.5	12.6	6.3	18.9	5.3	10.6	15.9	51.4	32.7	48.6
WestKen Vincent 19	74	25	102.7	1,538	10.8	9.1	19.9	7.4	8.8	16.2	54.9	29.4	45.1
Weighted Average (n_T = 121)		33	110.5	1,292.3	11.5	8.0	19.5	6.6	9.5	16.1	53.5	30.7	46.5

Calculation of Reservoir Volume and Western Kentucky Tar-Sand Resources

Isopach maps of the net thickness of oil-saturated sand within each reservoir formation constructed in Petra were constrained by fault offsets and depositional trend options (Fig. 10). Reservoir volume ($h \times A$ in m^3, where h is the net thickness of oil-saturated sand in meters and A is the area of the reservoir inside the zero-value isopach contours in m^2; thus, hA was calculated by Petra from the isopach maps for each reservoir in five to 10 evaluation areas with hydrocarbon resources (Fig. 10), then summing the volumes to determine the total resources in place in the reservoir (Table 4). These evaluation areas were selected by fault blocks and in consideration of the distribution of coreholes and surface samples. Soφ was calculated for each well with porosity and oil-saturation data, or from weight-percent bitumen content for surface and sample data from the literature. Average Soφ was calculated from the core analysis for each evaluation area of each reservoir, including from coreholes within one Carter coordinate section outside of individual evaluation-area boundaries to account for reservoir continuity and similar properties (Table 4). Barrels of oil in place in the reservoirs was calculated by:

$$\text{barrels of oil in place} = So\varphi \times hA \times B_{oi} \times BO/m^3 \qquad (8)$$

where B_{oi} is the formation volume factor, the ratio of the volume of a barrel of oil at the surface compared to that in the reservoir at depth, a value of 1.0 for the tar-sand reservoirs, and

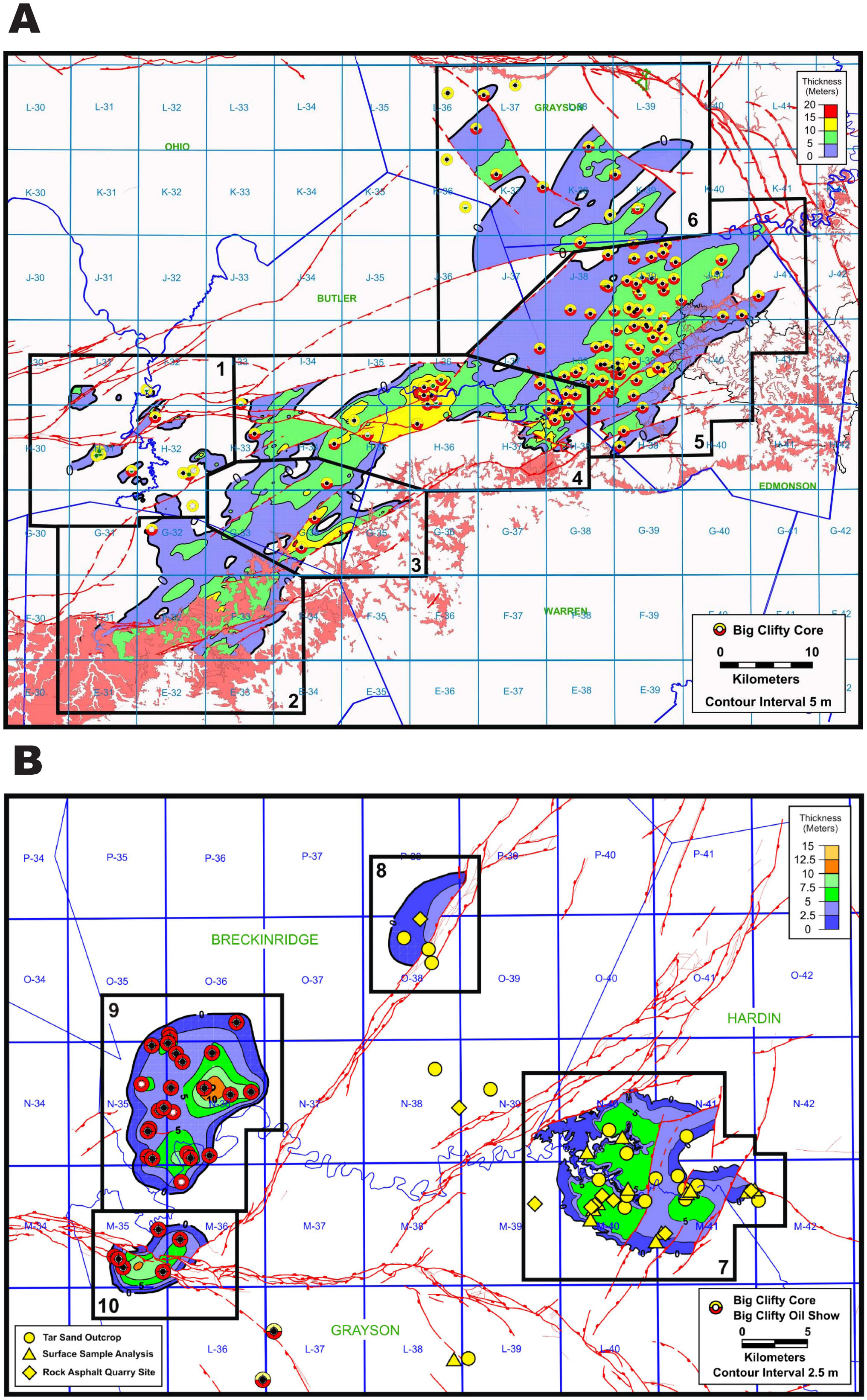

Figure 10. Thickness of net oil-saturated (bitumen plus movable heavy oil) Big Clifty Sandstone, Hardinsburg Sandstone, and Caseyville Limestone. Only wells with cores appear on Figures 10A, 10C, and 10E. All wells are shown in prospective areas in Figures 10B, 10D, and 10F. Locations of tar-sand outcrops, surface samples with bitumen-content analyses, and abandoned rock-asphalt quarries are shown in Figures 10B and 10F. Net oil-saturated sand was counted in each reservoir from core descriptions, drillers' logs, and by correlation. Barren intervals in the reservoir and interbedded shales and limestones were excluded. Evaluation data for each reservoir are shown in Table 4. Big Clifty outcrop is shown in red on Figures 10A, 10C, 10E, and 10F. Yellow circles with well symbols show the locations of coreholes, and colored lower sections (red Big Clifty, green Hardinsburg, blue Caseyville) show coreholes cored in the mapped reservoir. (A) The contingent resources in the Big Clifty tar sands south of the Rough Creek Fault System were evaluated in six areas with varying average values of bulk-volume of oil (Soϕ) in place. (B) Resources in the Big Clifty north of the Rough Creek Fault System include contingent resources in area 7, with surface and rock-asphalt mine analyses of bitumen content in the Big Clifty, and prospective areas 8–10. Wells with shows of oil, tar, or asphalt in drillers' logs through the Big Clifty are shown by red circles surrounding a well symbol. Continued on following pages.

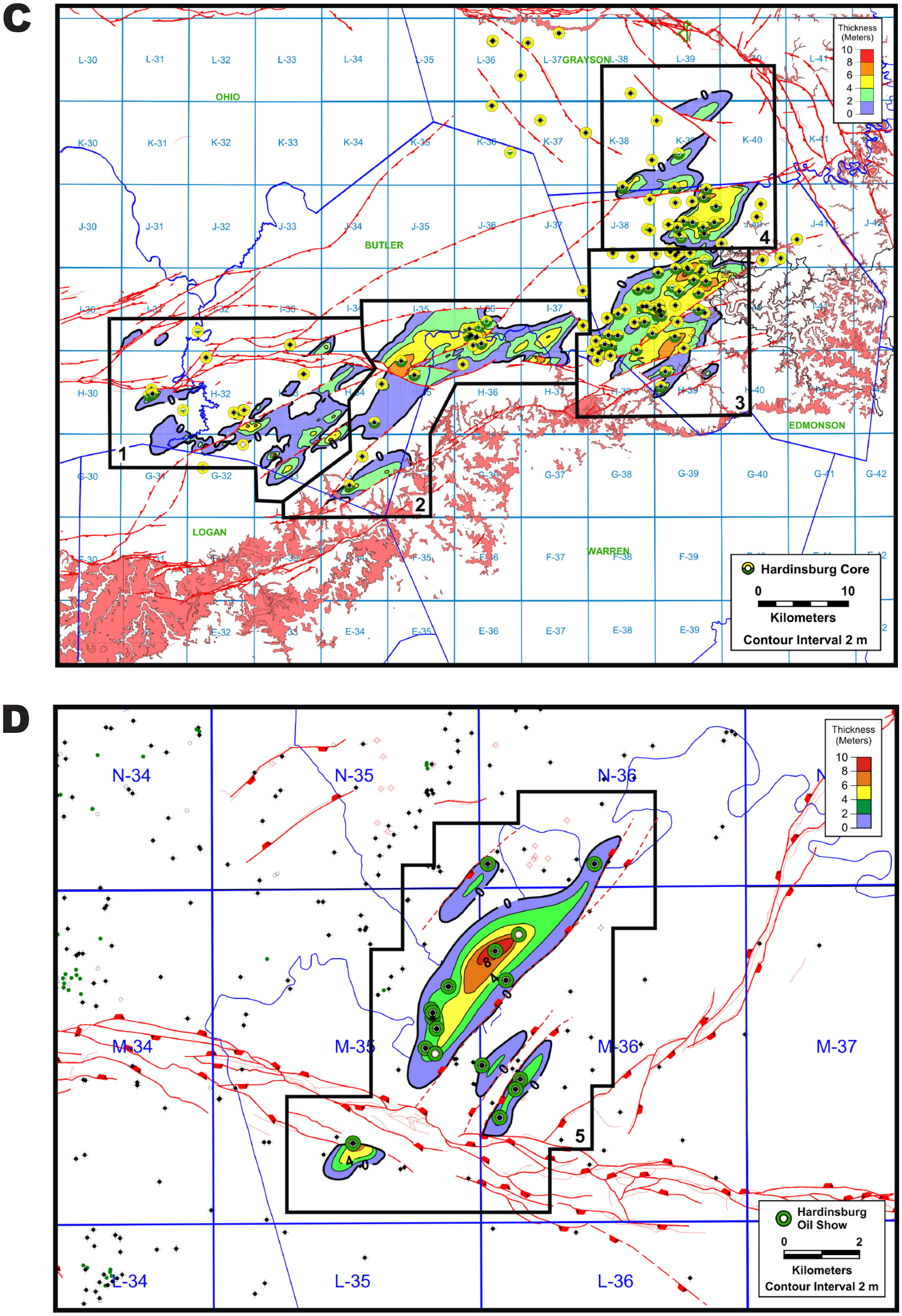

Figure 10. Continued. (C) Thickness of net Hardinsburg oil sand. Contingent resources were calculated in four evaluation areas. (D) Thickness of net oil sand in the Hardinsburg Sandstone in the prospective area along and north of the Rough Creek Fault System. Wells with shows of oil, tar, or asphalt in drillers' logs through the Hardinsburg are shown by green circles surrounding a well symbol. Continued on following page.

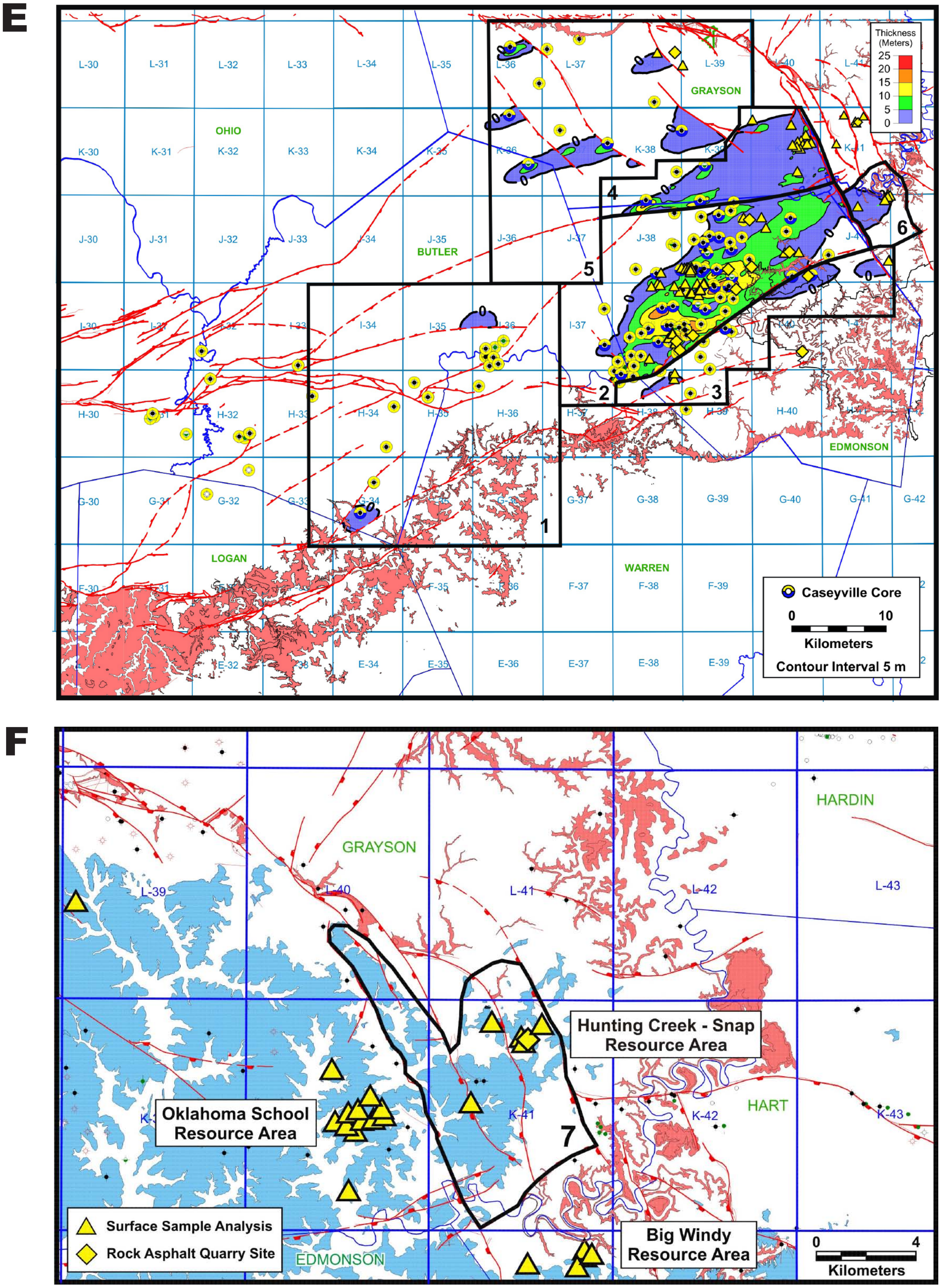

Figure 10. Continued. (E) The Caseyville was evaluated in six areas, largely in Edmonson County. (F) Caseyville prospective area 7 was contingent, based on surface samples from the literature (Jillson, 1925c, 1927c, 1929). Outcrops of Caseyville Formation are shown in blue.

Table 4. Volumetric summaries of the Big Clifty (A), Hardinsburg (B), and Caseyville (C) reservoirs by contingent and prospective evaluation area (Fig. 10).

(A) Big Clifty Volumetrics

Area	*CH**	*Samples (n)**	*A ($m^2 \times 10^6$)*	*Avg. h (m)#*	*hA ($m^3 \times 10^6$)*	*Avg. $So\varphi^{+\ddagger}$*	*Oil in Place (MMBO)*
1	3	47	36.8	2.1	78.7	0.030	15
2	12	199	218.9	4.3	942.3	0.059	350
3	5	127	132.5	5.1	680.1	0.034	147
4	24	573	236.8	7.1	1,686.8	0.052	555
5	60	1,241	389.9	4.3	1,661.9	0.056	583
6	9	92	212.5	3.0	647.8	0.055	222
7	0	15	123.0	3.6	403.5	0.085	216
Total	**113**	**2,294**	**1,350.5**	**4.5**	**6,101.1**	**0.055**	**2,087**
Prospective							
8	0	2	31.7	1.4	45.6	0.068	19
9	0	0	98.8	4.1	407.8	0.046	117
10	2	0	23.9	4.4	104.2	0.037	24
Total	**2**	**2**	**122.7**	**4.2**	**557.5**	**0.044**	**160**
						Total	2,247

(B) Hardinsburg Volumetrics

Area	*CH**	*Samples (n)**	*A ($m^2 \times 10^6$)*	*Avg. h (m)#*	*hA ($m^3 \times 10^6$)*	*Avg. $So\varphi^{O}$*	*Oil in Place (MMBO)*
1	4	53	97.2	1.4	136.7	0.035	30
2	6	73	167.1	2.6	426.1	0.054	145
3	20	270	138.8	3.3	456.2	0.043	125
4	2	5	86.8	2.7	231.6	0.043	62
Total	**32**	**401**	**489.8**	**2.6**	**1,250.5**	**0.044**	**345**
Prospective							
5	0	218+	17.7	2.5	44.8	0.043	12
						Total	357.1

(C) Caseyville Volumetrics

Area	*CH**	*Samples (n)**	*A ($m^2 \times 10^6$)*	*Avg. h (m)#*	*hA ($m^3 \times 10^6$)*	*Avg. $So\varphi^{O}$*	*Oil in Place (MMBO)*
1	3	35	12.9	1.9	24.8	0.047	7
2	6	9	22.8	2.1	47.1	0.060	18
3	81	602	229.9	6.6	1,517.6	0.046	440
4	15	48	108.3	3.6	392.6	0.079	195
5	5	21	59.5	1.9	111.0	0.043	30
6	7	7	15.4	1.8	28.0	0.077	13
Total	**117**	**722**	**448.7**	**4.7**	**2,121.2**	**0.053**	**704**
Prospective							
7+	0	16	24.5	3.2	78.53	0.077	38.0
						Total	742

Sources: Jillson (1925c, 1927c, 1928b, 1929), Glick (1963), and Moore (1965).
*Includes coreholes adjacent to the area evaluated.
[†] Number of wells evaluated.
#Combined average is weighted for the area contribution to the total evaluation area.
[O] Combined average is weighted for the number of samples per evaluation area.

BO/m^3 = 6.29 barrels of oil per cubic meter. Total barrels of oil in place for each reservoir formation was categorized as either contingent or prospective resources, based on Society of Petroleum Engineers (2001). Contingent resources are in areas where porosity and oil-saturation data are available to calculate barrels of oil in place, and prospective areas are those where oil-saturated intervals are described in the reservoir formations, but where core-analysis data are insufficient or lacking and Soφ was estimated from data outside of the prospective evaluation area.

Unrisked contingent and prospective heavy-oil and bitumen resources in the western Kentucky tar sands (see the definitions in Society of Petroleum Engineers, 2001) are estimated to total 3,346 million barrels of oil in place (Table 5): 2,247 million barrels of oil in place in the Big Clifty, 357 million barrels of oil in place in the Hardinsburg, and 742 million barrels of oil in place in the Caseyville. There are no demonstrable reserves. These results are about 10 percent greater than those of Lewin and Associates Inc. (1984a) and Noger (1984, 1987). The largest change is in the Caseyville: 35 percent greater resources than the estimates of Lewin and Associates Inc. (1984a) and Noger (1984, 1987); estimates for the Hardinsburg decreased by 17 percent compared to the previous estimates, and estimates for the Big Clifty increased by 7 percent (Table 5). The additional resources in the Big Clifty are, in part, largely attributable to the addition of 200.3 million barrels of oil of contingent resources in the northeastern Grayson County area (Big Clifty evaluation area 7) that had been omitted from prior tar-sand resource assessments (Bowersox, 2016a). This omission was likely because of the lack of data supporting oil-in-place calculations for the area, whereas this study used additional data from the reports of Jillson (1923c, 1925c, 1926a, b) that were unavailable before public release in October 2008.

Discussion

Early estimates of heavy-oil and bitumen resources in the western Kentucky tar sands focused

Table 5. Contingent and prospective resources in the Big Clifty Sandstone, Hardinsburg Sandstone, and Caseyville Formation total 3,346 million barrels of oil in place, about 10 percent more than estimated by Noger (1984, 1987) and Lewin and Associates Inc. (1984a, b).

Western Kentucky Estimated Heavy-Oil and Bitumen Resources							*This Study Oil in Place (MMBO)*	*Noger (1983)[5] Oil in Place (MMBO)*
Formation	*Coreholes[1]*	*Samples[1]*	*A ($m^2 \times 10^6$)*	*Avg. h (m)[#]*	*hA ($m^3 \times 10^6$)*	*Avg. Soφ*		
Big Clifty								
Contingent	113	2,294	1,345	4.5	6,101	0.055	2,087	1,190
Prospective[2]	2	2	123	4.2	558	0.044	160	910
						Formation Total	2,247	2,100
Hardinsburg								
Contingent	32	401	490	2.6	1,251	0.044	345	250
Prospective[3]	0	218	18	2.5	45	0.043	12	180
						Formation Total	357	430
Caseyville								
Contingent	117	722	449	4.7	2,121	0.053	704	300
Prospective[4]	0	16	25	3.2	79	0.077	38	250
						Formation Total	742	550
						Total Contingent Resources	3,136	1,740
						Total Prospective Resources	210	1,340
						Total Resources	3,346	3,080

Note: Resource classifications (contingent and prospective) follow the Society of Petroleum Engineers (2001).

[1] Includes coreholes and surface sample analyses adjacent to an individual area evaluated in this formation.

[2] Big Clifty in Grayson, Breckinridge, and Hardin Counties, unrisked. Speculative resources of Noger (1984).

[3] Hardinsburg in Breckinridge County, unrisked. Speculative resources of Noger (1984).

[4] Caseyville in southeastern Grayson County, unrisked. Speculative resources of Noger (1984).

[5] Noger (1984) included areas outside of Breckinridge County in his speculative resources.

on strippable mining resources as potential sources of feedstock for synthetic-fuels production (Ball, 1951; Ball and Associates Ltd., 1965). Ball (1951) estimated about 314.6 million tonnes of strippable rock-asphalt deposits in Edmonson and Logan Counties containing 87 million barrels of oil of recoverable bitumen. Ball and Associates Ltd. (1965) expanded their tar-sand review to cover the larger region of Grayson, Hardin, Hart, Edmonson, Warren, and Logan Counties. They estimated a total recoverable resource of 494 million tonnes of rock asphalt, containing 0.24 to 0.35 barrels of oil per tonne of ore, or a total of 119 to 179 million barrels of oil in place. Including the more recent evaluations of Lewin and Associates Inc. (1984a) and Noger (1984) makes the results of this evaluation materially different than results of previous studies.

These differences stem, in part, from (1) larger databases of wells, cores, and surface samples used in this study versus those from previous evaluations, (2) the capability of constructing isopach maps and calculating reservoir volumes using modern computer software, and (3) the difference in evaluation methodology. The classification of identified and potential resources, called "measured" and "speculative" resources in Lewin and Associates Inc. (1982, 1984b) and applied by Noger (1984, 1987), differs from modern industry definitions applied in this study. Lewin and Associates Inc. (1984a) and Noger (1984, 1987) classified their resources as measured, supported by well control and core analysis, and speculative, supported by drillers' logs and geologic interpretation (Lewin and Associates Inc., 1984b). This study considers contingent resources in which drillers'-log descriptions are supported by correlation to wells with electric logs and core analysis. Because the studies of Lewin and Associates Inc. (1984a) and Noger (1984, 1987) used smaller databases and largely focused on resources recoverable by mining and evaluated by categories of probable richness of the tar-sand deposits in barrels of oil per acre-foot, their methodology (Lewin and Associates Inc., 1982) understates contingent resources when compared to the volumetric resources of this study and overstates prospective resources.

Lewin and Associates Inc. (1984a) and Noger (1984, 1987) classified about 55 percent of their Chesterian and Caseyville resources as measured, whereas contingent resources comprise 94 percent of the totals in this study. In part, some resources classified as contingent in this study were classified as speculative by Lewin and Associates Inc. (1984a) and Noger (1984, 1987), and some resources classified as speculative by Lewin and Associates Inc. (1984a) and Noger (1984, 1987) were found to be unsupportable and excluded from this study. For example, the speculative Welchs Creek and Shrewsbury areas of the Big Clifty in Lewin and Associates Inc. (1984a) and Noger (1984, 1987), approximately evaluation area 6 of this study (Fig. 10A), are classified as contingent resources in this study by core and well data and the area's proximity to very well-defined resources in evaluation area 5 (Fig. 10A). Big Clifty evaluation area 7 of this study (Fig. 10B), discussed above, is well defined by historical rock-asphalt production and surface samples, but was not addressed by Lewin and Associates Inc. (1984a) and Noger (1984, 1987). In the Hardinsburg, the Short Creek/West Short Creek speculative area of Lewin and Associates Inc. (1984a) and Noger (1984, 1987) is supported as prospective in this study (Fig. 10D). The East Fordsville speculative area of Lewin and Associates Inc. (1984a) and Noger (1984, 1987), however, could not be supported by well data available from the KGS Oil and Gas Records Database. Both measured and all speculative areas of the Caseyville of Lewin and Associates Inc. (1984a) and Noger (1984, 1987) are supported as contingent resource areas in this study. The Hunting Creek–Snap resource area of this study (Fig. 10F) could not have been evaluated by Lewin and Associates Inc. (1984a) and Noger (1984, 1987) because the reports of Jillson (1925c, 1927c, 1929) were not available at the time of their evaluations.

Overestimation of Western Kentucky Tar-Sand Resources

There have been resource estimates made of as much as 5,000 to 6,000 million barrels of oil in place in the western Kentucky tar sands (unpublished data; May, 2013). These estimates are likely from misinterpreting gas saturation in the pore space as void space representing lost oil saturation (e.g., see May, 2013). This misinterpretation could cause an overestimation of oil saturations in the tar sands. For example, because median So and Sw in the Big Clifty are 34.0 percent and 28.6 percent, respectively (Table 2), and median total fluids saturation is then 62.6 percent, the difference between total fluid saturation measured in the cores and 1, 37.4 percent, may then be interpreted as lost oil saturation. The "corrected" oil saturation (So_{corr}) thus becomes

$$So_{corr} = [100 - (So + Sw)] + So, \qquad (9)$$

with a median value of 71.4 percent for the Big Clifty, an overestimation of So of 110 percent. Applied to all tar-sand reservoirs, the effect of this misinterpretation could be a substantial overestimation of western Kentucky tar-sand resources (e.g., see May, 2013).

Origin of the Tar Sands by Physical Processes

The origin of the western Kentucky tar sands has been controversial for more than 100 yr, and many possible physical origins have been proposed: oxidation (Orton, 1891; Eldridge, 1901; Weller, 1927; Russell, 1933; McFarlan, 1943; McGrain, 1976), leakage (Lewan and others, 1995), devolatilization (Weller, 1927; McGrain, 1976), and water washing (Lewan and others, 1995). At their simplest, explanations of the origin of the western Kentucky tar sands proposed before there was substantial drilling and coring in the tar-sand belt fail for the same reason: Most tar-sand deposits occur as isolated fault-trapped reservoirs in the subsurface (Fig. 10). They have not been exposed at the surface post-burial. Orton (1891) and Eldridge (1901) proposed that bitumen in the tar sands developed by oxidation of light hydrocarbons when reservoir rocks were exposed at the surface and in the shallow subsurface. Russell (1933) proposed that the heavy oil and bitumen in the Chesterian and Caseyville reservoirs were the result of oxidation of light oil by the circulation of oxygen-charged groundwater before erosion exposed these strata at the surface. McFarlan (1943) added that alteration began with groundwater circulating through light-oil reservoirs in the subsurface, as proposed by Russell (1933), followed by atmospheric oxidation upon exposure at the surface. Review of core descriptions, and mineralogy of the tar-sand reservoirs (Butler, 2013; May and Butler, 2014a, b), demonstrate that oxidation of the tar-sand reservoirs does not extend into the subsurface far from the outcrops and that reservoirs remain in geochemically reducing environments in the subsurface. Origins for the tar sands requiring circulation of oxygenated meteoric water (Russell, 1933; McFarlan, 1943) also fail because there are no active aquifers below tar-sand reservoirs and the reservoirs are undersaturated in water and would imbibe and bind any water circulating through them. Thus, any mechanisms for the formation of bitumen in these reservoirs requiring oxidation are unlikely.

Petroleum losses from a basin, visible at the surface as oil and gas seeps, may result from untrapped petroleum leaking from porous carrier beds or seal breaches from faults and near-surface fractures (Macgregor, 1993; Lewan and others, 1995). Lewan and others (1995) suggested that tar deposits in the Chesterian and Caseyville reservoirs were evidence of significant petroleum-leakage losses from the New Albany–Chesterian petroleum system. Lewan and others (2002) suggested that the Chesterian-Pennsylvanian tar sands in Breckinridge, Hardin, and Grayson Counties (Fig. 10B, D) were indicative of petroleum leakage. Seeps result from breaching of a reservoir and the slow destruction of the oil accumulation (Macgregor, 1993). Heavy-oil seeps seen in outcrops, for example the tar spring in Breckinridge County described by Owen (1856), are evidence that the petroleum system in the region has been destroyed through erosion (Macgregor, 1993). Heavy-oil and tar seeps seen in outcrops in the tar-sand belt (May, 2013, 2014) are evidence of active leakage from the eroded and exposed tar-sand reservoirs; however, they may also be evidence of methane expansion in the tar sands causing slow oil expulsion, similar to that observed in cores recovered from the subsurface (Ward and Ward, 1984) where there are fresh exposures in quarries and roadcuts. Comparing sulfur enrichment of heavy oil produced from the western Kentucky tar sands to that of light oils produced from the Illinois Basin, Lewan and others (1995) concluded that 13.3 weight-percent of the original oil in place in the tar sands (3,400 million barrels) remains, and that 27,000 million barrels of oil have been lost by degradation from near-surface leakage. The median total pore space in the tar sands, from data in Tables 2 and 5, is equivalent to 13,335 million barrels, or less than half of that required by Lewan and others (1995). Because outcrops of the Big Clifty do not show the residual oil saturation expected if oil had migrated through the rocks (e.g., see Jillson, 1925c), it is unlikely that the western Kentucky tar-sand resources are the remnants of a leaked volume eight times larger.

Low-pressure devolatilization, or inspissation (Barbat, 1967; Milner and others, 1977), is the evaporative loss of gases and lighter liquid hydrocarbons from oil in the reservoir through leakage or surface seepage (Barbat, 1967). This proceeds from the lightest hydrocarbons progressively to heavier fractions, although the ratio of components of the residuum correlates with that of unaltered oils (Barbat, 1967), until evaporation becomes negligible in the heavy residuum fraction. Weller (1927) proposed that the western Kentucky tar sands developed by the loss of more-volatile hydrocarbons to the atmosphere when the reservoirs were erosionally exposed at the surface; this explanation was also favored by McGrain (1976) in his review of the western Kentucky tar sands. Experimental devolatilization, however, found that only 15 to 20 percent of oil volume is lost and API gravity is reduced by only a few units (Milner and others, 1977, and sources cited therein). Likewise, Noble and others (1997) found that although a 44° API gravity oil will have lost 40 percent of its weight after 120 minutes of evaporation, a 26° API gravity oil will have only lost 15 percent of its weight over the same period. Extrapolated to oil gravity versus evaporative loss, there is effectively no evaporative losses of 10° API gravity oil from the western Kentucky tar sands that would further reduce the oil gravity to that of bitumen; thus, it is unlikely that devolatilization alone could have formed the tar-sand deposits.

Water washing (fractionation of light and heavy oils during migration and in-reservoir maturation) changes the composition of oil by the loss of the more water-soluble gasoline-range hydrocarbons (less than C_{15}), especially benzene and toluene, relative to heavier C_{15+} hydrocarbons (Lafargue and Barker, 1988). It can occur during petroleum migration when oil passes through water-saturated carrier beds, or after accumulation when water washing will only affect oil close to the oil-water contact (Lafargue and Barker, 1988). The effect of water washing is difficult to determine because it is typically accompanied by biodegradation (Lafargue and Barker, 1988; Palmer, 1991; Min and Jun, 2000). Water washing is precluded from the western Kentucky tar sands, however, because there is no continuous porous bed capable of serving as a regional carrier bed between the New Albany source rock and tar-sand reservoirs in the Big Clifty, Hardinsburg, and Caseyville (Lewan and others, 1995). There is no discernable oil-water contact in any of the tar-sand reservoirs, and they are undersaturated in water and without connection to an active aquifer. The only model that explains the formation of the western Kentucky tar sands is microbial biodegradation.

Origin of the Western Kentucky Tar Sands by Microbial Biodegradation

The pore-lining bitumen in the tar-sand reservoirs point to anaerobic microbial biodegradation as the origin of the western Kentucky tar sands. Bitumen in a reservoir can be considered a diagenetic cement precipitated on the surfaces of the pore space, although it may be formed by either thermal alteration to dry gas and residual bitumen, deasphalting of the oil to residual asphaltenes, or biodegradation (Rogers and others, 1974; Lomando, 1992). The western Kentucky tar sands were never heated to the point at which thermal alteration would occur. Deasphalting occurs when gas or very light oil migrates through oil-saturated rock (Lomando, 1992); however, the lack of a carrier bed and the isolated fault blocks comprising the tar-sand reservoirs preclude this. Biodegradation, on the other hand, has been shown to have adversely affected the majority of the world’s oil (Roadifer, 1987), and is the model that best explains the origin of the western Kentucky tar sands. Miller and others (1987), in a study of common crude oils and tars from Oklahoma, found that biodegradation reduced API gravity from 32° to 4°, increased sulfur from 0.6 to 1.6 weight-percent, and increased asphaltenes from 2 to 21 weight-percent. These bitumen characteristics are comparable to those of 5.9° API gravity bitumen extracted from the Big Clifty in Logan County (Groves and Hastings, 1983; Hosterman and others, 1990) and in Caseyville rock asphalt from the Indian Creek Quarry in Edmonson County (Hosterman and others, 1990).

Although it is widely believed that crude oil is not a preferred microbial habitat because of its potential toxicity and high hydrophobicity, at least 16 genera of microorganisms have been found living in petroleum reservoirs (Cai and others, 2015). In particular, hydrogen or hydrogen-utilizing bacteria and archaea preferentially utilize crude oil (Cai and others, 2015). Anaerobic bacteria are common in the subsurface, even in shallow petroleum reservoirs (less than 500 m deep) containing fresh water (Widdel and Rabus, 2001; Wenger and others, 2002; Head and others, 2003). The problem with biodegradation of the western Kentucky tar sands is that the last influx of waters containing microbes prior to hydrocarbon migration would have been during Caseyville deposition during the Pennsylvanian, whereas hydrocarbon migration from the New Albany commenced in the Early Triassic (Hickman, 2013), a lag of about 70 million years (Fig. 11). A biodegradation model in which bacteria would have been introduced to the tar sands following reservoir breaching in the Cenomanian, subsequently causing biodegradation, is unlikely. The recharge of fluids and consequent migration of microorganisms from the surface to reservoirs once deeply buried is insignificant (Wilhelms and others, 2001; Head and others, 2003). This model implies that microorganisms in these reservoirs were present during burial and survived and evolved since reservoir deposition (Head and others, 2003); indeed, viable microorganisms were cultured from drill cuttings from the deep subsurface in the KGS 1 Hanson Aggregates research well, Carter County, Ky. (Perry, 2013).

Where the isolated subsurface fluid environments are capable of supporting life, microorganisms of the deep subsurface biosphere appear to conduct little metabolic activity because of the low availability of nutrients, particularly methane and sulfates, in these environments, so the microorganisms exist in dormant states (Holland and others, 2013; Rajala and others, 2015). These anaerobic microorganisms survive until the migration of oil into the reservoir rocks (Wilhelms and others, 2001; Head and others, 2003; Rajala and others, 2015). These bacteria, long sequestered in the reservoir sands, would have begun metabolizing the sulfur and hydrocarbons, as well as iron reduced from primary liesegang bands at the diagenetic interface at the front of the migrating oil and degrading light oils in the reservoirs. Other bacteria have a known ability to degrade aromatic crude-oil compounds using oil-specific enzymes (Cai and others, 2015). The common bacteria *Pseudomonas* can produce biosurfactants that help it attach to crude oil and degraded aromatic carbon sources (Cai and others, 2015). What remains is not light oils comparable to underlying reservoirs in Lower Mississippian carbonates, but only heavily biodegraded 6° API gravity bitumen (Groves and Hastings, 1983; Moore and others, 1984) that line pore spaces and 10° to 11° API gravity heavy oil (Terwilliger, 1976; Groves and Hastings, 1983; Moore and others, 1984; Ward and Ward, 1984), comprising the mobile oil in the tar-sand reservoirs (Fig. 9A, B, D).

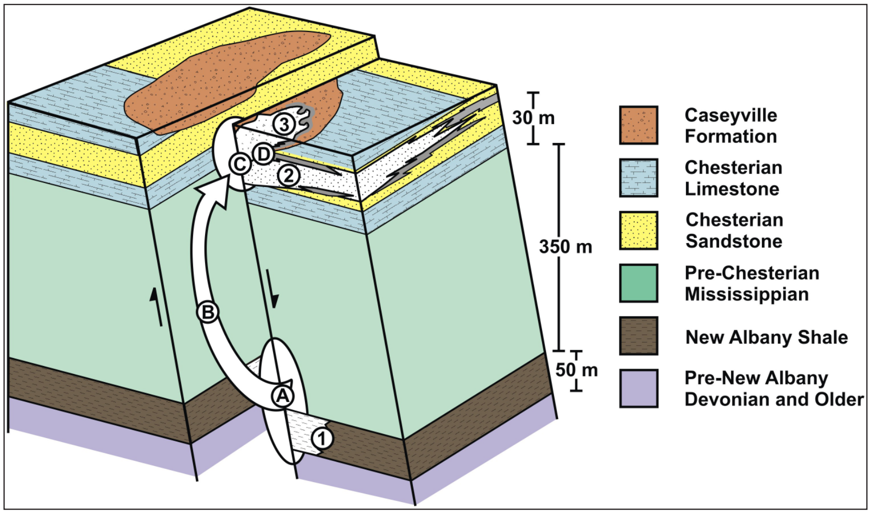

Figure 11. Conceptual block model of oil migration from the New Albany Shale into the tar-sand reservoirs. Modified from Rowe and Burley (1997); used with permissionof the Geological Society of London. Oil generated in the New Albany (1) enters the fluid entry window along a fault (A), migrates vertically along the fault (B), enters the Big Clifty and Hardinsburg reservoirs (C), migrating laterally (2), and into the Caseyville (D) and migrating laterally (3).

Original Distribution of Tar-Sand Reservoirs in Western Kentucky

Chesterian and Caseyville strata are absent in the Illinois Basin south and east of the Big Clifty outcrop (McDowell and others, 1981); thus, the original extent of the tar-sand reservoirs is unknowable. Bryant (1914) identified tar sands in an area of 20,720 ha in western Kentucky, but declined to speculate on its original extent. McFarlan (1943) described the tar sands as "defunct oil pools," and estimated that the original resources in Edmonson County and vicinity would have exceeded 1,000 million barrels of oil. Neither author suggested a regional extent beyond that known at the time of their research. The distribution of oil fields occurring in Lower to Middle Mississippian carbonate reservoirs in the southern Illinois Basin south of the Big Clifty outcrop; the largest, in central Warren County, suggests that the original southern extent of the tar-sand reservoir would not have been substantially greater than the present known extent (Fig. 12). The lack of carrier beds in the section and fault/fracture conduit systems would have limited migration of oil into Chesterian reservoirs and, in turn, secondarily into the Caseyville. Therefore, it is unlikely that there were many oil reservoirs in the Big Clifty and Hardinsburg south of the present resource areas. Additional Caseyville resources may have been present where erosion of the Pennsylvanian Brownsville and Madisonville Paleovalleys (Fig. 6) breached underlying petroleum reservoirs northeast of the present extent of the Caseyville's resources. The distribution of Big Clifty rock-asphalt deposits north of the Rough Creek Graben (Fig. 2B) suggests that there may have been additional resources present in Hardin and Hart Counties, and farther east on the western flank of the Cincinnati Arch, that were later removed by erosion. The limited distribution of Hardinsburg tar sands north of the Rough Creek Graben (Fig. 2B), however, does not encourage speculation of substantial resources beyond their present extent.

Bitumen Extraction and Enhanced-Oil-Recovery Projects in Western Kentucky Tar Sands

Before 1920, tests extracting bitumen from ground rock asphalt used either retorts or hot water (Table 6). The yield of these tests proved insufficient to encourage the operators to attempt commercial production (Crump, 1913; Bryant, 1914; Weller, 1927; Hagan, 1942). Two pilot projects in

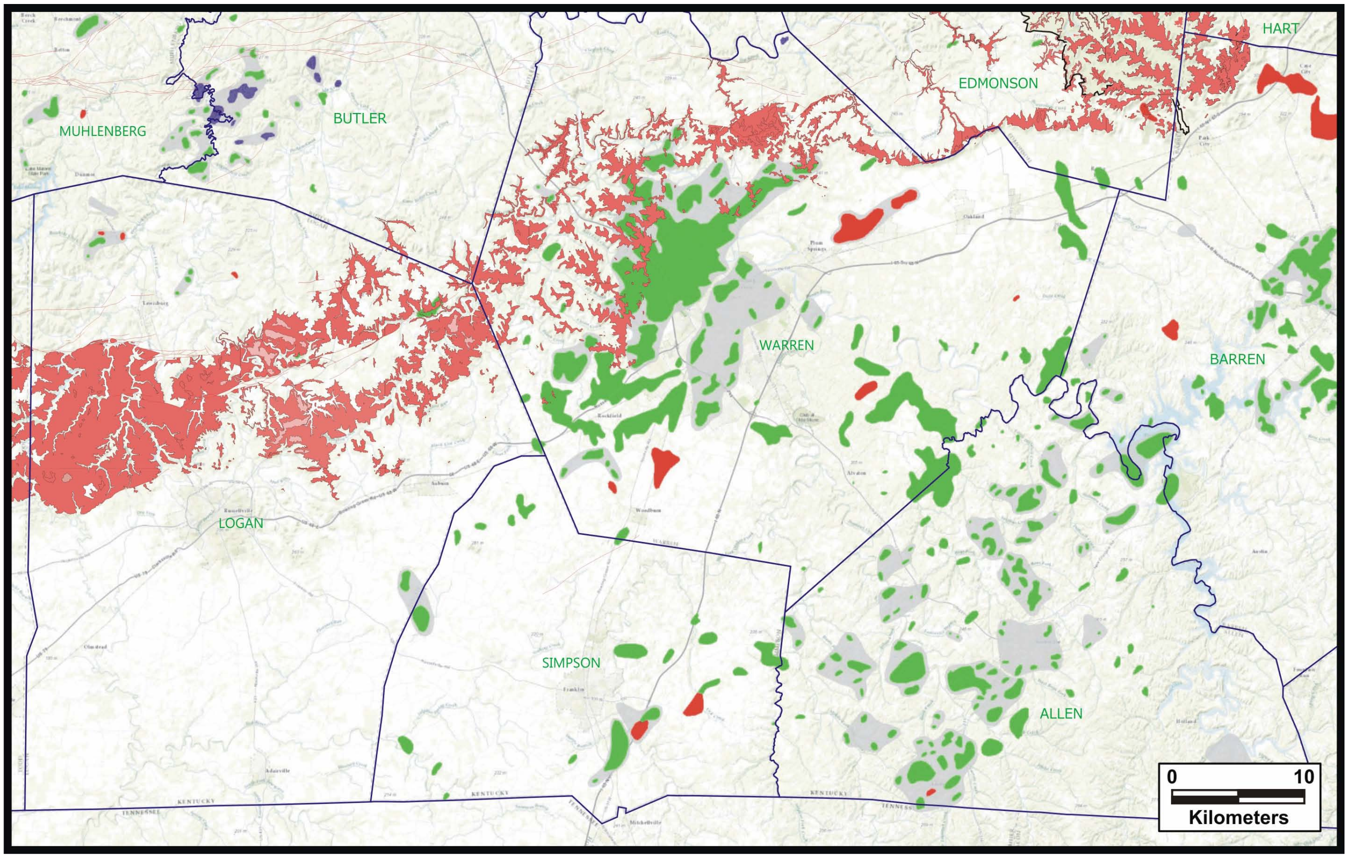

Figure 12. The sizes and distribution of oil fields in western Kentucky, south of the Big Clifty outcrop, suggest that it is unlikely that substantial tar-sand reservoirs and resources developed outside their known extent.

Table 6. Pilot bitumen-extraction projects, though technical successes, have not led to commercial production. Locations of bitumen-extraction pilot projects are visible on satellite photography served by the KGS Kentucky Geologic Map Information Service.

Operator	*Year*	*Reservoir*	*County*	*Process*	*Recovery*	*Source*
American Bituminous Rock Co.	circa 1893	Big Clifty	Grayson	retort	80 gallons	Weller (1927), Hagan (1942)
Snap bitumen retort site	circa 1910	Caseyville	Grayson	retort	na	Hagan (1942)
J.N. Alvy farm bitumen retort site	before 1914	Caseyville	Grayson	retort	na	Bryant (1914)
Dismal Creek bitumen retort site	before 1913	Caseyville	Edmonson	hot water	1.9 BO/tonne	Crump (1913)
TXG/Cresset	1984	Big Clifty	Logan	Dravo solvent[1]	0.25 BO/tonne	Benson and Tis (1984)
Tarco	1984	Big Clifty	Logan	Tarco solvent[2]	0.3–0.4 BO/tonne	Groves and Hastings (1983)
Stampede Mine	2014	Big Clifty	Logan	Sandklene 950 solvent[3]	not released	Bartlett (2014)

[1] Hexane
[2] Methylene chloride
[3] Proprietary water-based solvent

the early 1980's tested mining surface deposits of Big Clifty tar sands near Homer, northern Logan County, and extracting heavy oil and bitumen from crushed tar-sand ore with hydrocarbon solvents (Groves and Hastings, 1983; Noger, 1984, 1987; Benson and Tis, 1984; Tis, 1984; Kelley and Fedde, 1985) (Fig. 13, Table 6). Although both projects were technical successes, recovering approximately 100 percent of the bitumen in the ore during testing, both projects were abandoned by 1985.

The failure to recognize that the majority of the oil in place in the western Kentucky tar sands is pore-lining bitumen, and that mobile oil in place is less than 40 percent of the total oil in the tar sands, have been the causes of several failed enhanced-oil-recovery projects (Fig. 14). Operators appear to have been lured by the promise of huge volumes of oil in place, overlooking the fact that the tar sands are trapped in thin, undersaturated reservoirs with intraformational diagenetic barriers to fluid flow (see Butler, 2013; May and Butler, 2014a, b, 2015). Bitumen lining the pore space reduces effective porosity and permeability, limits the available mobile oil for exploitation, while causing the appearance of greater resources available for enhanced-oil-recovery development than are actually present (Fig. 9D). A consequence of the western Kentucky tar-sand reservoirs being undersaturated in water is that they will imbibe water where available (see Hoffman, 2008, 2013), for example, during drilling or secondary-recovery waterflooding. Low-pressure methane in the pore space acts as void space that has to fill during enhanced-oil-recovery injection projects. Attempts were made to develop the tar sands in the shallow subsurface, less than 800 ft deep, with conventional vertical wellbores from late 1959 to 1985 by in situ combustion enhanced-oil-recovery (fireflood) processes (Terwilliger, 1976; Williams and others, 1982; Ward and Ward, 1984; Noger, 1984, 1987; May, 2013). These projects were, in part, technical successes (Terwilliger, 1976; Noger, 1984; Ward and Ward, 1984; May, 2013; this study) (Table 7). The Gulf Oil Co. fireflood produced 14.5° API gravity heavy oil from the Caseyville, whereas the in situ oil was 10.4° API gravity (Terwilliger, 1976). This difference in oil gravity demonstrates that some thermal cracking of the heavier oil in the reservoir was occurring as part of the fireflood process. The wet-combustion enhanced-oil-recovery process used by Westken does not appear to have caused thermal cracking (Ward and Ward, 1984) (Table 7), and thermal cracking appears to have been limited in the Sunset Petroleum wet-combustion enhanced-oil-recovery project (May, 2013) (Table 7). Thus, despite these technical successes (Table 7),

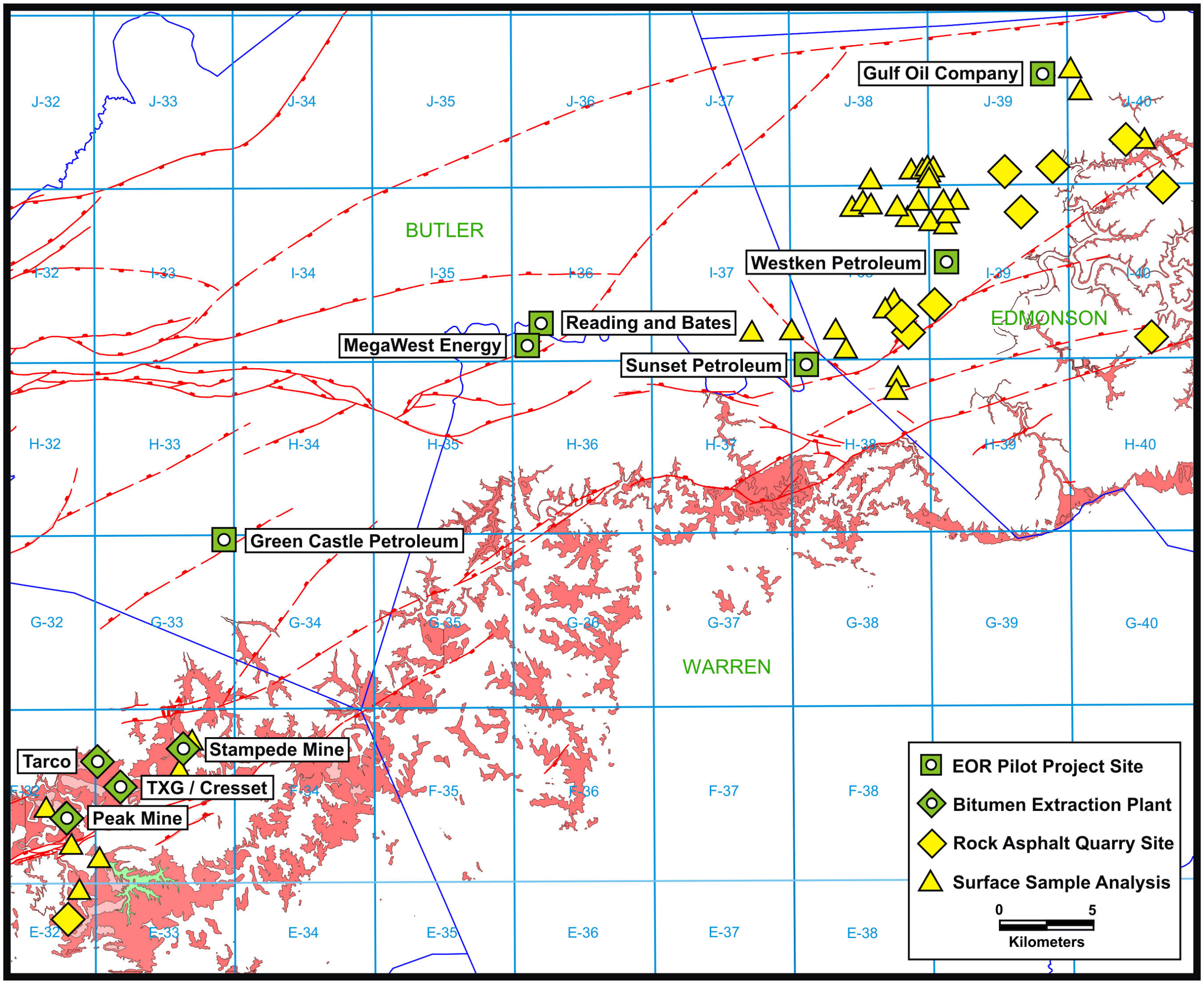

Figure 13. Locations of tar-sand enhanced-oil-recovery pilot projects from the KGS Oil and Gas Records Database (Table 7) and locations of bitumen-extraction pilot projects (Table 6) are visible on satellite photography and 5-ft LiDAR (light detection and ranging) imagery served by the Kentucky Geologic Map Information Service. All enhanced-oil-recovery and bitumen-extraction pilot projects developed the Big Clifty, or planned to develop the Big Clifty, except the Gulf Oil Co. pilot in situ combustion project in the Caseyville Formation.

the total yield of all enhanced-oil-recovery projects in the tar sands was less than 20 million barrels of heavy oil, and all were abandoned by the operators. Two other steamflood enhanced-oil-recovery projects were proposed in 1981 and 2007, and coreholes were drilled to assess tar-sand resources in proposed pilot areas, but these projects were never installed (Table 7).

Recent Tar-Sand Development Activities

The Kentucky Geological Survey has been contacted many times since 2012 for information about the western Kentucky tar sands. There have been reports of speculative leasing of tar-sand properties in the area. Several large lease tracts of about 8,100 ha or more are said to have been assembled, although no specific development activities are proposed for these tracts. The largest tracts reported are in Logan, Warren, and Edmonson Counties. The lure of huge resources, shallow working depths, and low-cost leases have been enough to encourage oil and mining companies to reevaluate the tar-sand resources in western Kentucky. In 2014, two new pilot projects were initiated to re-

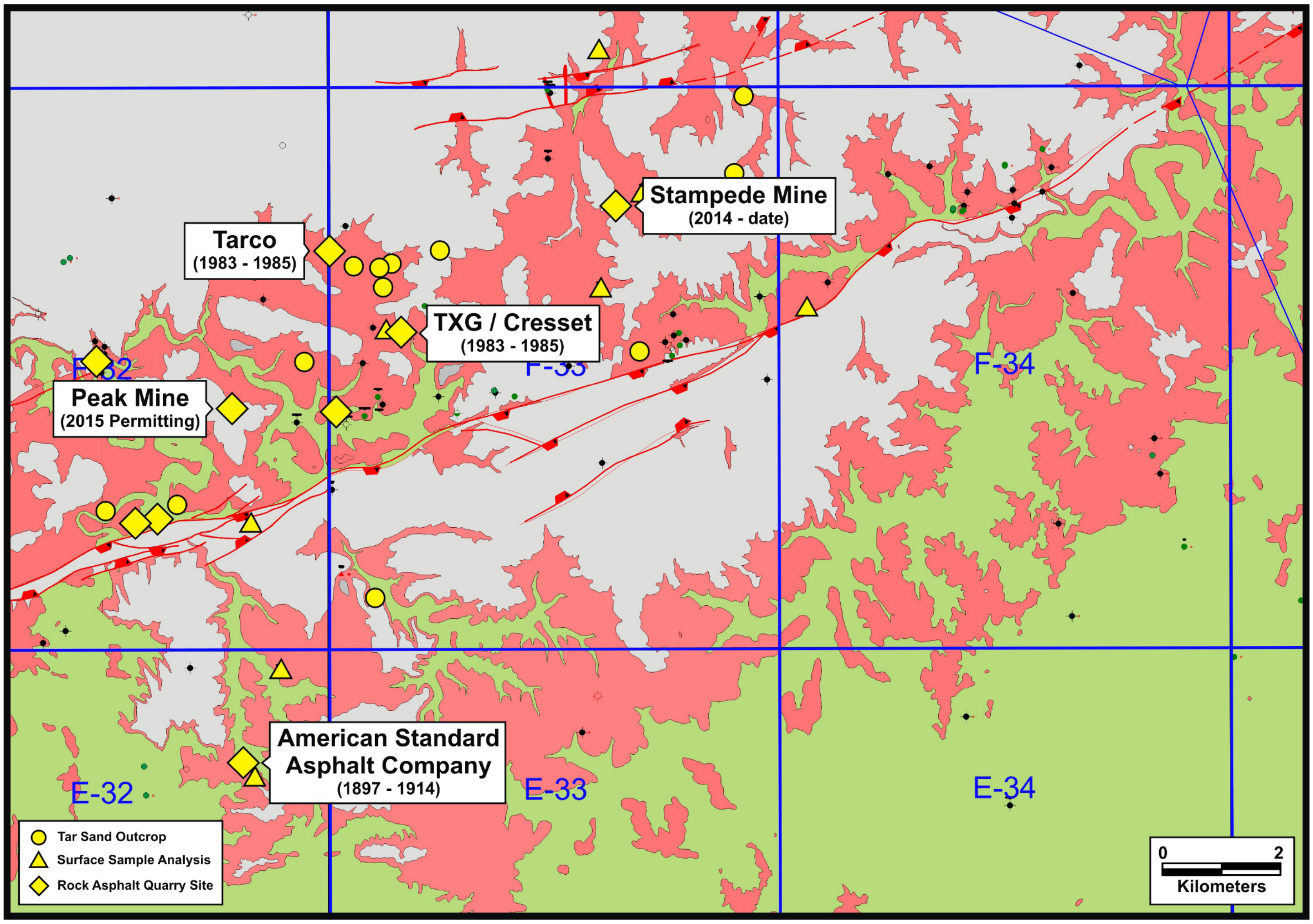

Figure 14. Bitumen-extraction projects in northern Logan County (Fig. 13, Table 6) were developed on the upthrown block of a northeast-trending fault system where potential for resources was suggested by outcrops of rock asphalt. Historical rock-asphalt production was less well indicated, although also on an outcrop of Big Clifty rock asphalt, in the downthrown fault block. Overburden is colored pink, the Big Clifty is colored red, and underburden is colored green.

cover bitumen from surface deposits of Big Clifty tar sands in northern Logan County (Bartlett, 2014; Archer Petroleum Corp., 2015) (Fig. 14). Both projects will use SandKlene 950, a proprietary, nonthermal mechanical and chemical process using a nontoxic water-based solvent, to extract bitumen from the crushed Big Clifty ore (Bartlett, 2014; Archer Petroleum Corp., 2015) (Table 6). A pilot plant operated at the Stampede Mine near Costelow has demonstrated that the process can recover 100 percent of the heavy oil and bitumen from the crushed ore (Bartlett, 2014), but results of this project are inconclusive. Archer Petroleum Corp. is permitting a bitumen-recovery project at a mine in Logan County approximately 1.5 km southwest of Homer (Archer Petroleum Corp., 2015) (Table 6); however, the progress of this project is unknown.

Conclusions

1. This evaluation of western Kentucky's tar-sand resources is the first large-scale study of the surface and subsurface distribution and heavy-oil and bitumen resources in the Big Clifty and Hardinsburg Sandstones and Caseyville Formation. The unrisked resources in the western Kentucky tar sands are conservatively estimated to total 3,346 million barrels of heavy oil and bitumen in place (Table 7), about 10 percent more than previous estimates: 2,247 million barrels of oil in place in the Big Clifty, 357 million barrels of oil in place in the Hardinsburg, and 742 million barrels of oil in place in the Caseyville.
2. Measurement of porosity in samples before and after fluid extraction allowed calculation

of the volume of approximately 6° API gravity immobile, pore-lining bitumen and 10° API gravity mobile heavy oil in tar-sand reservoirs. Median immobile pore-lining bitumen saturation in all tar-sand zones is 17.1 percent, and median mobile oil saturation is 15.1 percent, about 47 percent of the total oil in place (Table 2). The immobile pore-lining bitumen reduced permeability and porosity (Fig. 9D) and has caused the tar-sand reservoirs to be oil-wet (Fig. 9C), thus limiting the potentially producible oil in the pore space.

3. The apparent discrepancy in total fluid saturations measured in tar-sand cores, in which oil plus water saturations do not sum to 1, is because the reservoirs are not in capillary equilibrium and undersaturated in water. Uplift and erosion of the tar-sand reservoirs caused water volume shrinkage in the reservoirs as temperature reduced, while decreasing rock density as pressure was reduced caused the pore space to expand and decreased water saturation. That is, the absolute volume of fluids in the tar-sand reservoirs, oil plus water, was unchanged but the reservoir pore space increased. The pore volume that had been occupied by water was filled with low-pressure methane that evolved from the pore water. Thus, median gas saturation of the tar sands ranges from 20.8 percent in the Hardinsburg to 53.5 percent in the Caseyville (Table 2). Pressure release during core recovery releases the gas and causes oil to bleed from the cores; however, because the relative permeability to gas is much higher than that to heavy oil, the amount of oil lost as gas escapes from cores is minor.

Table 7. Enhanced-oil-recovery pilot projects in the tar sands were largely technical successes; however, none led to commercial production. Locations are from the KGS Oil and Gas Records Database.

Operator	*Year*	*Reservoir*	*County*	*Carter Coordinate Location*	*Enhanced Oil Recovery Method*	*Enhanced Oil Recovery Pattern*		*Recovery*		*Oil Gravity (° API)*	*Source*
						Area (ha)	*Oil in Place (BO)*	*(BO)*	*(% BO)*		
Gulf Oil Co.	1959	Caseyville	Edmonson	10-J-39	in situ combustion[1]	0.11	5,700	3,100	54	14.5°	Terwilliger (1976)
Sunset Petroleum	1969	Big Clifty	Warren	5-H-38	wet in situ combustion[2]	0.51	27,050	na	> 50	11–12°	May (2013); this study
Reading and Bates	1981	Big Clifty	Butler	25-I-36	CO_2-enhanced steamflood[3]			project was never installed			
Westken Petroleum	1981	Big Clifty	Edmonson	15-I-39	wet in situ combustion[3]	0.40	21,650	6,005	28[+]	10°	Ward and Ward (1984); this study
MegaWest Energy	2007	Big Clifty	Warren	25-I-36	four-pattern steamflood pilot[3]	0.41	15,000	project was never installed			this study
Green Castle Petroleum	2015	Big Clifty	Butler	1-G-33	not released[3]	1.32	19,500	project installation is pending			this study

[1] Inverted five-spot pattern configuration
[2] Inverted nine-spot pattern configuration
[3] Inverted seven-spot pattern configuration
*Produced oil gravity, 10.4° API gravity in situ
[+] 22.5% per Ward and Ward (1984)

4. The origin of the heavy oil and bitumen in the western Kentucky tar sands is likely because of microbial degradation. Bacteria were introduced to the reservoirs at the time of Caseyville deposition, sequestered by subsequent burial and existing in a dormant state. When hydrocarbons migrated into the reservoirs, they began metabolizing the sulfur and hydrocarbons, as well as iron reduced from primary liesegang bands, at the diagenetic interface with the migrating oil. Sequestered hydrogen-utilizing bacteria would have preferentially degraded aromatic hydrocarbons in crude oil. What remains is heavily biodegraded, low–API gravity bitumen.
5. The only commercial process for developing Kentucky's tar-sand resources was mining rock asphalt for road surfacing. No subsequent bitumen extraction or enhanced-oil-recovery process to date has successfully demonstrated commercial development of the western Kentucky tar sands.

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Disclaimer

This evaluation was completed using data and information (herein collectively referred to as the data) in the possession of the Kentucky Geological Survey, some of which may be nonpublic data. The public data are available from the Kentucky Geological Survey Oil and Gas Records Database (kgs.uky.edu/kgsweb/DataSearching/OilGas/OGSearch.asp).

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