Heavy-Oil and Bitumen Resources of the Big Clifty Sandstone, Northeastern Grayson County and Adjacent Hardin County, Kentucky

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Abstract

Rock asphalt (bitumen-saturated sandstone) was produced from the Big Clifty Sandstone near Tar Hill and Big Clifty in northeastern Grayson County, and at Summit in adjacent Hardin County, from 1889 to 1940. Noncommercial amounts of oil were distilled from Big Clifty rock asphalt before 1930. Resource assessments conducted throughout the area during the mid-1920's described substantial rock-asphalt deposits. Later assessments in 1951, 1965, and the early 1980's, however, overlooked the northeastern Grayson County area. A new evaluation in 2015 estimated that the historically developed area between Clifty Creek and Meeting Creek, and between the Summit Fault and Eveleigh Fault Zone, contained 200.3 million barrels of heavy oil and bitumen in place in the Big Clifty Sandstone. This study estimates an additional 29.6 million barrels of heavy oil and bitumen in place in less than 9,600 ha of the Big Clifty southwest of Clifty Creek, or about 7,600 barrels per hectare.

The rock-asphalt industry in the northeastern Grayson County area left substantial surface damage that is still visible, especially at Summit, more than 70 yr later. Although leaching of hydrocarbons from rock-asphalt mine-spoil piles is a reasonable environmental concern, tests have shown no leaching of hydrocarbons using a synthetic rainwater at a pH above 3.5; natural rainwater has a pH of about 5.5.

Introduction

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, 2A). They occur in a belt of surface outcrops extending from southern Hardin and eastern Breckinridge Counties on the north to Logan County on the south, encompassing 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, 2016, in press). These resources are hosted in Upper Mississippian to Lower Pennsylvanian (Serpukhovian to Bashkirian; Chesterian North American Stage) (Swezey, 2009) Big Clifty Sandstone (Cypress Sandstone of Jillson, 1927), Hardinsburg Sandstone (Fig. 2B), and the Kyrock and Bee Springs Sandstone Members of the Early Pennsylvanian Caseyville Formation (McGrain, 1976; Williams and others, 1982; Noger, 1984, 1987). Rock asphalt in the Big Clifty is exposed in outcrops on the north and south flanks of the Rough Creek Graben and Western Kentucky Coal Field (Figs. 1, 2A), and commercially developed in northeastern Grayson County and adjacent Hardin County in northern Carter coordinate quadrangles[1] M-40 and M-41 from 1889 to 1946 (Fig. 3, Table 1). These quadrangles were not, however, the only known rock-asphalt deposits in the region, and additional prospecting conducted during the 1920's defined a rock-asphalt resource area of about 110 km^2 (Fig. 4, Tables 2–3).

[1]For an explanation of the Carter coordinate system, see www.uky.edu/KGS/emsweb/kyogfaq/kyogfaq9.html.

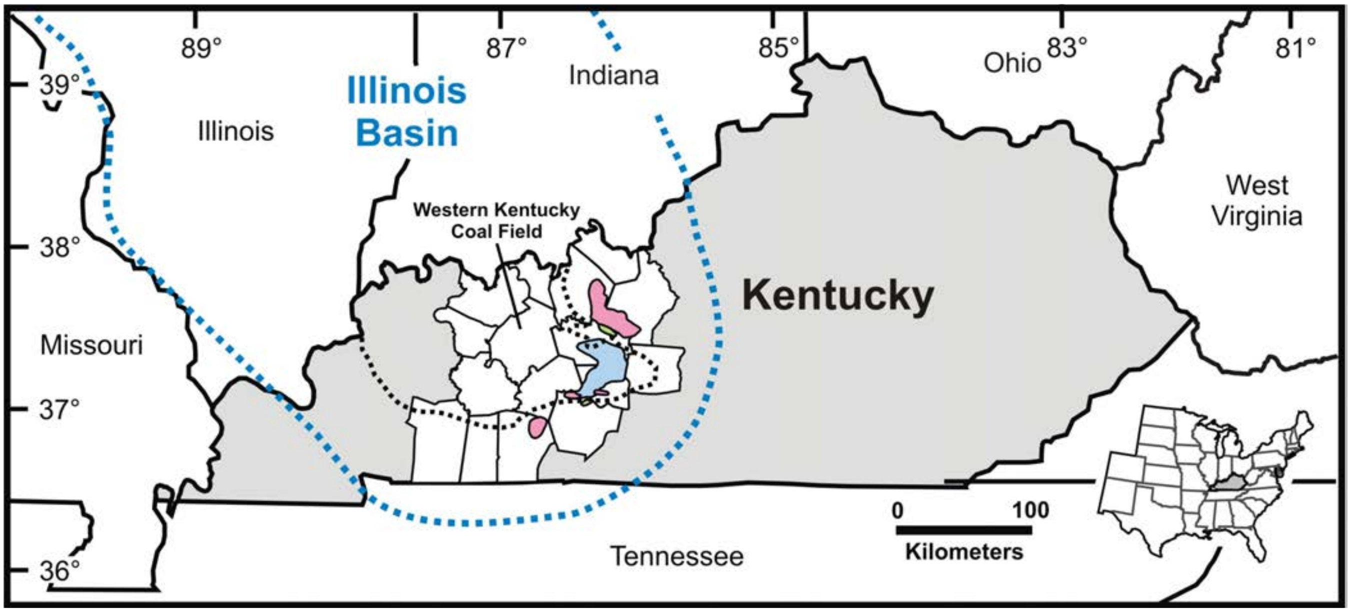

Figure 1. Location of the western Kentucky tar-sand belt in the southern Illinois Basin (dashed blue line) and Western Kentucky Coal Field (from Bowersox, in press). Tar sands are hosted in the Upper Mississippian (Chesterian) Big Clifty Sandstone (red), Hardinsburg Sandstone (green), and Lower Pennsylvanian Caseyville Formation (blue) on the margins of the Western Kentucky Coal Field (dashed line). The margin of the coal field approximates the Big Clifty outcrop belt.

Previous Work

The first commercial development of western Kentucky's bituminous sandstone deposits, tar sands, or rock asphalt began in the late 19th century and continued, somewhat sporadically, until the mid-20th century (Bowersox, 2016). Orton (1891) described the Big Clifty section on the Whitfield farm in Grayson County. Jillson (1923, 1925) later sampled and analyzed the bitumen content, commenting on the irregular distribution of bitumen-saturated sand in its uppermost beds. The geology and rock-asphalt resources of the Big Clifty and quarries in northern Grayson County were described by Eldridge (1901). Eldridge (1901) described the stratigraphy of the Big Clifty in the idled Breyfogle Quarry in Flutter Creek Canyon, south of Tar Hill, commenting on the irregular distribution of bitumen, cross-cutting crossbedded intervals and lacking continuity within a layer. Nevertheless, the productive interval in the quarry was about 3 m thick, the richest 1.5 to 2 m containing an estimated 7 weight-percent bitumen and seeping heavy oil (Eldridge, 1901). Jillson (1924) discussed development of the Big Clifty rock-asphalt deposits in Grayson and Hardin Counties, providing analyses of bitumen content in samples from quarries, although without disclosing where these samples were collected. Richardson (1924) discussed rock-asphalt mining in Grayson and Hardin Counties, providing details of thicknesses of the rock-asphalt deposits being mined by Continental Rock Asphalt Co. near Tar Hill and by Ohio Valley Rock Asphalt Co. at Summit. The earliest mapping of rock-asphalt deposits in the northern Grayson County area was by Jillson (1926a), where outcrops were identified along the creeks dissecting the area. Jillson (1923, 1925, 1926b, c) also conducted some of the earliest resource evaluations of rock-asphalt deposits in the area, including detailed descriptions of the deposits and their thicknesses, analysis of the bitumen content, and estimates of their commercial value.

Later resource evaluations were largely compilations of earlier reports of the Kentucky Geological Survey. Ball (1951, p. 6), in a regional survey of strippable tar-sand deposits in Kentucky, discounted the northern Grayson County deposits for lack of information demonstrating that they met minimum thickness and bitumen richness requirements of the study, "at least 10 million tons within 5 square miles in beds at least 15 feet thick under no more than their own thickness of over-

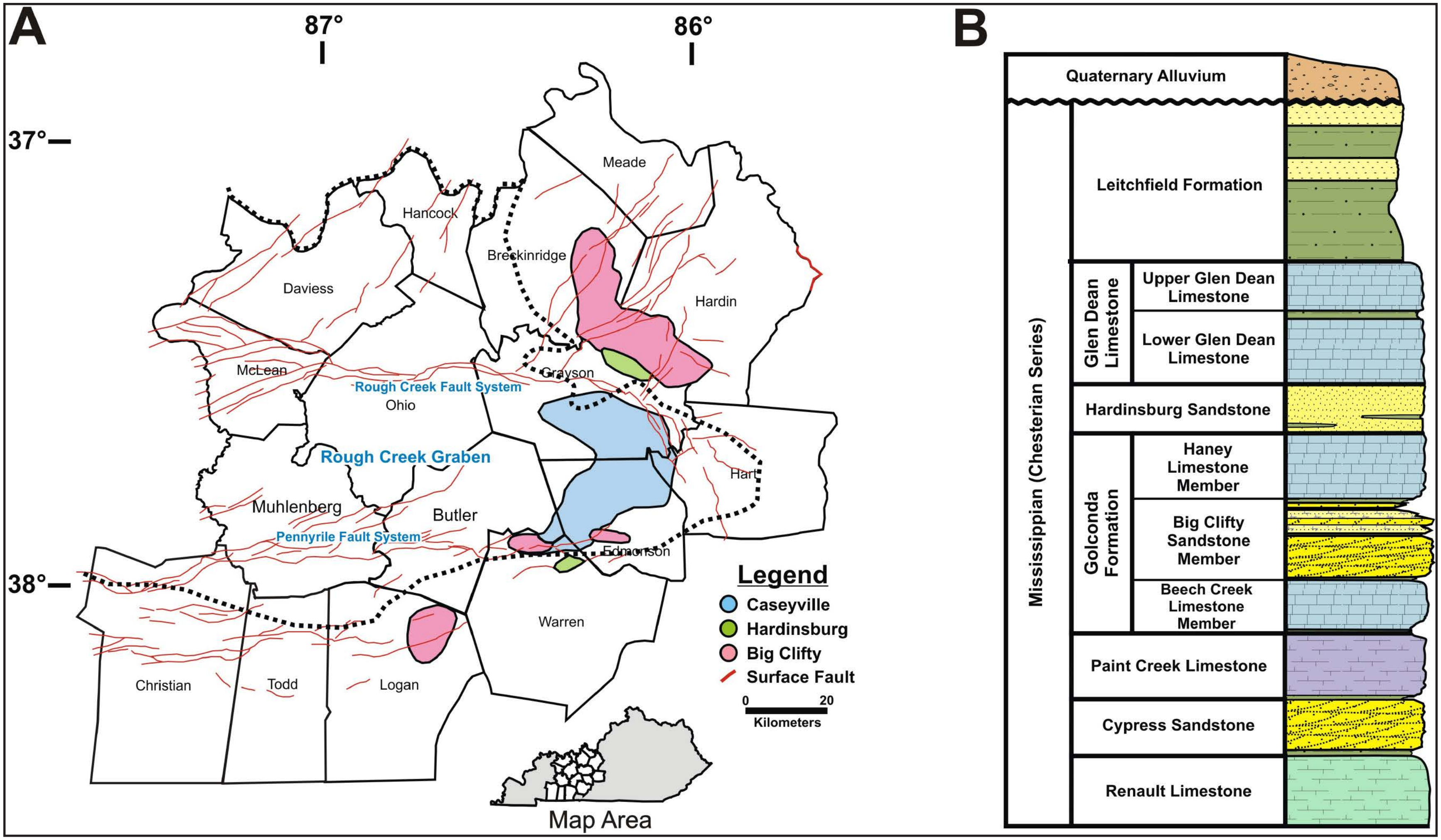

Figure 2. Generalized locations of tar sands in western Kentucky and stratigraphy of the northeastern Grayson County region. Boundary of the Western Kentucky Coal Field is shown by the dashed line. (A) The Big Clifty tar sands are present in outcrops flanking the Rough Creek Graben on the north and south (modified from Bowersox, in press). Commercial deposits were mined for rock-asphalt road topping in Breckinridge, Grayson, Hardin, and Logan Counties. A noncommercial deposit of tar sands hosted in the Hardinsburg Sandstone is located on the southern margin of the Big Clifty deposits in Grayson County. (B) Stratigraphy of the northeastern Grayson County area (modified from Swadley, 1962). The Big Clifty consists of interbedded sandstone and thin shales, and ranges from 18 to 34.5 m thick. Net commercial bitumen-saturated intervals in the Big Clifty range from about 1.5 to 7.6 m thick.

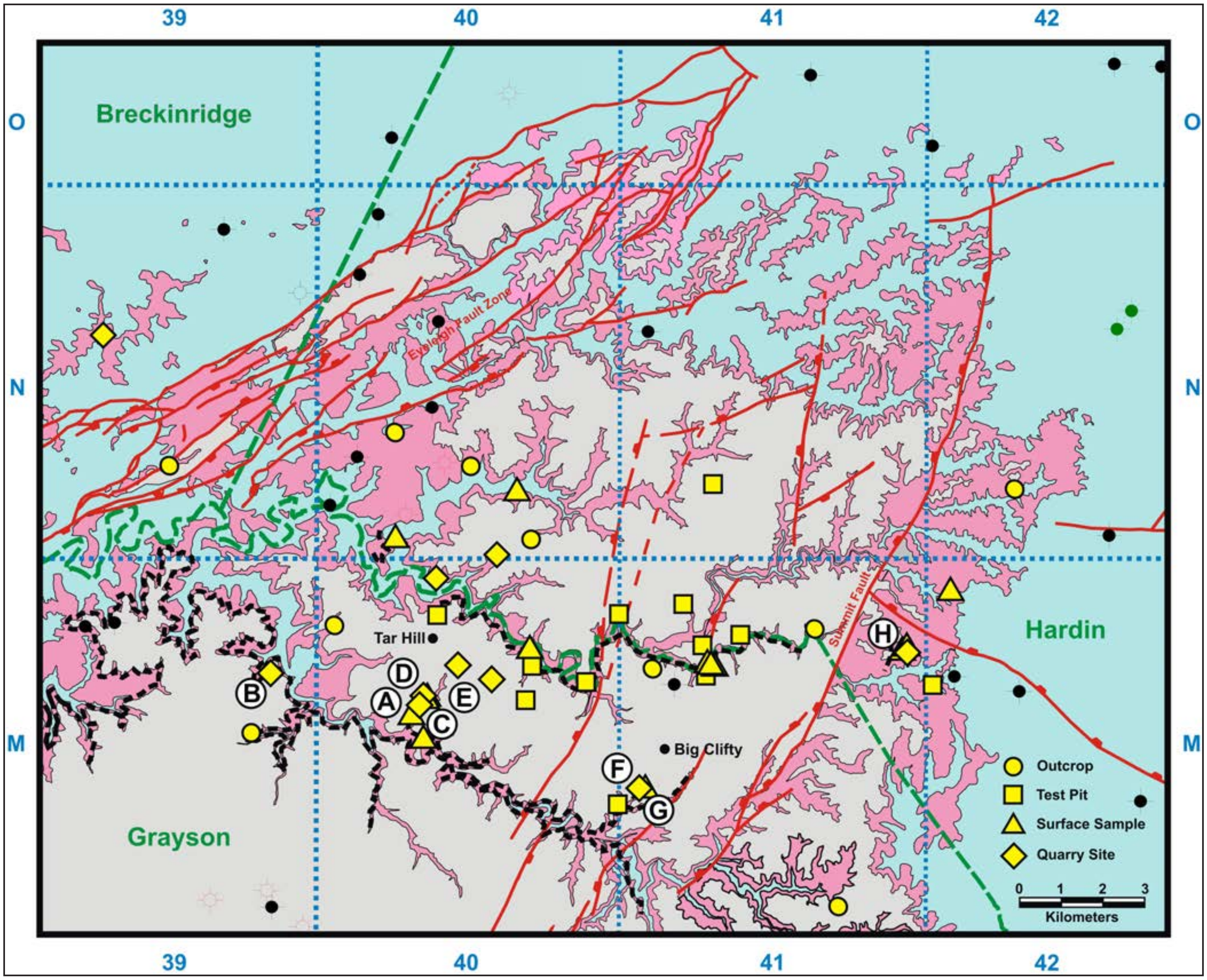

Figure 3. Generalized geology and locations of historical rock-asphalt quarries, rock-asphalt surface sample sites, prospect test pits, outcrops of rock asphalt, and locations of oil and gas wells in northeastern Grayson County and adjacent Hardin County. This map is used as a base in following figures. Geology is modified from Swadley (1962), Moore (1964), and Johnson (1978). Areas underlain by the Big Clifty Sandstone are shaded red, Haney Limestone and younger strata are in gray, and Beech Creek Limestone and older strata are in blue. The 5-minute Carter coordinate quadrangle grid for the region is shown by the blue dashed lines. The northern boundary between Grayson and Hardin Counties (heavy dashed green line) is Meeting Creek. Clifty Creek runs northwest from southern Carter coordinate quadrangle M-41 to northeast quadrangle M-39 where it joins Meeting Creek. Outcrops of tar sands in the Big Clifty mapped by Jillson (1926a) are shown by the dashed heavy black lines. Quarry locations are from descriptions in Eldridge (1901) and maps by Jillson (1923, 1925, 1926a–c), Swadley (1962), Moore (1964), and Johnson (1978). Details of quarry locations and elevations, and the thickness of rock asphalt mined in the quarries and its bitumen content are in Table 1.

burden and averaging not less than 10 gallons of oil per ton." Ball and Associates (1965), as part of a national evaluation of oil sands and shallow oil reserves in the United States, evaluated the northeastern Grayson County tar-sand deposits. Deposits were classified as reserve, known potential, occurrence, or inadequate information (Ball and Associates, 1965, p. 12):

> As used in this report a reserve is any deposit big enough, accessible enough, and well enough known to appear to be potentially valuable as a commercial rock asphalt or bitumen source under present or foreseeable local conditions in the opinion of the compiling author.

Table 1. Locations of historical rock-asphalt quarries in northwestern Grayson County and adjacent Hardin County (Eldridge, 1901; Jillson, 1923, 1925, 1926a–c, Swadley, 1962; Moore, 1964; Johnson, 1978; Bowersox, in press). Descriptive and mapped locations and elevations were verified from satellite photography served by Google Earth and 5-ft LiDAR imagery served by the Kentucky Geological Survey's Geologic Map Information Service (kgs.uky.edu/kgsmap/kgsgeoserver/viewer.asp). All locations should be considered approximate. Rock-asphalt-deposit thicknesses and bitumen content in weight-percent are from Eldridge (1901), Richardson (1924), Jillson (1928), and Ball and Associates (1965). Conversion of weight-percent bitumen to bulk volume of oil in place (Soϕ) is discussed in Bowersox (in press).

Location	*Operator*	*Production*		*County*	*Geologic Quadrangle Map*	*Location*		*Elevation (m)*	*Height (m)*	*Bitumen (wt-%)*	*Soϕ (calculated)*
		Opened	*Closed*			*Latitude*	*Longitude*				
A	American Bituminous Rock Co.	1889	1895	Grayson	Big Clifty	37.550842	–86.222875	169	3.0	7.00	0.067
B	Schillinger Brothers, Prospect 1	1892	1892	Grayson	Madrid	37.558395	–86.262447	189	2.4	5.50	0.053
C	Federal Rock Asphalt Co.	1901	1904	Grayson	Big Clifty	37.550547	–86.222598	168	3.0	9.50	0.092
D	United Rock Asphalt Co.	1927	1930	Grayson	Big Clifty	37.552613	–86.219502	175	3.0	9.17	0.088
E	Continental Rock Asphalt Co.	1923	1924	Grayson	Big Clifty	37.557198	–86.205880	217	3.2	8.29	0.080
F	Crown Rock Asphalt Co.	1925	1940	Grayson	Big Clifty	37.533061	–86.161207	205	1.8	6.50	0.063
G	Ohio Valley Rock Asphalt Co.	1922	1946	Hardin	Summit	37.563078	–86.087860	252	1.8	7.50	0.072

Ball and Associates evaluated northern Grayson County in five resource areas, based on descriptions in the literature, giving thicknesses of the deposits and weight-percent bitumen content where available. These deposits were then classified as either occurrences without other information available (two deposits), minor occurrences (two deposits, both with historical commercial production), and possibly commercial (one deposit at Big Clifty with historical commercial rock-asphalt production) (Ball and Associates, 1965). McGrain (1976) summarized the prior reports of Ball (1951) and Ball and Associates (1965) and provided routine core-analysis data from surface samples collected in Grayson County. McGrain (1979) summarized the geology of the western Kentucky tar sands, noting that significant deposits of rock asphalt in the Big Clifty were present in parts of Grayson and Hardin Counties.

Regional reevaluations of western Kentucky tar-sand resources were conducted in the 1980's in association with a national effort to assess the U.S. heavy-oil and bitumen resources (Lewin and Associates Inc., 1984a, b). Using the methodology outlined in Lewin and Associates Inc. (1982), Lewin and Associates Inc. (1984b) evaluated the heavy-oil and bitumen resources in the Kentucky tar sands, reporting measured resources of 1,190 million barrels of oil and speculative resources of 910 million barrels of oil in the Big Clifty. Omitted from this evaluation, however, were the Big Clifty rock-asphalt deposits in the northeastern Grayson County area and its estimated 200 million barrels of heavy oil and bitumen (Bowersox, in press). Noger (1984, 1987), in a review conducted by the Kentucky Geological Survey, slightly revised the western Kentucky tar-sand evaluation of Lewin and Associates Inc. (1984b), although accepting the prior estimate of Big Clifty heavy oil and bitumen resources.

The regional heavy oil and bitumen resources of the western Kentucky tar sands were reevaluated by Bowersox (in press). Although the Big Clifty resources in northeastern Grayson and adjacent Hardin Counties were included, evaluation of the area was presented only in summary without specific discussion of the deposits. Thus, the purpose of the present report is to supplement Bowersox (in press), providing the data and geologic details defining the heavy-oil and bitumen resources

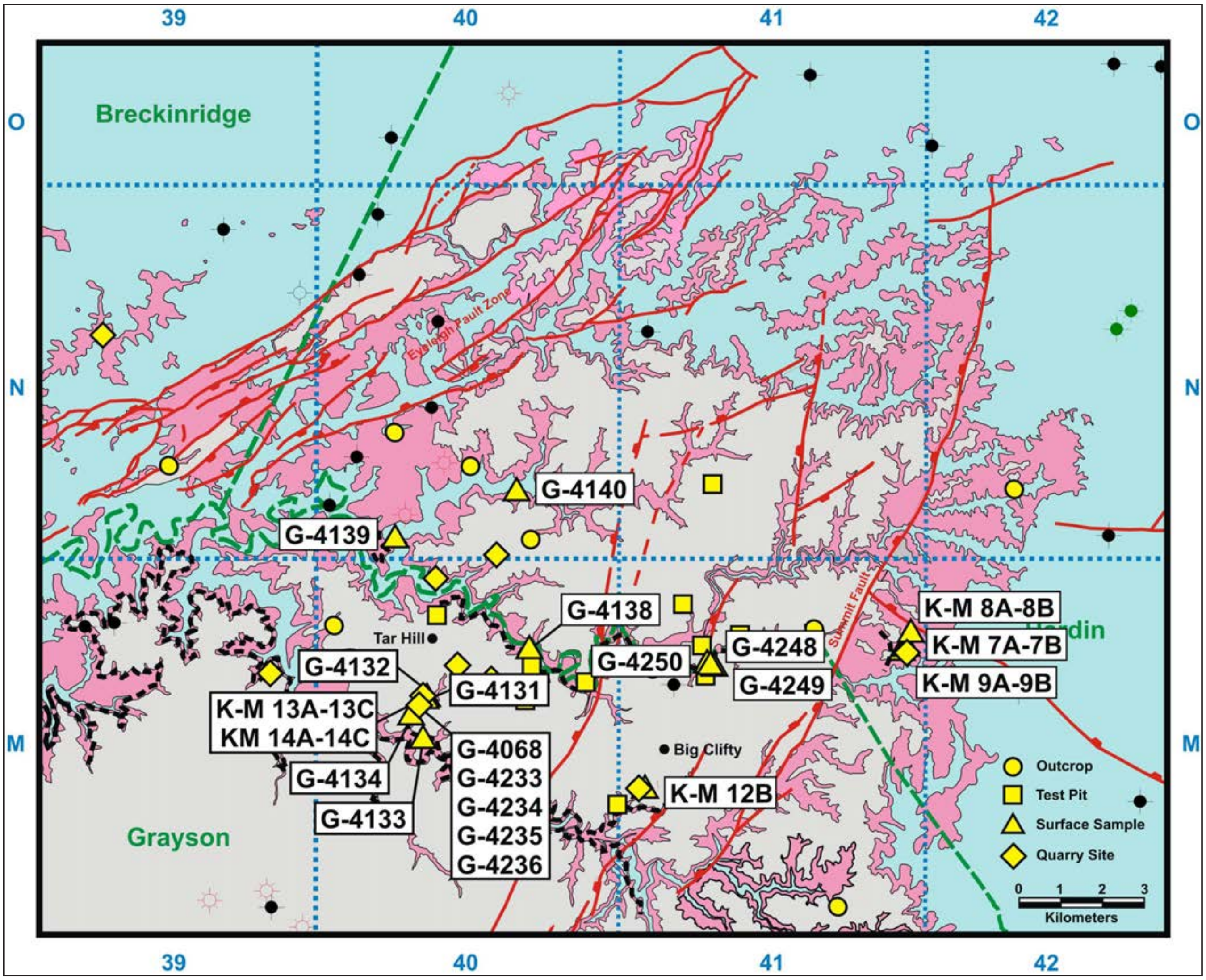

Figure 4. Location of surface samples with bitumen-content analysis. Details of locations and elevations, rock-asphalt thickness at the sample sites, and bitumen content are in Table 2. Samples labeled with a G were analyzed by the Kentucky State Chemical Laboratories (Jillson, 1923, 1925, 1926b, c) (Table 2), and samples labeled K–M were collected by Kerr-McGee Oil Industries Inc., March 15–18, 1963 (Table 3). Most samples are from the historical quarry sites in Flutter Creek Canyon. No samples were collected south of Clifty Creek in Carter coordinate quadrangles M-39 to M-41, despite the extensive exposure along the creek mapped by Jillson (1926a), likely because of the poor accessibility, steep creek bank along Clifty Creek, and limited exposures farther south in Grayson County.

in the area. This study discusses the potential for additional rock-asphalt resources in northeastern Grayson County and gives a conservative estimate of their volume pending new industry activity and acquisition of additional data on the extent and richness of these deposits.

Geology

Surface geology in the study area was mapped at a scale of 1:24,000 by Swadley (1962), Moore (1964), and Johnson (1978). Only a limited set of subsurface data is available for the area, however. Records are available from 29 wells drilled in the area (Fig. 5). Of these wells, 25 were drilled on or outside of the Big Clifty outcrops and provide no additional data. Only two of the wells drilled through the Big Clifty in Carter coordinate quadrangle M-39 have geophysical electric logs of the interval. A southwest-plunging asymmetrical syncline is developed between the Eveleigh Fault Zone on the northwestern flank and the Summit Fault on the southeastern flank (Fig. 6A). Strata in the

Table 2. Locations of surface samples of rock asphalt in northwestern Grayson County, with the thickness of the bitumen-saturated section at the sample sites and bitumen content analyses (Jillson, 1923, 1925, 1926a–c). Descriptive and mapped locations and elevations were verified as described in Table 1. Soϕ was calculated from weight-percent bitumen content as described in Bowersox (in press).

Sample	*County*	*Geologic Quadrangle Map*	*Latitude*	*Longitude*	*Elevation (m)*	*Height (m)*	*Bitumen (wt-%)*	*Soϕ (calculated)*
G-4068	Grayson	Big Clifty	37.563078	–86.087860	252	1.8	7.50	0.072
G-4131	Grayson	Big Clifty	37.552705	–86.219182	176	1.8	9.17	0.089
G-4132	Grayson	Big Clifty	37.552561	–86.219587	176	1.8	8.28	0.080
G-4133	Grayson	Big Clifty	37.548439	–86.223619	176	3.0	8.68	0.084
G-4134	Grayson	Big Clifty	37.548775	–86.223676	176	3.0	6.83	0.066
G-4138	Grayson	Big Clifty	37.563423	–86.191273	178	2.3	5.70	0.055
G-4233	Grayson	Big Clifty	37.550656	–86.222483	168	2.3	7.20	0.070
G-4234	Grayson	Big Clifty	37.550656	–86.222483	168	2.3	7.30	0.071
G-4235	Grayson	Big Clifty	37.550656	–86.222483	168	2.3	9.00	0.087
G-4236	Grayson	Big Clifty	37.550656	–86.222483	168	2.3	7.80	0.076
G-4248	Grayson	Big Clifty	37.559666	–86.140329	202	7.6	6.80	0.066
G-4249	Grayson	Big Clifty	37.560351	–86.142067	191	6.1	5.40	0.052
G-4250	Grayson	Big Clifty	37.560351	–86.142067	191	6.1	5.10	0.050
G-4139	Hardin	Big Clifty	37.588203	–86.228211	175	2.7	9.92	0.096
G-4140	Hardin	Big Clifty	37.598392	–86.195006	181	1.8	9.92	0.096
					Average	3.2	7.64	0.074

syncline are cut by near-vertical northeast-trending normal faults with hanging walls generally down to the northwest, and a complex of northeast-trending horsts and grabens inside the Eveleigh Fault Zone (Fig. 6A, B). The Big Clifty is exposed west of the Locust Hill Fault, bounding the Eveleigh Fault Zone on the northwest, inside the Eveleigh Fault Zone, on the synclinal flanks, and southeast of the Summit Fault (Fig. 6A). Inside the syncline, the Big Clifty is exposed in valleys eroded by creeks (Fig. 6A, B). In the northeastern Grayson County area, thin shales at the base of the Big Clifty unconformably overlie the Beech Creek Limestone and, in turn, thin shales at the top of the Big Clifty section are unconformably overlain by the Haney Limestone (Swadley, 1962) (Figs. 2B, 6B). The Big Clifty is composed of fine- to medium-grained, silica-cemented quartzarenite (Fig. 7) with interbedded thin shales (Swadley, 1962) (Fig. 2B). The Big Clifty is thick-bedded, commonly crossbedded, and ranges from 18 to 33.5 m thick (Swadley, 1962) (Fig. 6B, 8). The Big Clifty is interpreted to have been deposited in rivers and river-mouth intertidal bars (see the discussion in Bowersox, in press).

Reservoir Properties

Rock and reservoir properties of the Big Clifty tar sand in the northeastern Grayson County (Fig. 9) region were determined from analysis of surface samples of bituminous sandstones. Analysis of samples taken during the 1920's (Jillson, 1923, 1925, 1926b, c) measured weight-percent bitumen content (Table 2). The process for measuring weight-percent bitumen in rock-asphalt samples by ignition is described in Crump (1913) and by solvent in Jillson (1923). Laboratory analysis of samples collected in 1963 by Kerr-McGee (Table 3) measured permeability (k, in millidarcys) and porosity (φ, in percent) before and after bitumen extraction, then measured bitumen content (as oil saturation, So, as a percentage of the pore space) and water saturation (Sw, as a percentage of the pore space). Bulk volume of hydrocarbon, bitumen, and heavy oil in rock-asphalt samples (Soφ; e.g., So × φ) (Table 2) and weight-percent bitumen (B_w) content in the samples in which So and φ were measured (Table 3) can be calculated as discussed in Bowersox (in press). One aspect of reservoir properties of the western Kentucky tar sands

Table 3. Locations and analyses of rock-asphalt samples collected by Kerr-McGee in 1963 (McGrain, 1976) in northwestern Grayson County and adjacent Hardin County. Samples were analyzed by Core Laboratories Inc., Oklahoma City, Okla. Kerr-McGee limited its sampling to abandoned rock-asphalt mine sites (Figs. x3–4). Descriptive locations and elevations were verified as described in Table 1; however, all locations should be considered approximate. Weight-percent bitumen-oil was calculated from $So\phi$ as weight-percent bitumen-oil = $So\phi \times \rho_B \times 100$, where ρ_B is the density of 6° API gravity bitumen (1.03 g/cm^3) (Bowersox, in press).

Sample	*County*	*Geologic Quadrangle Map*	*Quarry*	*Latitude*	*Longitude*	*(m)*											
7A	Hardin	Summit	G	37.563873	−86.088046	256	8.3	21.6	2,193	28.2	13.1	4.0	17.1	80.6	2.3	19.4	0.048	5.0
7B	Hardin	Summit	G	37.563873	−86.088046	256	1.3	21.5	985	25.1	52.9	8.9	61.8	38.2	0.0	61.8	0.155	16.0
					Average Analysis		**4.8**	**21.6**	**1,589**	**26.7**	**31.9**	**7.5**	**39.5**	**59.4**	**1.2**	**40.6**	**0.105**	**10.5**
8A	Hardin	Summit	G	37.566977	−86.080575	259	770	25.1	1,368	28.1	13.6	1.6	15.2	77.2	7.6	22.8	0.043	4.4
8B	Hardin	Summit	G	37.566977	−86.080575	259	8.7	25.6	na	na	na	na	46.2		4.7	50.9	na	na
					Average Analysis		**389.4**	**25.4**	**1,368**	**28.1**	**13.6**	**1.6**	**15.2**	**77.2**	**7.6**	**22.8**	**0.043**	**4.4**
9A	Hardin	Summit	G	37.563166	−86.089111	255	1.5	24.1	175	27.1	43.1	5.4	48.5	48.6	2.9	51.4	0.131	13.5
9B	Hardin	Summit	G	37.563166	−86.089111	255	21	21.0	2,280	28.4	39.5	13.9	53.4	42.3	4.3	57.7	0.152	15.6
					Average Analysis		**11.3**	**22.6**	**1,228**	**27.8**	**41.4**	**9.5**	**51.0**	**45.5**	**3.6**	**54.6**	**0.142**	**14.6**
12B	Grayson	Big Clifty	F	37.532755	−86.160494	198	18	16.9	697	20.7	32.3	7.3	39.6	58.1	2.3	41.9	0.082	8.4
13A	Grayson	Big Clifty	D	37.552725	−86.219422	172	2.5	15.1	446	21.7	35.0	15.3	50.3	47.8	1.9	52.2	0.109	11.2
13B	Grayson	Big Clifty	D	37.552725	−86.219422	172	0.8	16.3	1,241	21.4	45.3	14.2	59.5	40.5	0.0	59.5	0.127	13.1
13C	Grayson	Big Clifty	D	37.552725	−86.219422	172	<0.1	19.5	303	20.1	75.7	2.3	78.0	22.0	0.0	78.0	0.157	16.1
					Average Analysis		**1.7**	**17.0**	**663**	**21.1**	**50.4**	**12.2**	**62.6**	**36.8**	**0.6**	**63.2**	**0.132**	**13.5**
14A	Grayson	Big Clifty	D	37.552701	−86.219480	172	71	19.2	83	20.5	16.6	1.1	17.7	80.3	2.0	19.7	0.036	3.7
14B	Grayson	Big Clifty	D	37.552701	−86.219480	172	0.6	22.7	1,112	25.0	53.9	5.5	59.4	40.6	0.0	59.4	0.149	15.3
14C	Grayson	Big Clifty	D	37.552701	−86.219480	172	16	18.5	386	20.5	28.2	3.1	31.3	66.0	2.7	34.0	0.064	6.6
					Average Analysis		**29.2**	**20.1**	**527**	**22.0**	**33.1**	**3.1**	**36.1**	**62.3**	**1.6**	**37.7**	**0.079**	**8.5**

that appears to be problematic is that total fluid saturations, which is the amount of oil plus water in the pore space (Tf), do not add up to 1 (Table 3). This is because the nonfluid-filled porosity is filled with air at the surface and low-pressure methane in the subsurface (Bowersox, in press). Weight-percent bitumen in all samples, measured and calculated (Tables 2–3), ranges from 4.4 to 16.1 percent. Average total porosity measured in samples from the Big Clifty ranges from 20.7 to 28.1 percent and total oil saturation ranges from 15.2 to 62.6 percent. The calculated heavy-oil fraction of the total oil saturation (see the discussion in Bowersox, in press) is small, ranging from 1.6 to 12.2 percent. Bulk volume of oil in all 25 samples ranges from 0.043 to 0.157 (Tables 2–3) and averages 0.076 (Bowersox, in press, Table 4a).

Compartmentalization of the Big Clifty reservoir by precipitation of calcite has long been noted in outcrops and cores (Orton, 1891; see also the photographs in Jillson, 1924; McGrain, 1976, 1979; May, 2013). Secondary pore-filling calcite, observed in cores from the Big Clifty has caused irregular distribution of oil in these reservoirs. Butler (2013) and May and Butler (2014a, b) documented

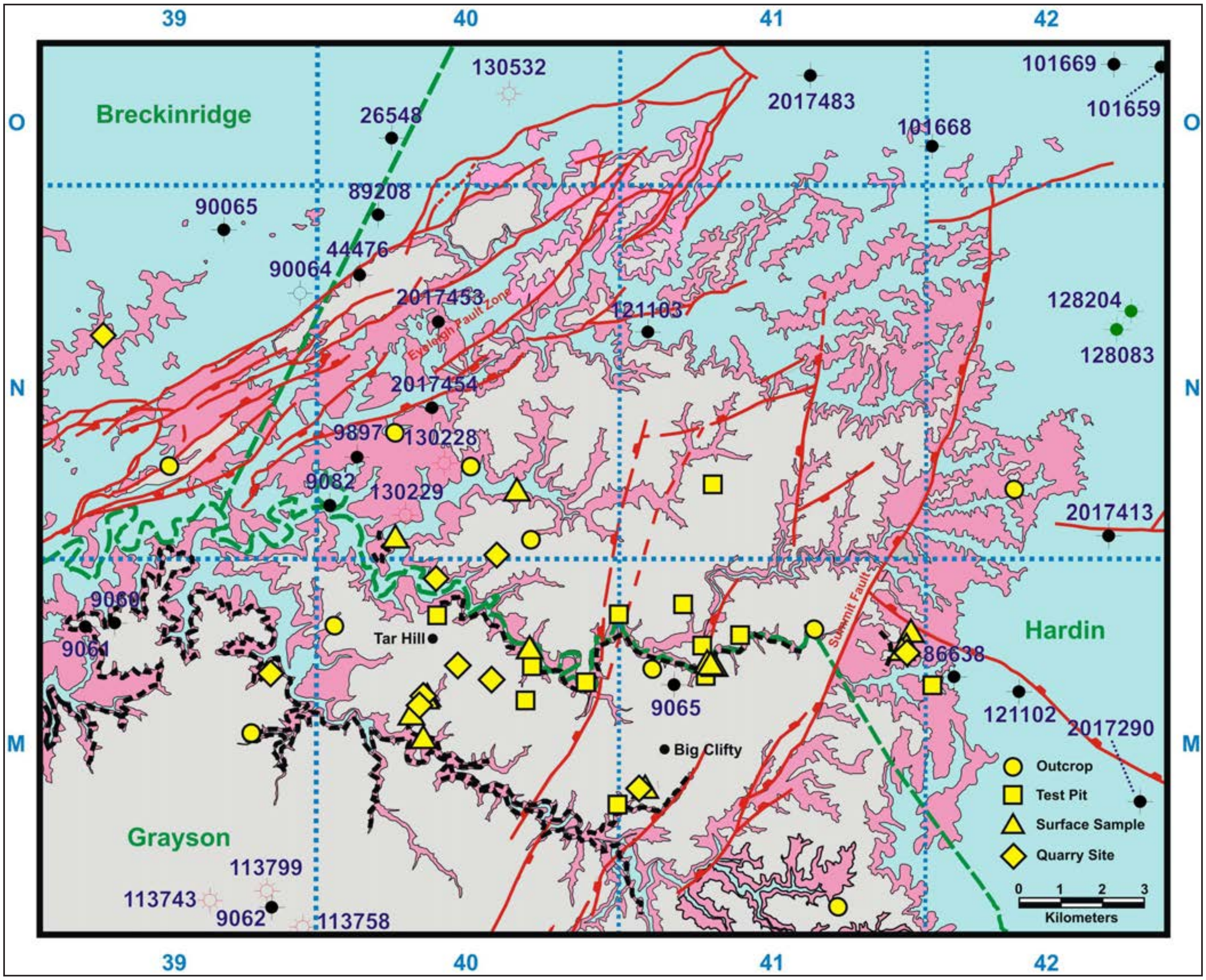

Figure 5. Index of oil and gas wells drilled in the study area. KGS record number noted in purple. Of 30 wells drilled in the study area, four in southeast Carter coordinate quadrangle M-39 drilled through a complete section of the Big Clifty inside of its outcrop area, although logs of the interval were available for only two of these (Fig. 6).

compartmentalization of the Big Clifty reservoir from possible redox reactions precipitating calcite and pyrite, replacing quartz framework grains and primary quartz cement, to form intraformational seals. May and Butler (2014a) speculated on whether these diagenetic minerals precipitated from water migrating from the deeper basin or from post-exposure meteoric water. This diagenetic mineral suite, however, is a product of hydrocarbon migration, discussed in Bowersox (in press), leading to a reducing geochemical environment in the reservoir rocks (Bowersox, in press, and sources cited therein). A consequence of hydrocarbon-induced diagenesis is the irregular distribution of oil in the reservoir rocks, as observed during the development of the western Kentucky tar-sand industry (Richardson, 1924; McGrain, 1976) and illustrated in historic photographs of mine and quarry walls (Jillson, 1924; Richardson, 1924) (Fig. 10A, B). Although the reducing geochemical environment has been preserved in the subsurface (Fig. 10C), uplift and exposure of the Big Clifty has moved it into a near-surface oxidizing meteoric environment close to the outcrop. Oxidizing conditions led to the development of an opal-CT, kaolinite, potassium feldspar, and plagioclase mineral suite. The lack of secondary calcite suggests dissolution in the

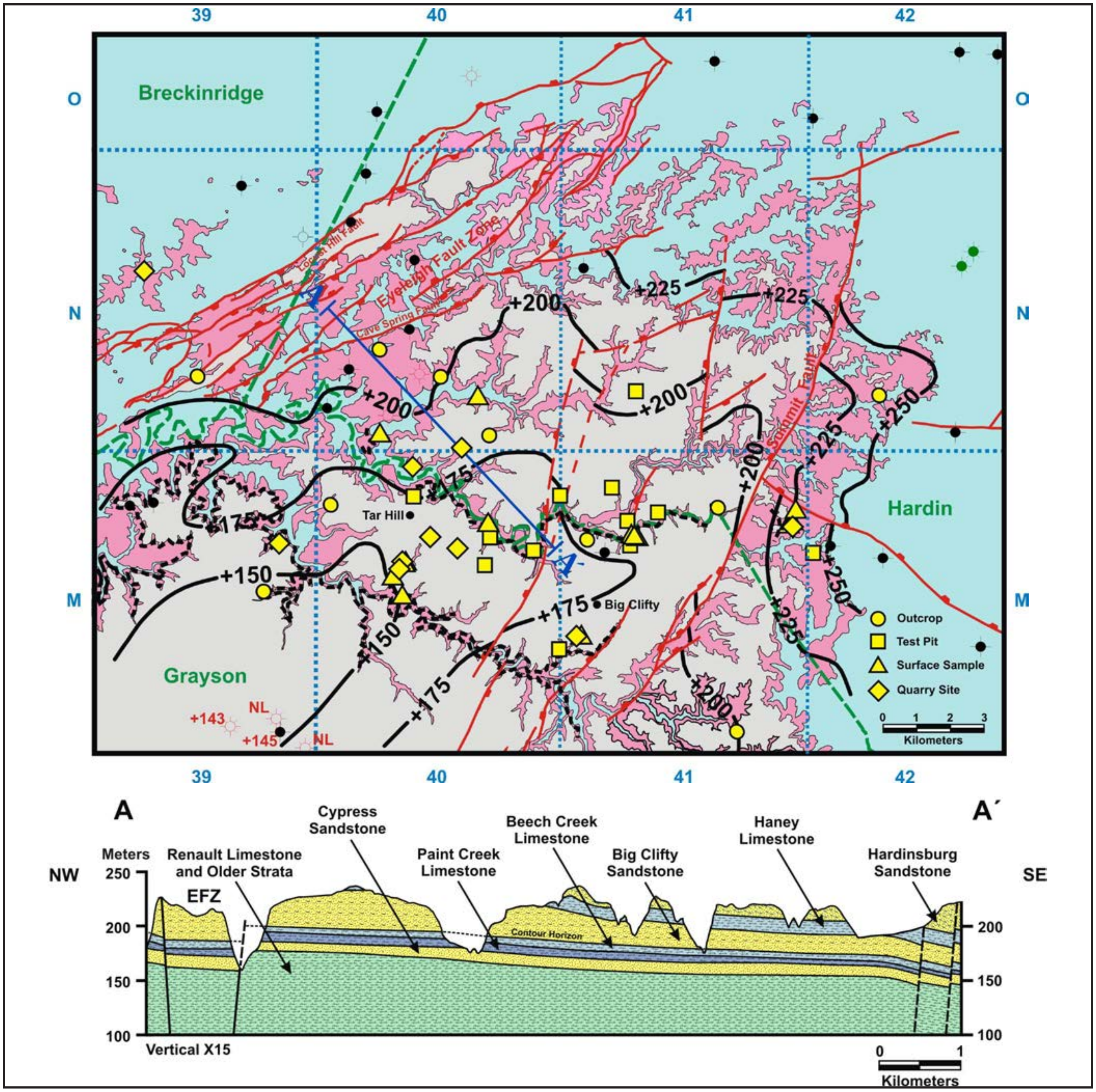

Figure 6. Structural contours and cross section of northeastern Grayson and adjacent Hardin Counties. Modified from Swadley (1962), Moore (1964), and Johnson (1978). Faults are in red, dashed where inferred. Downthrown sides of normal faults are marked with red symbols. Contour horizon is the top of the Beech Creek Limestone (Fig. 6B) or equivalent point, and contours are inferred where the Beech Creek is eroded and the projected top is above ground level. Contour interval is 25 m. Line of cross section A–A′ (Fig. 6B) is in blue. Subsea elevations of the top of the Beech Creek from electric-log correlations are posted next to well symbols in red (NL = not logged). (A) A southwest-plunging syncline is developed between the Eveleigh Fault Zone and Summit Fault. Normal faults have footwalls down to the northwest inside the syncline. The Eveleigh Fault Zone forms a complex of northeast-trending horsts and grabens, with the Big Clifty section preserved in the grabens. Secondary faults generally trend northeast, approximately parallel to the major faults and downthrown to the northwest. Primary joints strike northeast, dipping 55° northwest to vertical (Swadley, 1962). (B) Northwest–southeast cross section A–A′ from the Eveleigh Fault Zone in west-central Carter coordinate quadrangle N-40 to the center of the syncline in the northeast quarter of Carter coordinate quadrangle M-40. Modified from Swadley (1962). The line of section is 10 km long, vertical exaggeration times 15. This cross section illustrates the thickening of the Big Clifty from east to west in the study area.

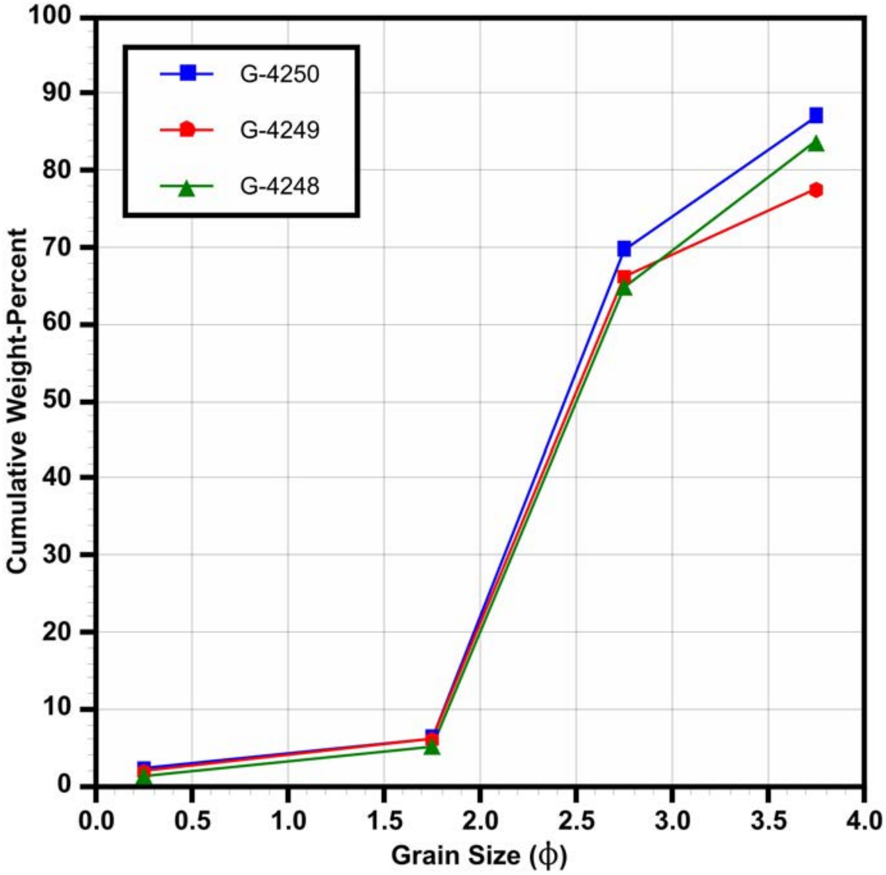

Figure 7. Sieve-analysis grain-size distributions of three samples from the Big Clifty (data from Jillson, 1926c; grain size in φ units) (Krumbein and Aberdeen, 1937). Sample sites are shown in Figure 4. Although the analysis used a limited number of sieves, the sample mean, either at 50 weight-percent or the graphic mean of Folk (1968), is 2.5 φ, fine sand.

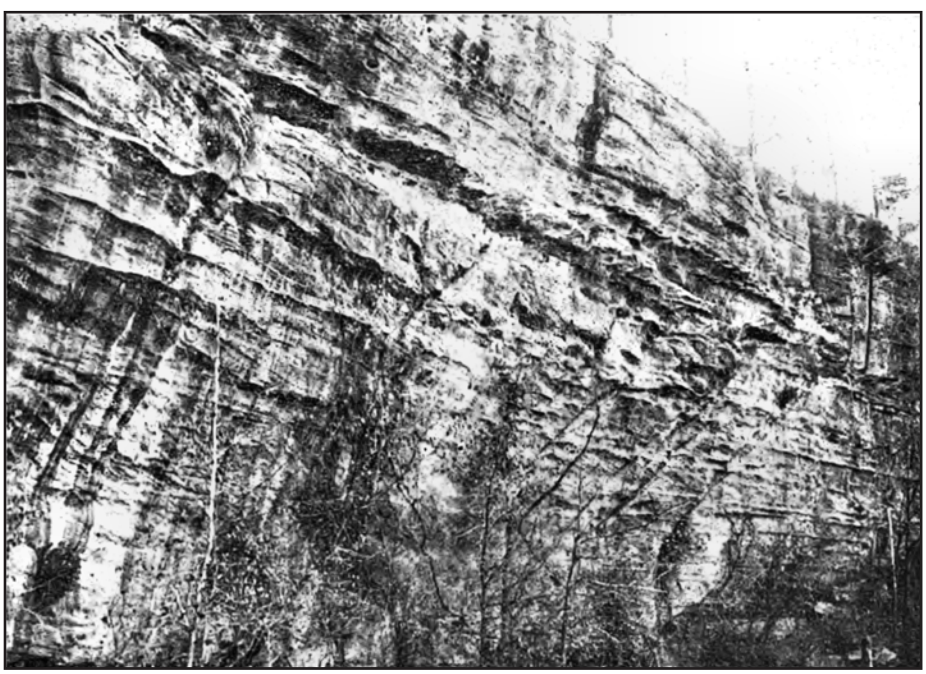

Figure 8. A 12-m section of the Big Clifty Sandstone exposed in Big Clifty Creek, northeastern Grayson County, about 0.4 km downstream of the Illinois Central Railroad trestle in the southwest quarter of the northwest quarter of Carter coordinate section 20-M-40. Photo modified from Butts (1917, Plate 22A). View is to the east. Crossbeds are visible throughout the section.

meteoric zone is contributing to secondary reservoir porosity (Bowersox, in press).

Reservoir Volume and Resources

This evaluation was completed using Petra version 3.8.3 petroleum database and analysis software to calculate reservoir volumetrics. The resource area evaluated is area 7 of Bowersox (in press). An isopach map of the net thickness of commercial oil and bitumen-saturated sand deposits in the Big Clifty was constructed (Fig. 11) and its reservoir volume calculated in Petra. Because the 29 wells drilled in the study area provided only very limited structural data (Fig. 6A), oil in place was calculated from reservoir properties measured in the 35 mine and surface samples (Figs. 3–4, Tables 1–3). Net oil-saturated intervals in the reservoir sands, where available, were compiled by sample site into the Petra database. Considering the limitations of relying on surface samples largely saturated with bitumen measured as weight-percent (Tables 1–2), oil in place was calculated without differentiating the small heavy-oil fraction from bitumen (Table 3). The total defined resource area is 11,740 ha, average reservoir height is 3.6 m,

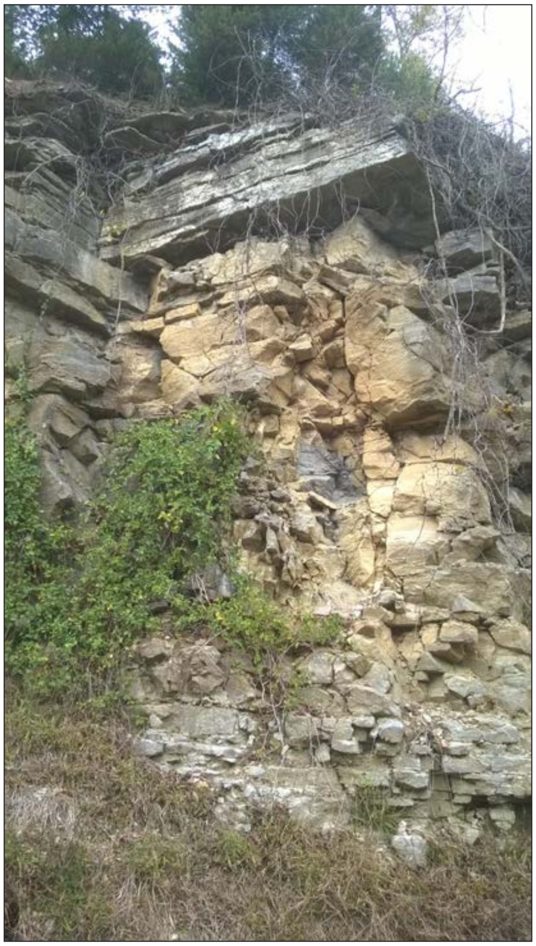

Figure 9. Roadcut on the Western Kentucky Parkway 4 km south of the town of Big Clifty at mile marker 115.2. This exposure is about 5 m high. (A) In this cut, resistant beds of gray Haney Limestone overlie yellow-weathered, crossbedded Big Clifty Sandstone. (B) An approximately 2-m-high section of clay-bounded, thin channels filled with light brown, unsorted crinoidal biosparite limestone is exposed at the base of the Big Clifty section exposed in the cut. For scale, the hammer is 34 cm long and the yellow oval on the handle is 3 cm long and 1 cm wide.

and average bulk volume of hydrocarbons is 0.076 (Bowersox, in press). Total oil in place is estimated to be 200.3 million barrels (Bowersox, in press), or about 17,060 barrels of oil per hectare.

Heavy-Oil and Bitumen Production in Grayson County

Rock-asphalt–bearing outcrops were described in early geologic reports of the northeastern Grayson County region (Orton, 1891; Eldridge, 1901; Bryant, 1914) and mapped in a later study by Jillson (1926a). The potential economic value of the heavy-oil and bitumen resources in the rock-asphalt deposits of northeastern Grayson County was first recognized in the early 1880's by Charles F. Very, a geology professor from New Albany, Ind. (Bowersox, 2016). Very began examining the deposits on the eastern margin of the Western Kentucky Coal Field in 1887 for William L. Breyfogle of Louisville (Weller, 1927), who subsequently acquired properties in northeastern Grayson County, near the town of Tar Hill, and incorporated the American Bituminous Rock Co. (Fig. 3, location A) in 1888 (Bowersox, in press). American Bituminous Rock Co.'s mine began operations by early 1889 (Bowersox, in press), and produced 112 tons of rock asphalt, the first commercial rock asphalt from Kentucky, that year (Orton, 1891; Parker, 1892). Quarrying rock asphalt for road topping soon expanded throughout the rest of the tar-sand belt (Bowersox, 2016, and sources cited therein). In northeastern Grayson and adjacent Hardin Counties, rock-asphalt development occurred in three periods: 1889–1904 near Tar Hill, 1923–40 near Tar Hill and near Big Clifty in Grayson County, and 1922–46 at Summit in adjacent Hardin County (Bowersox, 2016). Minor amounts of petroleum products were refined from the Big Clifty rock asphalt before 1930, but production was insufficient to support commercial development (McCormack, 1925; Weller, 1927; Hagan, 1942).

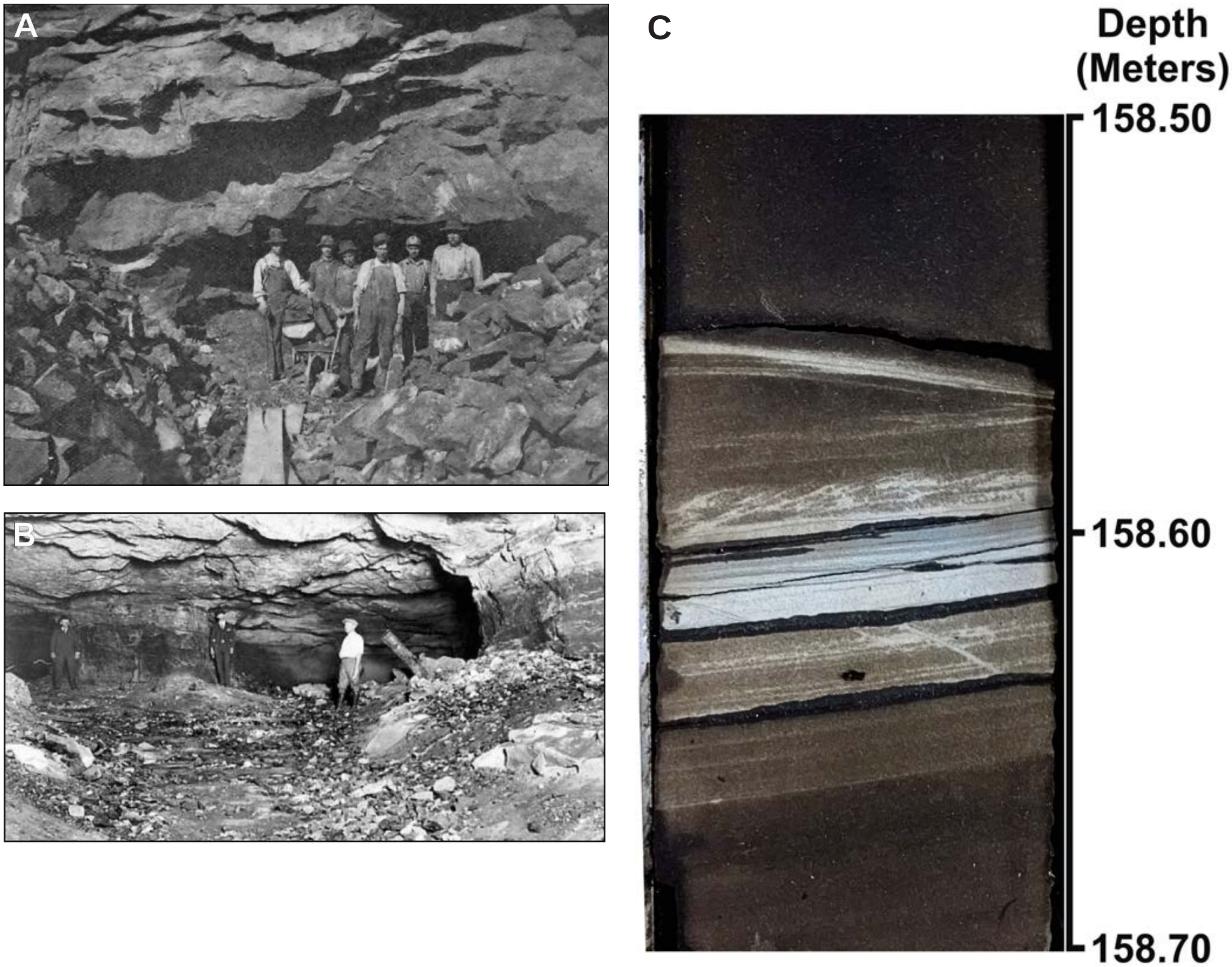

Figure 10. Evidence for diagenesis during oil migration into the Big Clifty Sandstone. (A) Entrance to a Federal Asphalt Co. mine adit in Flutter Creek, Grayson County (1903) showing a thick section of bitumen-saturated Big Clifty sandstone in the mine face above the miners and in the waste-rock piles in the foreground. Compartmentalization of the Big Clifty oil reservoir is visible as light-colored streaks and areas in the waste rock pile to the right of the miners. Photo is from *Municipal Engineering* (1903, p. 301). (B) Interior of one of the Federal Asphalt Co.'s abandoned mines in Flutter Creek (about 1923). Compartmentalization of the Big Clifty oil reservoir is visible in the tunnel face on the right where dark-colored, bitumen-saturated sandstone has interbeds of light-colored, calcite-cemented sandstone. The overlying light-colored rock shows thin layers of bitumen-saturated sandstones in an otherwise barren section of calcite-cemented sandstone. Photo from Jillson (1924, Plate 25C). (C) Section of Big Clifty core from Megawest corehole 102 Clark, Warren County, at 158.5–158.7 m. White layers and streaks in this core are intervals of sandstone with reservoir-compartmentalizing calcite cement (white) and brown to black oil-saturated intervals. Calcite was precipitated in a reducing geochemical environment during migration of oil into the reservoir (Bowersox, in press, and sources cited therein).

Discussion

Many resource assessments were undertaken in the early 20th century to determine the value of individual rock-asphalt deposits for quarrying as road-topping material. Jillson (1923, 1925, 1926a–c) mapped the locations of coreholes and outcrops of rock asphalt in northeastern Grayson County and adjacent Hardin County in Carter coordinate quadrangle N-40, as well as the locations of operating and former rock-asphalt quarries. Jillson (1923, 1925, 1926a–c) also collected and analyzed the bitumen content in 15 samples (Figs. 3–4, Tables 1–2). Additional sampling at three abandoned mine and quarry sites, supplementing the earlier work, was

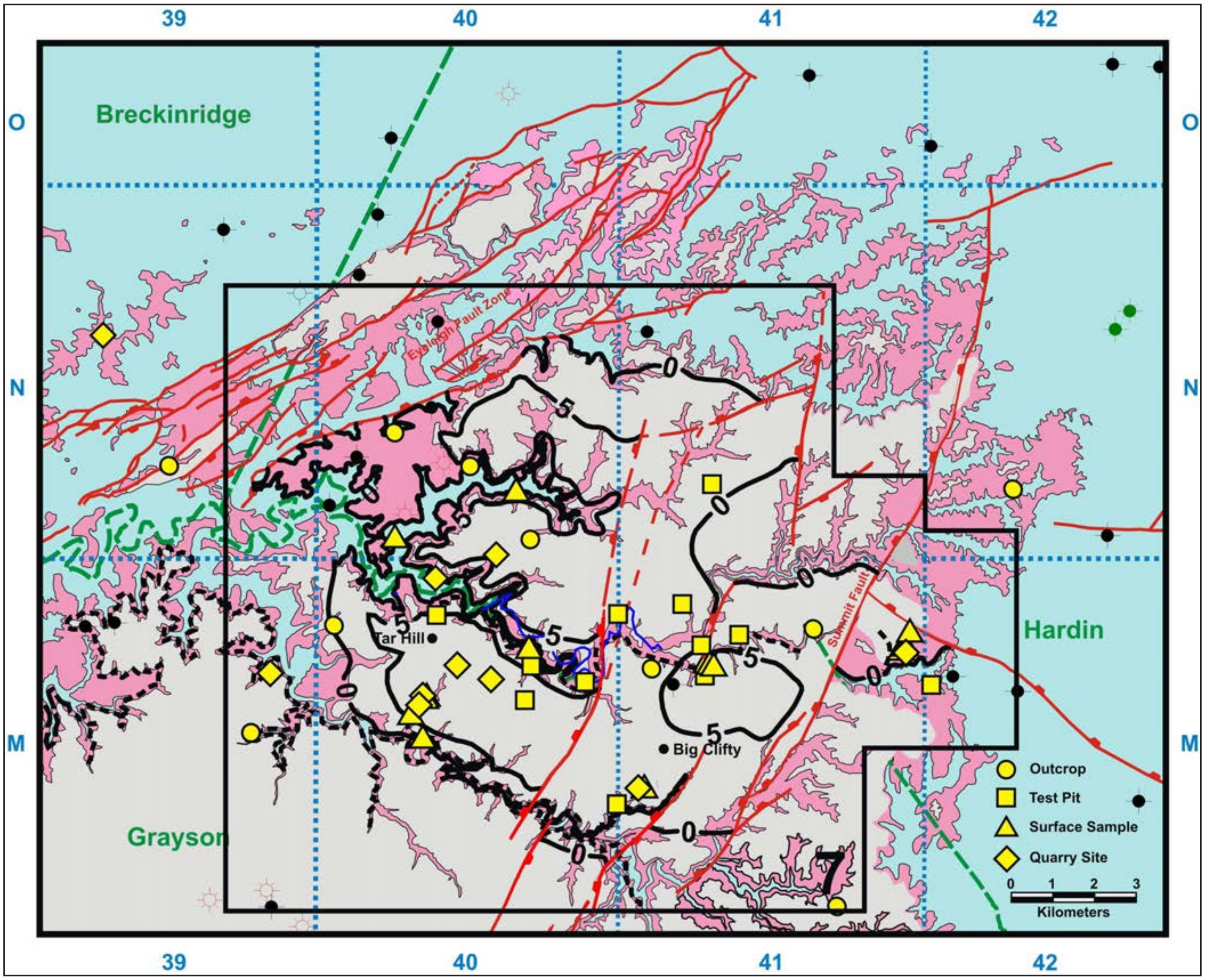

Figure 11. Isopach thickness of the net oil- and bitumen-saturated interval in the Big Clifty constructed from descriptions of ore-body thicknesses in the rock-asphalt mines, quarries, and sections present at surface sample sites (Tables 1–2). As outlined on the map, this is resource area 7 of Bowersox (in press). Because ore thicknesses reported at mines and sample sites are for only the ore with the minimum commercial bitumen content of 7 to 7.25 weight-percent (Richardson, 1924; Jillson, 1925), and bitumen-saturated sections as much as 9 m thick are known (Jillson, 1925), for the purposes of this evaluation, maximum inferred net reservoir thickness is conservatively estimated as slightly more than 5 m.

conducted by Kerr-McGee in 1963 (unpublished data; see McGrain, 1976) (Fig. 4, Table 3). Together, these mapping and sampling efforts define three rock-asphalt resource areas: (1) between Meeting and Clifty Creeks northwest of the Summit Fault in Grayson County, (2) a less well-defined area north of Meeting Creek and southeast of the Eveleigh Fault Zone, and (3) the small fault-bounded outcrop area at Summit in Hardin County (Figs. 4, 11). All of the commercial rock-asphalt mining was conducted inside these areas (Fig. 3) where access to the rock-asphalt deposits was possible in creek valleys and canyons with relatively gently sloping walls (Jillson, 1923). Lateral access to the Big Clifty rock-asphalt deposits in creek walls avoided the substantial effort and expense of underground mining or large-scale open-pit mining, which would otherwise have been necessary for quarrying through 12 to 30 m of Hardinsburg Sandstone and Haney Limestone overburden (Fig. 6B). Although the Big Clifty in this area may reach thicknesses of 24 to 27 m, bitumen-saturated intervals occur in lenses 1 to 9 m thick (Jillson, 1923, 1925, 1926b). Commercial rock-asphalt deposits, with 7.0 to 7.5 weight-percent bitumen content, range from 1.5 to 4.9 m thick (Jillson, 1923, 1925, 1926b). Thicknesses of lean rock-asphalt deposits with subcommercial bitumen content are generally not reported in the literature (see Jillson, 1923). Net thicknesses of commercial rock-asphalt deposits therefore understate the total saturated intervals and total heavy-oil and bitumen resources in the Big Clifty. Thus, the resources in the northeastern Grayson County area presented in Bowersox (in press) are conservative.

Additional Resources Southwest of Clifty Creek

Jillson (1926a) mapped outcrops of rock asphalt in the Big Clifty Sandstone along the southwestern wall of Clifty Creek, downstream of the southeastern walls of Rough River and Peter Cave Creek (Fig. 11), suggesting substantial rock-asphalt deposits southwest of Clifty Creek. Jillson's mapping has not been field checked as part of this study and it is notable that neither Swadley (1962) nor Johnson (1978) mapped rock-asphalt outcrops in the Big Clifty other than on a tributary of Beaver Dam Creek in east-central Carter coordinate quadrangle M-39 (Fig. 11). Swadley (1962) did not map rock-asphalt outcrops anywhere in the Big Clifty quadrangle, however, even adjacent to historic rock-asphalt mines or where rock-asphalt outcrops were mapped and sampled by Jillson (1923, 1925, 1926a–c) or sampled by Kerr-McGee (McGrain, 1976) (Table 3). Lack of subsequent verification of Jillson's (1926a) mapping is problematic. Any exposure of rock asphalt in the south wall of Clifty Creek will be difficult to verify, however, because of steep walls along the creek and limited access at three road crossings along Clifty Creek.

One limited rock-asphalt prospect pit in the Hardinsburg Sandstone was opened southwest of Clifty Creek in the early 1890's by Schillinger Brothers, a Toledo, Ohio, paving contractor, at a location in northeast Carter coordinate quadrangle M-39 (Fig. 3, location B). Eldridge (1901, p. 252) provided the only description of the rock asphalt in the Schillinger Brothers pit:

> The sandstone in which bitumen is found has a thickness of 8 feet, but only 3 feet is sufficiently rich to be worked. The sandstone differs from that in which bitumen is found at the Breyfogle quarry in being fine grained and thin bedded.

Commercial development never followed (Eldridge, 1901), and Schillinger Brothers ceased operations and left Kentucky by 1893 (Bowersox, 2016). Likely, the problems with developing any Big Clifty rock-asphalt deposit southwest of Clifty Creek were the greater overburden thickness, in excess of 20 m (Swadley, 1962), requiring expensive underground mining for development, and remoteness from rail transport. Although overburden thicknesses northeast of Clifty Creek are comparable (Jillson, 1925) (Fig. 6B), extensive topographic dissection by creeks there (Swadley, 1962) made for comparatively easier access for commercial development in open pits and underground mines.

Assuming that Jillson's (1926a) map is accurate, the Big Clifty rock-asphalt outcrops mapped along the synclinal axis in Clifty Creek, west-central Carter coordinate quadrangle M-40 (Fig. 11) lie at subsea structural elevations of slightly less than +150 to +185 m (Fig. 6A). The most western exposures, mapped by Jillson (1926a) on the southeastern bank of Peter Cave Creek in west-central Carter coordinate quadrangle M-39 (Fig. 11), lie at +170 to about +180 m subsea structural elevation. The Barron Kidd 1 Argile Willis well (KGS record number 9062, Fig. 5), drilled in southeastern Carter coordinate quadrangle M-39 about 3 km south of the nearest rock-asphalt outcrop on Beaver Dam Creek, penetrated a 14.3-m section of the Big Clifty at +162 m subsea elevation, as recorded on the well's geophysical electric log, below 54 m of overburden and 3 m downdip of the nearest rock-asphalt outcrop (Figs. 6A, 11). The driller's log of this well has no oil show in the Big Clifty, thus no discernible oil-water contact in the Big Clifty (Bowersox, in press). Hence, the Barron Kidd 1 Argile Willis well may have coincidentally penetrated the Big Clifty at a location where compartmentalization excluded oil emplacement, which Jillson (1923, 1925, 1926b) also observed while describing outcrops to the north. The prospective area shown in Figure 12, limited to the area inside of a line connecting the outcrops along the southwestern wall of Clifty Creek and Beaver Dam Creek, is 3,900 ha. Assuming an average 1.8 m of bitumen-saturated

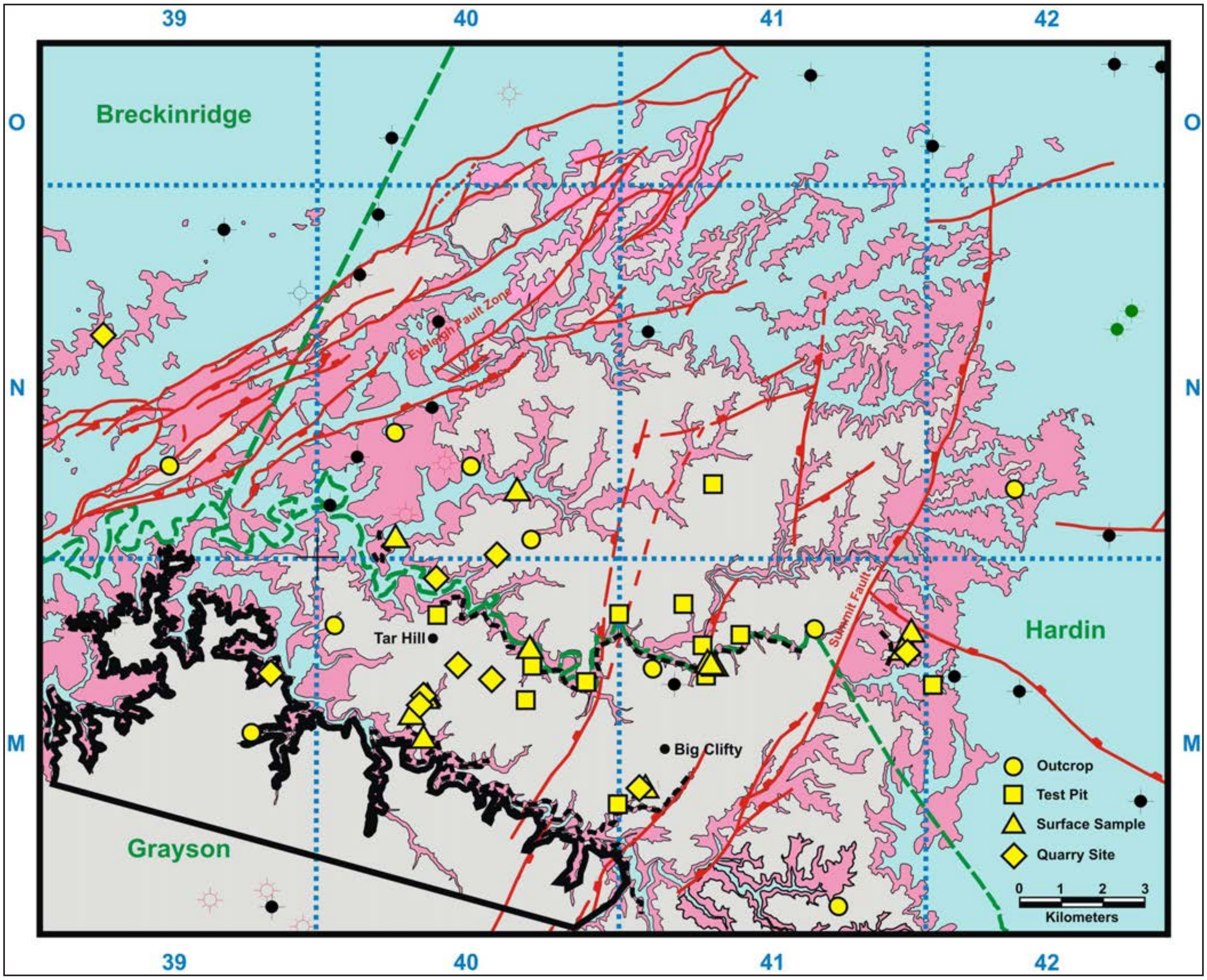

Figure 12. Jillson (1926a) mapped Big Clifty rock-asphalt outcrops along the southwest wall of Clifty Creek and southeast wall of Beaver Dam Creek from southwest Carter coordinate quadrangle M-41 to northwest Carter coordinate quadrangle M-39. Jillson (1926a) did not map rock asphalt in the walls of Barton Run in west-central Carter coordinate quadrangle M-40, however, suggesting that he had reached the limit of what he was able to access. In southeast Carter coordinate quadrangle M-41, the Barron Kidd No. 1 Argile Willis well did not encounter hydrocarbons (labeled "NS," no show) while drilling through the Big Clifty. Thus, the evaluation area southwest of Clifty Creek was limited by bounding the southern side by a straight line connecting the limits of the Big Clifty rock-asphalt deposits mapped in southwest Carter coordinate quadrangle M-41 to the rock-asphalt outcrop mapped in west-central Carter coordinate quadrangle M-39, or approximately halfway between the rock-asphalt outcrops and the Barron Kidd No. 1 Argile Willis well. The resulting prospective area is 3,900 ha.

rock asphalt in this area, half of the average thickness evaluated in area 7 in Bowersox (in press) (Fig. 11) and a 7 weight-percent commercial bitumen content, oil in place in the prospective area is 29.6 million barrels, or about 7,600 barrels of bitumen per hectare.

Developing Heavy Oil and Bitumen in the Big Clifty Sandstone

The only commercial development of any of the western Kentucky tar sands was the rock-asphalt industry from 1889 to 1957 (Bowersox, 2016, in press). Although the shallow depth to the Big Clifty below overburden in the northeastern Grayson County area does not preclude enhanced oil recovery, projects at comparable depths were tested in the Caseyville Formation in Edmonson County, the Gulf Oil Co. fireflood (Terwilliger, 1976) and Pilot Oil project at Kyrock (May, 2013), and oil recoveries were insufficient to support commercial development. Heavy-oil and bitumen deposits in the Big Clifty are generally thin and have variable reservoir continuity (Bowersox, in press), precluding an effective project design for enhanced oil recovery. Oil extraction from the Big Clifty by retorting (heating in a furnace) the rock asphalt was tested in the Grayson County area before 1930 (McCormack, 1925; Weller, 1927; Hagan, 1942), and small noncommercial volumes were recovered. Larger-scale pilot projects for bitumen recovery from the Big Clifty in surface mines have been tested in Logan County (Groves and Hastings, 1983; Kelley and Fedde, 1985; Bartlett, 2014; Bowersox, in press) without demonstrable commercial success. Although the northeastern Grayson County area and Logan County tar-sand deposits are comparable, the thicker overburden in the Grayson County area may discourage surface mining and bitumen-extraction development.

Legacy of the Rock-Asphalt Industry in the Northeastern Grayson County Area

During the historic period of rock-asphalt production, mine-site reclamation and surface recontouring were not required, as is mandated by current regulations. Consequently, even though the last active quarry in the northeastern Grayson County area closed in 1940, scars of mine and quarry operations are still evident. Figure 13A–C shows LiDAR (light detection and ranging; an aerial pulsed-laser method for imaging the earth's surface) imaging, served by KGS's Kentucky Geologic Map Information Service (kgs.uky.edu/kgsmap/kgsgeoserver/viewer.asp) for rock-asphalt mines and quarry sites near Tar Hill, Big Clifty, and at Summit. Pits and mine-spoil piles are visible (Fig. 13A, B) as well as areas that have been filled (Fig. 13C). A reasonable environmental concern would be surface and groundwater contamination by hydrocarbons leaching from the mined areas and spoil piles. Rock asphalt in western Kentucky has been exposed at the surface since the Late Cretaceous (Cenomanian) (Bowersox, in press) and any mobile hydrocarbons should have long since been degraded. What remains are solid to semisolid bitumen in rock-asphalt outcrops and sparse natural seeps of heavy oil. Kasulavada (2013) measured the leaching of hydrocarbons from Caseyville Formation rock-asphalt mine spoil in Edmonson County. He tested leaching in six samples of synthetic rainwater with a pH range of 3 to 9 and found that hydrocarbons were leached only by very acidic water with a pH of 3. Natural rainwater in western Kentucky has a higher pH of about 5.5 (Merideth, 2009). Thus, although the unreclaimed mine and quarry sites may be unsightly where not covered by vegetation, it is unlikely that hydrocarbons are being leached from the mine and quarry sites and mine-spoil piles in the northeastern Grayson County area and contaminating surface- or groundwater resources.

Conclusions

Rock asphalt was produced from the Big Clifty Sandstone for about 57 yr in northeastern Grayson County and adjacent Hardin County (Bowersox, 2016). Although Jillson (1923, 1925, 1926b, c) conducted resource assessments throughout the area, describing substantial rock-asphalt deposits and estimating their commercial values, development centered on sites in Flutter Creek Canyon, at Big Clifty, and at Summit. Later assessments by Ball (1951), Ball and Associates (1965), Lewin and Associates Inc. (1984a, b), and Noger (1984, 1987) overlooked the northeastern Grayson County area.

1. Historical rock-asphalt production in northeastern Grayson County was from the area between Clifty Creek and Meeting Creek and between the Summit Fault and Eveleigh Fault Zone, as well as the area around Summit in adjacent Hardin County. Bowersox (in press) summarized the heavy-oil and bitumen resources of the Big Clifty Sandstone in this area and estimated 200.3 million barrels of oil in place.
2. Jillson (1926a) mapped outcrops of rock asphalt in the Big Clifty Sandstone along the southwestern wall of Clifty Creek. Rock asphalt was never commercially produced from this 3,900-ha area, and wells drilled here encountered no oil shows in the Big Clifty. Despite these limitations,

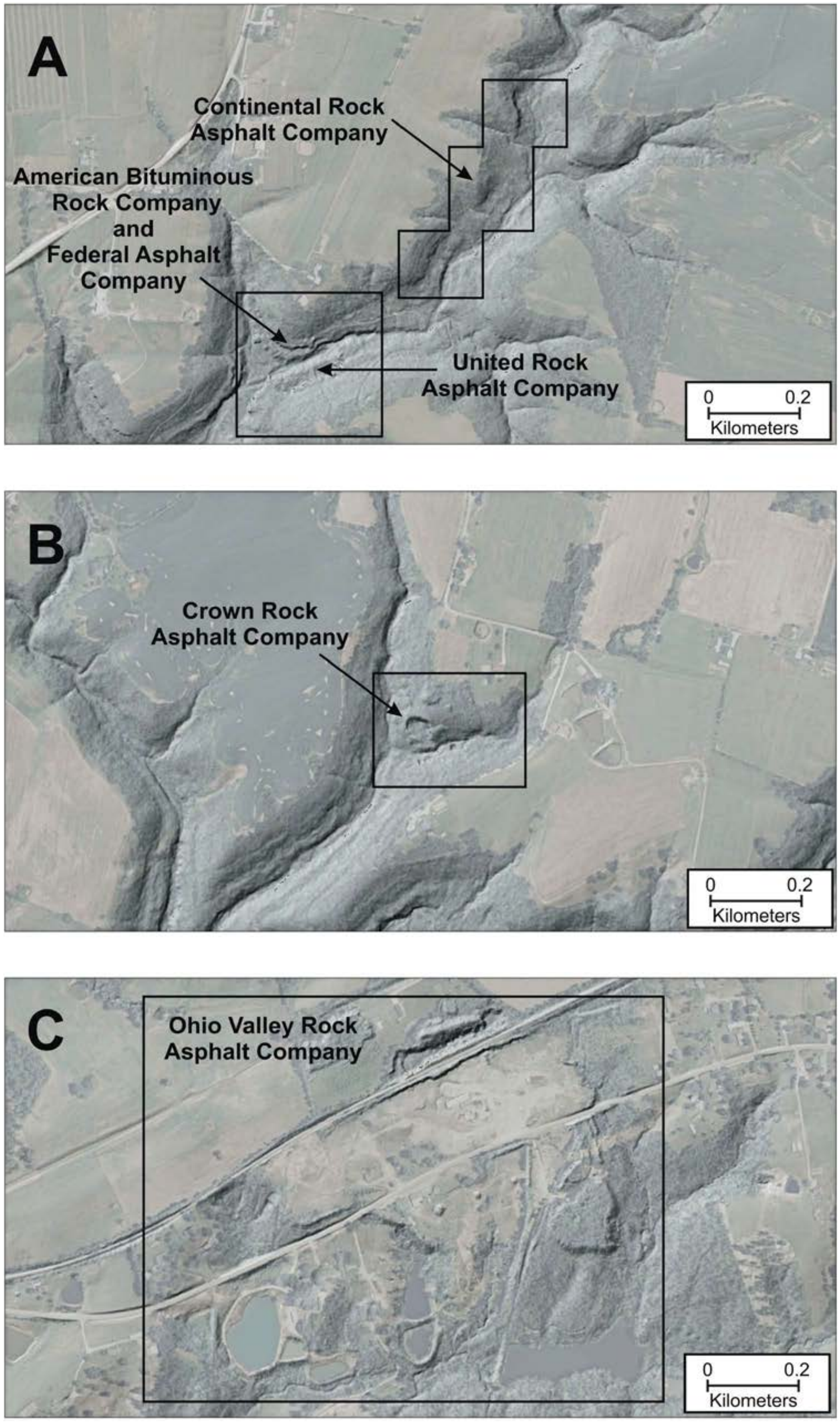

Figure 13. Surface impact of rock-asphalt mining in the northeastern Grayson County area. Three areas of surface disturbance are evident on the 5-ft-resolution LiDAR image of Flutter Creek, about 1.5 km south of Tar Hill, served by KGS's Geologic Map Information Service (kgs.uky.edu/kgsmap/kgsgeoserver/viewer.asp). (A) The American Bituminous Rock Co. mined rock asphalt in Flutter Creek from 1889 to 1895; then its mines were reopened and operated by Federal Asphalt Co. from 1901 to 1904 (Bowersox, 2016, and sources cited therein). Mine adits are visible as six to eight black spots above a ledge along the canyon wall. United Rock Asphalt Co. quarried rock asphalt in Flutter Creek across from the Federal Asphalt Co. mine from about 1927 to 1930 (Bowersox, 2016). The mine-spoil pile is visible in the southwestern corner of the box. Continental Rock Asphalt Co. briefly quarried rock asphalt from the Big Clifty at three pits in Flutter Creek from 1923 to 1924 (Bowersox, 2016), transporting the material to Big Clifty for milling and shipment. (B) After the failure of Continental Rock Asphalt Co. in 1924, Crown Rock Asphalt Co., acquired the mill at Big Clifty and commenced quarrying rock asphalt on a nearby tributary of the Sugar Branch of Clifty Creek, about 1.4 km to the southwest (Bowersox, 2016). Crown operated the mill and quarry sporadically from 1925 to its closure in 1940. (C) Ohio Valley Rock Asphalt Co. operated a quarry and mill in Summit, Hardin County, from 1922 to 1940 (Bowersox, 2016). Its pit and mill were adjacent to the southeast side of the Illinois Central Railway tracks in Summit, providing for easy transport of rock asphalt from its pit to its mill, then from the mill directly into rail cars (Bowersox, 2016). Although this was an effective production process, the surface impact at Summit was substantial. The company closed its Summit operations in 1940 and moved them to Black Rock, Grayson County, before ceasing business operations in 1946 (Ball, 1951; Havens and Williams, 1956).

the prospective area is estimated to hold 29.6 million barrels of heavy-oil and bitumen resources in place in the Big Clifty. Access to these resources would require stripping more than 50 m of overburden or underground mining, however.

3. Although the shallow depths to the Big Clifty resources does not preclude enhanced oil recovery, no commercial process has been demonstrated to date. Likewise, no commercial bitumen extraction has been demonstrated to date.
4. The rock-asphalt industry in the northeastern Grayson County area left substantial surface damage and rock-asphalt mine-spoil piles that are still visible, especially at Summit, more than 70 yr later. A study of rock-asphalt mine spoil using synthetic rainwater showed no leaking hydrocarbons at a pH above 3.5 (Kasulavada, 2013); thus, these legacy issues should not pose a serious groundwater or surface-water contamination threat in the area.

References Cited

Ball, M.W., 1951, The synthetic liquid fuel potential of Kentucky, oil impregnated strippable deposits: New York, Ford, Davis and Bacon Inc., 347 p.

Ball and Associates Ltd., 1965, Surface and shallow oil-impregnated rocks and shallow oil fields in the United States: U.S. Bureau of Mines Monograph 12, 375 p.

Bartlett, G., 2014, Oil recovery technology–Oil sands development [abs.]: 2014 Eastern Unconventional Oil & Gas Symposium, Lexington, Ky., www.euogs.org/proceedings/2014/0019-bartlett-dani-euogs2014.pdf, 2 p. [accessed 09/18/2015].

Bowersox, J.R., 2014a, Evaluation of western Kentucky's heavy oil and bitumen resources [abs.]: 2014 Eastern Unconventional Oil & Gas Symposium, Lexington, Ky., www.euogs.org/proceedings/2014/034-bowersox-euogs2014.pdf, 5 p. [accessed 02/27/2015].

Bowersox, J.R., 2014b, Evaluation of western Kentucky's heavy oil and bitumen resources [slides]: 2014 Eastern Unconventional Oil & Gas Symposium, Lexington, Ky., www.euogs.org/proceedings/2014/034-bowersox-euogs2014ppt.pdf [accessed 02/27/2015].

Bowersox, J.R., 2016, Rocks, roads, and ruin: A history of western Kentucky's rock-asphalt industry, 1888–1957: Kentucky Geological Survey, ser. 12, Information Circular 33.

Bowersox, J.R., in press, Heavy oil and bitumen resources of the western Kentucky tar sands: Kentucky Geological Survey, ser. 12, Report of Investigations 36.

Bryant, J.O., 1914, The economic geology of a portion of Edmonson and Grayson Counties: Kentucky Geological Survey, ser. 4, v. 2, pt. 1, p. 155–218.

Butler, K.H., 2013, Diagenetic compartmentalization of a Late Mississippian reservoir in Warren and Butler Counties, KY [abs.]: Geological Society of America, Abstracts with Programs, v. 45, no. 7, p. 174.

Butts, C., 1917, Descriptions and correlation of the Mississippian formations of western Kentucky: Kentucky Geological Survey, ser. 5, Report 4, No. 4, 119 p.

Crump, M.H., 1913, Kentucky rock asphalt: Kentucky Geological Survey, ser. 4, v. 1, pt. 2, p. 1053–1065.

Eldridge, G.H., 1901, The asphalt and bituminous rock deposits of the United States: U.S. Geological Survey Annual Report 22, pt. 1, p. 209–452.

Folk, R.L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphhill's, 170 p.

Groves, K.O., and Hastings, L., 1983, The Tarco process: For the surface extraction of tar sands: Synthetic Fuels from Oil Shale and Tar Sands: Symposium No. 3, p. 579–594.

Hagan, W.W., 1942, Geology of the Cub Run quadrangle, Kentucky: Urbana, University of Illinois, doctoral thesis, 242 p.

Havens, J.H., and Williams, E.G., 1956, Report No. 2: A study of the properties and performance of Kentucky (natural sandstone) rock asphalt: Kentucky Transportation Center Research Reports, Paper 1250, 56 p., uknowledge.uky.edu/ktc_researchreports/1250 [accessed 10/20/2014].

Jillson, W.R., 1923, Report of geologic reconnaissance, state of Kentucky, county of Grayson and Hardin, waters of Big Clifty and Big Meeting Creek: Property examined owned by Continental Rock Asphalt Co.: Report prepared for Continental Rock Asphalt Co., Big Clifty, Ky.: Dated Oct. 13, 1923: Frankfort, Ky., Willard Rouse Jillson, 21 p., kgs.uky.edu/kgsweb/olops/pub/kgs/JillsonTarSandsReport15.pdf [accessed 01/30/2014].

Jillson, W.R., 1924, Kentucky rock asphalt: Pan-American Geologist, v. 41, p. 251–258.

Jillson, W.R., 1925, Report of geologic reconnaissance, state of Kentucky, county of Grayson and Hardin, waters of Green River: Property examined owned by W.H. Giltner, Trustees, Louisville, Kentucky: Report prepared for Curtis C. Webb, 1505 Rosewood Ave., and William Crawford, Intersouthern Bldg., Louisville: Dated Dec. 24, 1925: Frankfort, Ky., Willard Rouse Jillson, 19 p., kgs.uky.edu/kgsweb/olops/pub/kgs/JillsonTarSandsReport04.pdf [accessed 02/10/2014].

Jillson, W.R., 1926a, Map of Grayson County showing approximate distribution of bituminous sandstone outcrops, fault pattern, and oil and gas wells: Kentucky Geological Survey, ser. 6, scale 1 in. = 1 mi.

Jillson, W.R., 1926b, Report of geologic reconnaissance, state of Kentucky, county of Grayson and Logan, waters of Ohio and Green Rivers: Property examined owned by United Rock Asphalt Company, Republic Building, Louisville, Ky.: Report prepared for United Rock Asphalt Company, E.J. Bigley, P.O.B. 54, Altoona, Pa.: Dated March 13, 1926: Frankfort, Ky., Willard Rouse Jillson, 12 p., kgs.uky.edu/kgsweb/olops/pub/kgs/JillsonTarSandsReport07.pdf [accessed 02/04/2014].

Jillson, W.R., 1926c, Report of geologic reconnaissance, state of Kentucky, county of Grayson, waters of Big Meeting Creek: Property examined owned by A.A. Hulette, Frankfort, Ky.: Report prepared for A.A. Hulette: Dated April 15, 1926: Frankfort, Ky., Willard Rouse Jillson, 3 p., kgs.uky.edu/kgsweb/olops/pub/kgs/JillsonTarSandsReport13.pdf [accessed 03/09/2015].

Jillson, W.R., 1927, The topography of Kentucky: Kentucky Geological Survey, ser. 6, v. 30, p. 1–60.

Johnson, W.D., Jr., 1978, Geologic map of the Madrid quadrangle, western Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1482, scale 1:24,000.

Kasulavada, S.K., 2013, Analysis of Kyrock for leaching of impurities in synthetic rainwater: Bowling Green, Western Kentucky University, master's thesis, 46 p., digitalcommons.wku.edu/theses/1276 [accessed 01/21/2016].

Kelley, M.N., and Fedde, P.A., 1985, The Kentucky tar sand project: Bitumen recovery by solvent extraction: Proceedings of the American Petroleum Institute Conference on Refining, American Petroleum Institute, Refining Department, New Orleans, La., 14 May 1984, v. 63, 5 p.

Krumbein, W.C., and Aberdeen, E., 1937, The sediments of Barataria Bay: Journal of Sedimentary Petrology, v. 7, p. 3–7.

Lewin and Associates Inc., 1982, Letter from Lewin and Associates to Martin C. Noger, Kentucky Geological Survey, February 1, 1982: Kentucky Geological Survey, Open-File Report OF-15-01, [15 p.], kgs.uky.edu/kgsweb/olops/pub/kgs/OFR%2015-01.pdf [accessed 03/09/2015].

Lewin and Associates Inc., 1984a, Major tar sand and heavy oil deposits of the United States, *in* Kuuskraa, V.A., and Hammershaimb, E.C., eds., Major tar sand and heavy oil deposits of the United States: Interstate Oil Compact Commission, p. 1–7.

Lewin and Associates Inc., 1984b, Kentucky, *in* Kuuskraa, V.A., and Hammershaimb, E.C., eds., Major tar sand and heavy oil deposits of the United States: Interstate Oil Compact Commission, p. 85–116.

May, M.T., 2013, Oil-saturated Mississippian–Pennsylvanian sandstones of south-central Kentucky, *in* Hein, F.J., Leckie, D., Larter, S., and Sutre, J.R., eds., Heavy-oil and oil-sand petroleum systems in Alberta and beyond: American Association of Petroleum Geologists Studies in Geology 64, p. 373–405.

May, M.T., and Butler, K.H., 2014a, Diagenetic partitioning in near-surface unconventional oil trends in south central Kentucky: Eastern Unconventional Oil & Gas Symposium 2014, Lexington, Ky., Nov. 5–7, 2014, Abstract 35, p. 40.

May, M.T., and Butler, K.H., 2014b, Diagenetic partitioning in near-surface unconventional oil trends in south central Kentucky: Eastern Unconventional Oil & Gas Symposium, Lexington, Ky., Nov. 5–7, 2014, www.euogs.org/proceedings/2014/035-may-euogs2014ppt.pdf [accessed 02/27/2015].

McCormack, C.P., 1925, The Kentucky rock asphalts—Their character and utilization: National Petroleum News, v. 17, no. 6, p. 41–42.

McGrain, P., 1976, Tar sands (rock asphalt) of Kentucky—A review: Kentucky Geological Survey, ser. 10, Report of Investigations 19, 16 p.

McGrain, P., 1979, Bitumen-impregnated Carboniferous sandstones along the southeastern rim of the Illinois Basin, *in* Palmer, J.E., and Dutcher, R.R., eds., Depositional and structural history of the Pennsylvanian System of the Illinois Basin, Part 2, Invited papers: Ninth International Congress of Carboniferous Geology and Stratigraphy, Field Trip No. 9, p. 62–65.

Merideth, J., 2009, Vadose zone hydrology near the vicinity of Edna's Dome, Mammoth Cave, Kentucky: Bowling Green, Western Kentucky University, master's thesis, 46 p., digitalcommons.wku.edu/theses/65 [accessed 01/21/2016].

Moore, F.B., 1964, Geology of the Summit quadrangle, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-298, scale 1:24,000.

Municipal Engineering, 1903, Pavement and roads: v. 24, no. 4, p. 301–305.

Noger, M.C., 1984, Tar-sand resources of western Kentucky: Proceedings, 1984 Eastern Oil Shale Symposium, University of Kentucky Institute for Mining and Minerals Research, p. 151–178.

Noger, M.C., 1987, Tar-sand exploration in Kentucky, *in* Meyer, R.F., ed., Exploration for heavy crude oil and natural bitumen: American Association of Petroleum Geologists Studies in Geology 25, p. 521–536.

Orton, E., 1891, Report on the occurrence of petroleum, natural gas and asphalt rock in western Kentucky, based on examinations made in 1888 and 1889: Kentucky Geological Survey, ser. 2, v. E, 233 p.

Parker, E.W., 1892, Asphaltum, *in* Day, D.T., Report of the mineral industries of the United States at the eleventh census: 1890: U.S. Department of the Interior, Census Office, p. 581–587.

Richardson, C.H., 1924, Road materials of Kentucky: Kentucky Geological Survey, ser. 6, v. 22, 209 p.

Russell, W.L., 1932, Geology of the oil and gas fields of western Kentucky: American Association of Petroleum Geologists Bulletin, v. 16, p. 231–254.

Russell, W.L., 1933, The origin of the asphalt deposits of western Kentucky: Economic Geology, v. 28, p. 571–586.

Swadley, W C, 1962, Geology of the Big Clifty quadrangle, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-192, scale 1:24,000.

Swezey, C.S., 2009, Regional stratigraphy and petroleum systems of the Illinois Basin, U.S.A.: U.S. Geological Survey Scientific Investigations Map 3068, 1 sheet.

Terwilliger, P.L., 1976, Fireflooding shallow tar sands—A case history: Journal of Canadian Petroleum Technology, v. 15, no. 4, p. 41–48.

Weller, J.M., 1927, The geology of Edmonson County, Kentucky: Kentucky Geological Survey, ser. 6, v. 28, 248 p.

Williams, D.A., Noger, M.C., and Gooding, P.J., 1982, Investigation of subsurface tar-sand deposits in western Kentucky: A preliminary study of the Big Clifty Sandstone Member of the Golconda Formation (Mississippian) in Butler County and parts of Edmonson, Grayson, Logan, and Warren Counties: Kentucky Geological Survey, ser. 11, Information Circular 7, 25 p.