Evaluation of Available Resources of the Lower Freeport (No. 6a) Coal Bed in Ohio

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CONTENTS

Abstract....1
Introduction....1
General geology of the Lower Freeport (No. 6a) coal bed....3
Methodology....5
Data collection....5
Map creation....6
Structure map....6
Original resources....6
Remaining resources....7
Available resources....7
County resource calculations....8
Results....8
Structure map....8
Original resources....8
Remaining resources....8
Available resources....10
Deep-minable coal....10
Surface-minable coal....10
Discussion....10
Uncertainty in the methodology....10
Results....10
Conclusions....11
Acknowledgments....12
References cited....13
Appendix....15

FIGURES

1. Map of the known extent of the Lower Freeport (No. 6a) coal bed during the most recent resource estimate....2
2. Stratigraphic column of the major lithologic units in the Pennsylvanian System in Ohio....3
3. Structural features that affect the Lower Freeport (No. 6a) coal bed....4
4. Examples of three different but valid contour maps, all drawn from the same data....6
5. Summary of the median estimation of the coal resources in the Lower Freeport (No. 6a) coal bed....11

A1. Percentile estimations of original resources for the Lower Freeport (No. 6a) coal bed in Ohio....15
A2. Percentile estimations of remaining resources for the Lower Freeport (No. 6a) coal bed in Ohio....16
A3. Percentile estimations of available surface-minable resources for the Lower Freeport (No. 6a) coal bed in Ohio....17
A4. Percentile estimations of available deep-minable resources for the Lower Freeport (No. 6a) coal bed in Ohio....18

TABLES

1. Restrictions to mining and the amount of buffer required for each restriction....8
2. Median estimation of coal tonnages for the Lower Freeport (No. 6a) coal bed in Ohio, by county and type of availability....9

PLATES

1. Structure map of the Lower Freeport (No. 6a) coal bed in Ohio.
2. Original resources isopach map of the Lower Freeport (No. 6a) coal bed in Ohio.
3. Remaining resources isopach map of the Lower Freeport (No. 6a) coal bed in Ohio.
4. Available deep-minable resources isopach map of the Lower Freeport (No. 6a) coal bed in Ohio.
5. Available surface-minable resources isopach map of the Lower Freeport (No. 6a) coal bed in Ohio.

ABBREVIATIONS USED IN THIS REPORT

Units of Measure

British Thermal Unit ..... BTU
Foot/feet ..... ft
Inch(es) ..... in
Mile(s) .....mi
Square feet ..... ft^2
Square mile(s) ..... mi^2

Other

Digital elevation model ..... DEM
Geographical Information System ..... GIS
Mean sea level..... m.s.l.

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ABSTRACT

The Ohio Department of Natural Resources (ODNR), Division of Geological Survey (Ohio Geological Survey) performed an estimation of the remaining and available coal resources of the Lower Freeport (No. 6a) coal bed in Ohio. This study represents the first statewide estimation of Lower Freeport coal resources in 55 years. Data points were collected to create base-elevation structure and isopach maps using Geographic Information Systems (GIS) technology. The base-elevation structure map was constructed from 7,190 data points using the Natural Neighbor interpolation technique. Sequential Gaussian simulation was used to create isopach maps from 3,277 data points, which were then summarized by county to obtain coal tonnages. Project results reveal that the Lower Freeport coal bed had an estimated 6.2 billion short tons of coal in Ohio before mining. Of that amount, 400 million short tons have been mined and approximately 5.8 billion tons remain. Of the remaining resources, 41 million short tons are available for surface mining, and 2.2 billion short tons are available for underground mining. The majority of the available resources exist in Harrison County (638 million short tons) and Jefferson County (625 million short tons). Given that the current rate of mining for the Lower Freeport is approximately 700,000 short tons per year, these resources will last for more than a century.

INTRODUCTION

Coal mined in Ohio is a significant natural resource that is of value not only to the economy and energy production in Ohio but also to the nation. Nationally, Ohio ranks eleventh in coal production with 22 million short tons produced in 2014 (Stucker, 2015). Ohio has 67 named coal beds with 24 coal beds containing minable resources (Brant and DeLong, 1960). During 2014, 15 named coal beds were mined (Stucker, 2015). Coal is the third-largest mineral-extraction industry in Ohio and represents 20 percent of the total value of fuel and non-fuel extractive industries, contributing annual revenues of $1.1 billion to the Ohio economy (Stucker, 2015).

Coal deposits were first described in Ohio during the 1740s and first mapped in 1752 (Crowell, 1995). Coal mining in Ohio began in 1795 (Bownocker and Dean, 1929). Coal was first used to heat homes as a cheaper alternative to heating with wood. During 1809, a cord of wood cost two dollars, while a bushel of coal cost only six cents (Tewalt and others, 2001). Coal use has evolved from its first use as heating fuel to fuel for railroad use and steel creation during the mid-nineteenth century. Currently, over ninety percent of coal in the United States is used for electrical generation (IER, 2015). Sixty-seven percent of the electricity used by Ohioans is generated by coal-burning power plants (EIA, 2015).

The Lower Freeport (No. 6a) coal bed is sixth-most productive coal bed in Ohio, producing 700,000 short tons of coal in 2014 (Stucker, 2015). The majority of the Lower Freeport coal deposits in Ohio exist in Harrison, Jefferson, Columbiana, and Carroll Counties.

Although the Lower Freeport coal bed is economically important and is presently mined in Ohio, the extents and quantities of remaining resources are not widely known. Historically, coal resource studies were limited to county, quadrangle, or coal basin. Regrettably, statewide coal resource studies for Ohio coal beds have not been performed for many years. Outdated resource estimates present a problem for the coal industry when planning and targeting new areas for mining. The last statewide resource assessment of the Lower Freeport coal (fig. 1) was published in 1960 (Brant and DeLong, 1960). Since that time, vast amounts of data from current and historical mining have accumulated, and techniques for resource estimation have evolved and improved. Where resource estimates once had necessitated extensive field work, today's techniques utilize digital orthophoto and LiDAR datasets, GIS, and computer-processing techniques that improve the accuracy and speed with which resource estimates can be performed. The objective of this study was to determine the amount and location(s) of coal currently remaining and available for mining in the Lower Freeport (No. 6a) coal bed within Ohio.

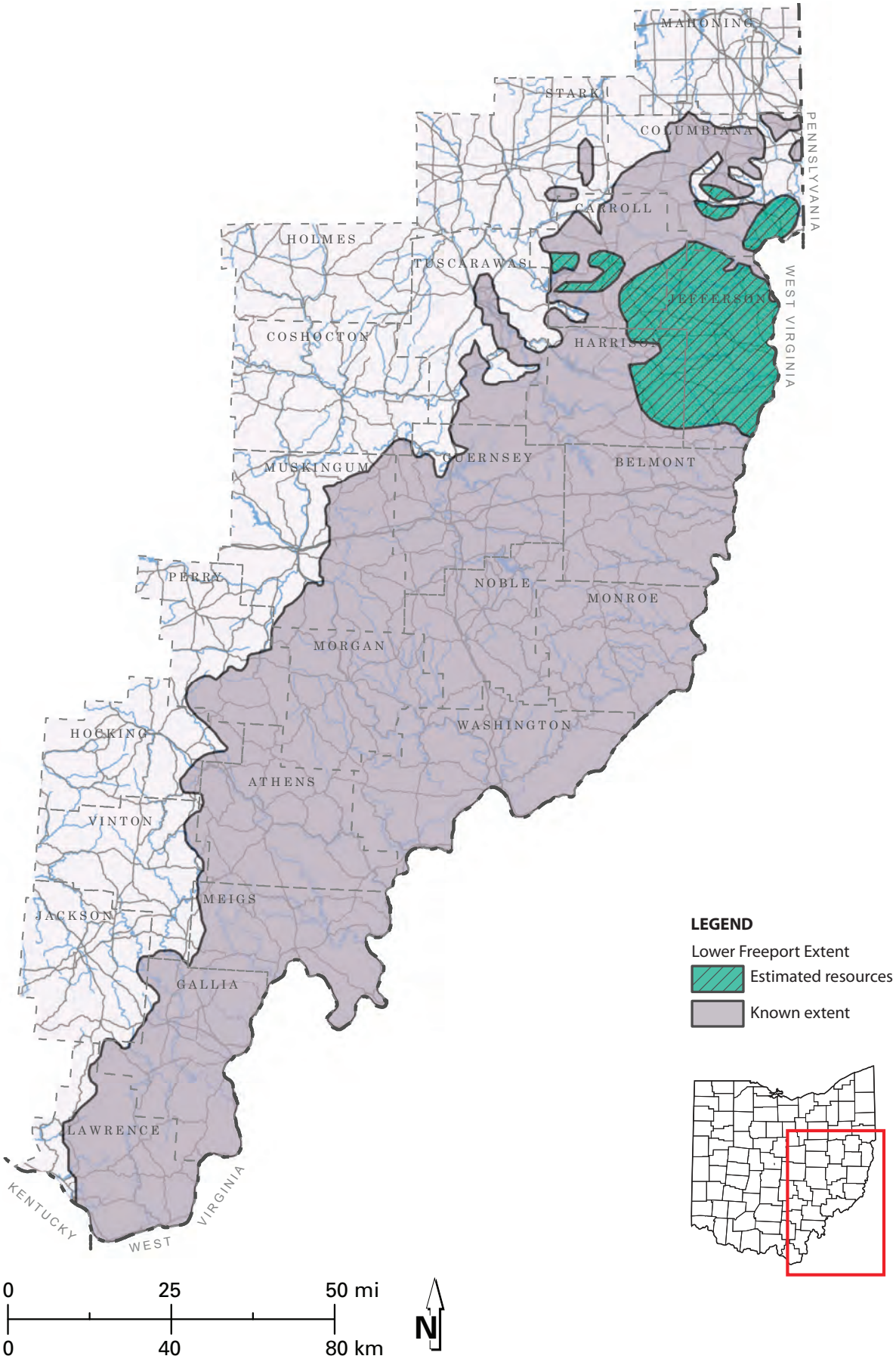

FIGURE 1. Known extent of the Lower Freeport (No. 6a) coal bed in Ohio during the last resource estimate (modified from Brant and DeLong, 1960 fig. 13).

GENERAL GEOLOGY OF THE LOWER FREEPORT (NO. 6a) COAL BED

The Pennsylvanian Period occurred from 323 million years ago to 299 million years ago (Cohen and others, 2013). Pennsylvanian-age rocks in eastern Ohio were deposited into a southeastward-thickening foreland basin (Tewalt and others, 2001). Sea level changes, orogenic events in the east, and a fluctuating deltaic environment contributed to the deposition of discontinuous, repeating lithologic sequences in Ohio. These sequences are composed of sandstones, mudstones, marine and freshwater limestones, clays, and coals (Collins, 1979). Lateral facies changes are often abrupt, and lithological continuity is rare. In Ohio, the Pennsylvanian System of rocks averages 1,100 feet (ft) in thickness and is divided, from oldest to youngest, into four Groups: Pottsville, Allegheny, Conemaugh, and Monongahela (fig. 2).

The Lower Freeport (No. 6a) coal bed lies in the upper portion of the Allegheny Group. Six major coal beds are present in the Allegheny Group in Ohio. Containing numerous coal beds, the Allegheny Group was previously named the Lower Coal Measures (Rogers, 1858).

The Lower Freeport coal bed was deposited in a deltaic setting. This is a chaotic and complex depositional environment; sandstones often replace the Lower Freeport coal bed where it was eroded by channels. In some areas it is absent and flint clays are observed in its depositional interval. Numerous marine transgressions and regressions are recorded in the Allegheny Group; as a result, the Allegheny Group consists of an average of 200 to 300 ft of cyclic deposits containing coal, sandstone, shale, clay, and limestone.

The Lower Freeport coal bed in Ohio is, on average, 40 ft above the Middle Kittanning (No. 6) coal bed and 40 ft below the Upper Freeport (No. 7) coal bed. It is laterally continuous, but it reaches minable thicknesses of greater than 28 inches (in) only in limited areas. The Lower Freeport coal has been predominately mined in Harrison and Jefferson Counties, with a variable mined thickness range between 36 and 80 in. Several structural features affect the Lower Freeport, such as the Cambridge Cross-Strike Structural Discontinuity in Coshocton, Guernsey, Noble, and Washington Counties; the Cadiz anticline in Harrison County, and the Highlandtown (Transylvania) fault zone in Columbiana County (fig. 3).

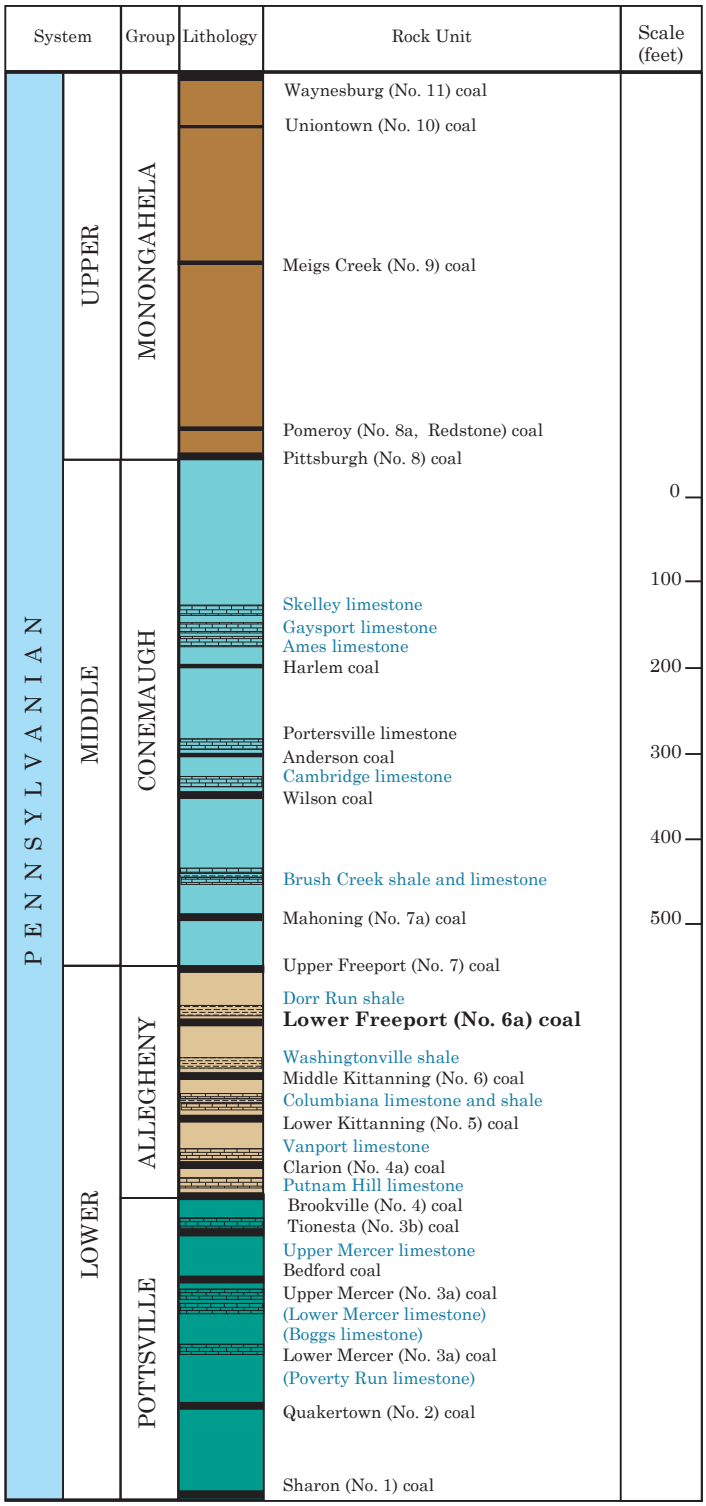

FIGURE 2. Generalized stratigraphic column of the major lithologic units in the Pennsylvanian System in Ohio. Marine units are in blue. (Modified from Struble and others, 1971, fig. 4.)

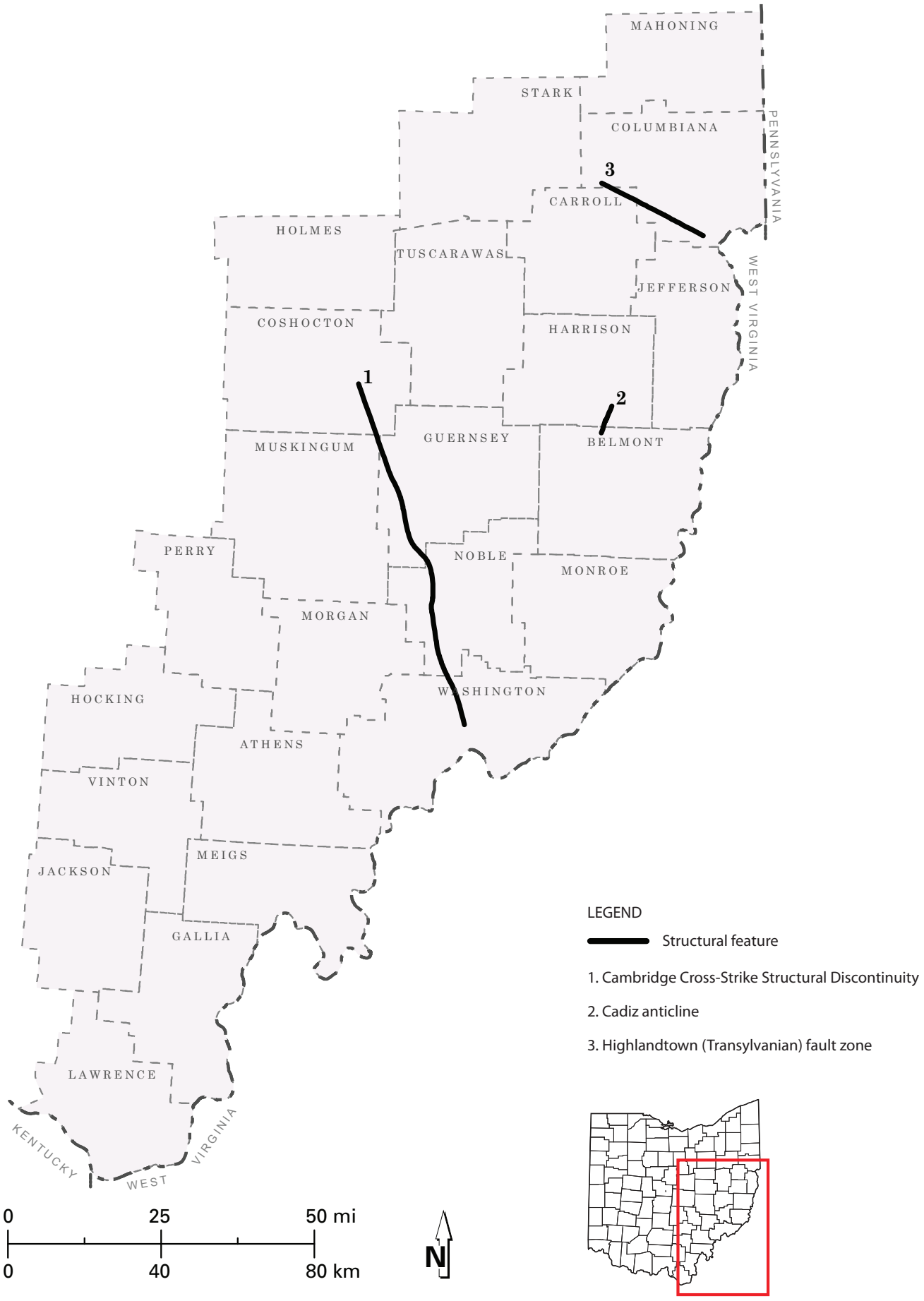

FIGURE 3. Structural features that affect the Lower Freeport (No. 6a) coal bed in Ohio (Modified from Baranoski, 2013).

METHODOLOGY

This investigation used the standard methodology developed by the United States Geological Survey (USGS) to assess coal resources (Wood and others, 1983; Olea and Luppens, 2014). Data points containing geographic coordinates, bottom coal elevations, and coal thicknesses for the Lower Freeport coal bed were compiled and entered into a database. These points were checked for spatial and stratigraphic accuracy and then interpolated to create both a structure map of the base elevation and a thickness (isopach) map for the Lower Freeport coal bed. The isopach map was used to calculate the original resources, which is defined as the amount of coal estimated to have been present prior to mining. The areas containing remaining resources were determined by subtracting the area of coal resources removed by surface and underground mining from the areas of original resources. Areas containing minable resources were calculated by subtracting the areas restricted by land-use and technological factors from areas containing remaining resources. The quantity of coal, summarized by county, was calculated for the original resources, remaining resources, and available resources. Each step in the procedure is described in detail in the following sections.

Data Collection

Data points containing coal thickness and elevation of the bottom of the Lower Freeport coal bed were compiled from the USGS National Coal Resource Data System, which contains over 25,000 stratigraphic points for coal beds throughout Ohio and was the primary data source for resource calculations. Other data sources include information from oil-and-gas wells, Ohio Department of Transportation engineering boring logs, ODNR Division of Soil and Water Resources water well log records, previously measured sections, previously published and unpublished Ohio Geological Survey reports, current mine production information, and abandoned underground mine data obtained through the Ohio Mine Subsidence Insurance program.

After all of the data for the Lower Freeport coal bed were compiled into a database, each record was verified for spatial and vertical accuracy. The data were brought into a GIS and displayed on a map to evaluate for flawed data. The data were assessed within GIS using a digital elevation model (DEM) to confirm that none of the data for the elevations of the coal beds were positioned at higher elevations than the land surface or located implausibly deep in the subsurface.

Miscorrelated points and data entry errors were discovered by (1) comparing adjacent data for the stratigraphic position of the Lower Freeport coal relative to overlying and underlying coal beds, (2) examining outliers of residuals from interpolation results, and (3) comparing the stratigraphic position of the Lower Freeport coal relative to the overlying and underlying coal beds by an examination of raster surfaces.

The first method to identify miscorrelated points and data entry errors compared adjacent elevation data points for the stratigraphic position of the Lower Freeport coal bed relative to the overlying Upper Freeport (No. 7) and underlying Middle Kittanning (No. 6) coal beds. Elevation data from the three coal beds were added to GIS and displayed on maps. If an elevation data point was designated as the Lower Freeport coal bed but neighboring points at approximately the same elevation were designated as a coal bed other than the Lower Freeport coal, it was assumed that there was an error in correlation. This method is useful for removing obvious miscorrelations except in unusual geologic circumstances, such as coal deposition in an erosional channel.

The second method assessed the outliers of residuals from interpolation results. Raster surfaces of coal thickness and structure were created from the point dataset. Residual values for each point were calculated by subtracting the observed value from the predicted value. Positive residuals indicate where the predicted value of the data point was greater than the observed value of the data point. Negative residuals indicate where the predicted value of the data point was less than the observed value of the data point. The residual outliers (highest and lowest residual values) were inspected closely for miscorrelation or data entry errors. Points were removed from the dataset if several adjacent points showed a significant and consistent difference in residual values. The elevation of a coal bed should remain relatively consistent in a localized area; however the thickness of a coal bed can vary dramatically over short distances beyond the localized area because of the variability of the environment in which the coal was deposited. If there were no surrounding points for comparison, or other justifiable reasons to remove a point, the outlier was kept in the database.

The third method of detecting miscorrelated points and data entry errors was to create structure elevation maps to compare the stratigraphic position of the Lower Freeport coal bed relative to the overlying Upper Freeport (No. 7) and underlying Middle Kittanning (No. 6) coal beds. If the Lower Freeport coal bed intersected either the underlying or overlying surfaces, there were obvious correlation or data entry errors in the data used to create the surfaces. Several correlation errors were found and eliminated using this method.

Map Creation

Structure map

The base elevation structure raster was created in GIS using the Natural Neighbor interpolation technique. Natural Neighbor is an interpolation technique that uses Voronoi tessellation to assign weights to nearby points and interpolate values based on those weights (Hiyoshi, 2008); this is also known as a Sibson or "area stealing" approach to interpolation. Natural Neighbor interpolation often is used for data comprised of large, clustered-point datasets similar to the Lower Freeport coal bed dataset (Childs, 2004). This technique does not infer trends nor interpolate beyond the maximum and minimum data values and the areal extent of the data. The Natural Neighbor interpolation produced a continuous surface of estimations for the structure of the coal bed. The extent of the continuous surface estimation encompasses the extent of all data points used in the interpolation. Therefore, the extents of the structure map were clipped to the outcrop of the coal bed and state boundary. The outcrop of the coal bed was delineated by removing areas of the surface estimation that had higher elevations than the DEM.

Original resources

Original coal resources are defined as the amount of coal estimated to have been present prior to mining. Simulation methods for coal resource assessments have been widely studied (Heriawan and Koike, 2008; Olea and others, 2011; Bertoli and others, 2013; Cornah and others, 2013; de Souza and others, 2013; Ertunç and others, 2013; Geboy and others, 2013; Pardo-Igúzquiza and others, 2013; Saikia and Sarkar, 2013; Srivastava, 2013; Tercan and others, 2013; Tercan and Sohrabian, 2013; Webber and others, 2013; Olea and Luppens, 2014).

A sequential Gaussian simulation approach using ArcGIS Geostatistical Analyst was used to create the original resources isopach map in accordance with the current USGS methodology for estimating coal reserves (Olea and Luppens, 2014).

Sequential Gaussian simulation produces different but equally probable raster layers, called *realizations*, from the thickness data points using a simple kriging interpolation method. Each realization is a different representation of the coal bed created from the same data. Figure 4 is a conceptual diagram that illustrates different but plausible maps created from a small hypothetical data set. For this study, 200 realizations were created for the thickness of the Lower Freeport coal bed. Each realization was created at a 500-ft raster cell grid size, the smallest spacing that ArcGIS could process because of the sizable extent of the dataset.

A single realization using indicator kriging was created to determine cells that had less than a 15 percent

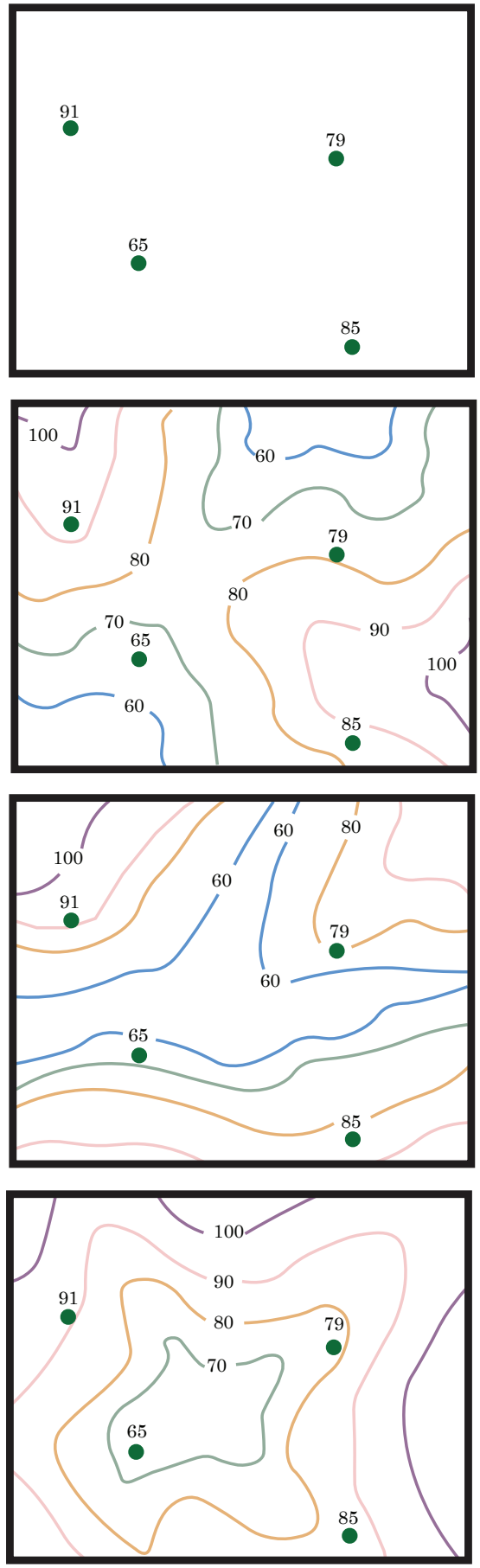

FIGURE 4. Example of three different but valid contour maps, all drawn from the same data (shown in the top image). Modified from Olea and others (2011).

probability of coal presence. These cells were removed from the original resource estimation. A single realization was created for this study because ArcGIS does not support sequential indicator simulation. This methodology diverges from Olea and others (2011) where multiple indicator kriging realizations are performed to determine the probability of coal presence.

The data distributions of the output of the 200 realizations were summarized on a per-cell basis to create rasters that represent the distribution of the estimation. For this study, output rasters, based on the distribution of values at each cell, include the 5th, 25th, 50th (median), 75th, and 95th percentiles. In this report, the median values are reported for the resource estimation. However, the appendix contains charts and tables of the distribution values summarized by county.

The next procedure took the 500-ft grid raster layer that represents the distribution of the estimation and resampled them to 100-ft cell size. This was necessary for removing land-use restrictions to estimate the available resource maps (as described in the section below). For example, oil-and-gas wells are required, by law, to have a 100-ft buffer around them in areas where the well penetrates a coal bed. Therefore, any cell that contains an oil-and-gas well is removed from the estimation. If the cell size of the estimation rasters were retained at 500 ft, a greater volume of coal would be removed from the estimation than compared to a 100-ft cell size.

The final procedure in creating the original resource isopach map was to remove specific areas from the original resources raster layer. First, areas in which the coal bed was less than 14 in thick were not considered a resource and were removed from the thickness map. Secondly, areas considered "hypothetical" by the Coal Resource Classification System of the USGS were removed from the thickness maps (Wood and others, 1983). Areas classified as hypothetical are areas where beds are located beyond a 3-mi radius from a thickness data-point measurement. Very few areas in the study area were excluded because of a lack of data, as most areas have at least one data point within a 3-mi radius; this was also a deviation from the methodology of Olea and Luppens (2014). Finally, the original resource isopach grids were clipped to the state boundary and outcrop extent based on the DEM.

Remaining resources

For the Lower Freeport coal bed, areas containing remaining resources were determined by subtracting areas of coal resources removed by surface and underground mining from areas of original resources. Using the abandoned underground mine and surface mine GIS datasets, the mined-out coal is removed from the original coal resource estimate to arrive at an in-situ resource estimate.

Two GIS layers, created by the ODNR Division of Mineral Resources Management, were used to delineate areas where the coal beds have been removed through surface mining. The first GIS layer portrays all of the recently permitted and documented surface mines. The second layer depicts all surface mine disturbances, shown on historic topographic maps, that were mined before documentation and permitting was required for surface mines.

GIS layers showing abandoned underground mines, created by the Ohio Geological Survey as part of a study for the Ohio Mine Subsidence Insurance Underwriting Association, were used to remove areas from the original resources where the coal was removed through deep-underground mining.

The remaining resources for the Lower Freeport coal were divided into remaining surface-minable coal and remaining deep-minable coal. To make this determination, a 20:1 overburden-to-coal thickness ratio was used as an indicator of the economic feasibility of surface mining or underground mining. Base structure maps of the coal beds and the DEM were used to create a 20:1 overburden-to-coal thickness delineation. Regions of remaining resources located in areas where the overburden was less than 20:1 were classified as surface minable, and areas greater than 20:1 were classified as deep minable.

Available resources

Areas containing available resources were determined by subtracting the areas restricted by land-use and technological factors from areas containing remaining resources; this method is based on the work of Eggleston and others (1990) and Axon (1996). Land-use restrictions affected the availability of surface-minable coal and technological restrictions affected deep-minable coal. Oil-and-gas wells affected both surface- and deep-minable coal. Buffers around the restrictions ensure that the restricted features are protected from potential damage that could result from mining activities (table 1).

GIS layers depicting restricted areas for surface- and deep-minable coal were created. Most maps that show restriction classifications came from existing GIS layers from the State of Ohio databases; exceptions include airports, wetlands, streams, and coal less than 28 in thick. Airports were digitized from topographic maps. Wetland polygons were taken from the National Wetlands Inventory compiled by the U.S. Fish and Wildlife Service. Stream maps came from the National Hydrography Dataset. The restriction for coals beds less than 28 in thick was derived from the remaining resources maps created for this project.

TABLE 1. ***Restrictions to mining and the amount of buffer required for each restriction***

Restriction	Buffer (ft)	Restriction Type		Type of Mining	
		Land use	Techno-logical	Surface	Deep
Airports	100	•		•	
Cemeteries	300	•		•	
Roads	100	•		•	
Railroads	100	•		•	
Towns	0	•		•	
Streams	100	•		•	
State parks	0	•		•	
Oil-&-gas wells	100	•		•	•
Wetlands	0	•		•	
Mine barrier	100	•			•
Coal too thin (< 28 in)			•		•

To create the available resources maps, the GIS restriction layers were buffered by their appropriate distances and the restrictions removed from the remaining resources layers.

County resource calculations

The quantity of coal, summarized by county, was calculated for the original resources, remaining resources, and available resources for the Lower Freeport coal using the following formula:

$$Q = S_c \times A_c \times T_c$$

where:

Q = quantity of coal in county (short tons)

S_c = sum of coal thickness in county from created resources maps (inches)

A_c = factor converting for resource map cell size to acres

T_c = constant, 150 short tons per acre-inch estimate for bituminous coal (Wood and others, 1983)

RESULTS

Maps depicting the base elevation structure and original, mined-out, remaining, restricted, and available coal resources were created for the Lower Freeport coal bed in Ohio. These maps were used to calculate statewide and county coal resource estimates and the results are shown in plates at the end of the report or as insets in the plates. Table 2 shows the total coal resources, summarized by county with state totals, for the Lower Freeport coal bed. Values represented in the text and depicted in the plates represent the median values of the estimations. The appendix contains charts and tables of the percentile distribution values of the resource estimations summarized by county.

Structure Map

Plate 1 shows the extent and base elevation structure for the Lower Freeport coal bed in Ohio. A total of 7,190 elevation data points were used to construct this map. Data points are clustered in the northern portion of the study area, where the highest concentration of mines is located, and in the western portions close to the outcrop of the coal bed. A cluster of data points in Athens County are from drilling logs targeting the Middle Kittanning (No. 6) coal bed, which underlies the Lower Freeport coal bed. Data points are more widely distributed in the eastern region of the study area and in regions of lowest coal bed elevation. Deep geophysical logs provided information in Washington County where the Lower Freeport coal lies deep below the surface.

The Lower Freeport coal bed underlies 24 counties in Ohio. Elevation of the base of the Lower Freeport coal is between –362 and 1,283 ft above m.s.l. Highest elevations are in the west where the lower Freeport coal outcrops, and the lowest elevations are along the Ohio River in Monroe, Washington, Athens, and Meigs Counties. The Lower Freeport coal bed dips approximately 20 ft per mile to the southeast.

Original Resources

Original resources are defined as the amount of coal estimated to have been present prior to mining. Plate 2 shows the original resources for the Lower Freeport coal in Ohio. A total of 3,277 thickness data points were used to create this map. Data points are clustered in the northern portion of the study area and throughout Athens and Perry Counties. Data points are less clustered and sparse in the eastern portions of the study area where overburden is the thickest.

Prior to mining, approximately 6.2 billion short tons of Lower Freeport coal existed in Ohio. Data points show that the thickness of the Lower Freeport coal bed varies from 0 to 111 in in Ohio. However, the maximum thickness data points were isolated near points showing considerably lower thickness values; thus the interpolation technique smoothed the data to a maximum thickness of 98 in. The thickest widespread deposits occur in Jefferson and Harrison Counties. The thickest deposits are in Harrison County where the thickness exceeds 100 in and the bed contains the highest amount of the original resources with 1.1 billion short tons.

Remaining Resources

Remaining resources were determined by subtracting areas of coal resources removed by surface and underground mining from areas of original resources. Plate 3 depicts the remaining resources of the Lower Freeport coal bed in Ohio. Approximately 6 percent of the

TABLE 2. ***Median estimation of coal tonnages[1] for the Lower Freeport (No. 6a) coal bed in Ohio, by county and type of availability***

				Surface-Minable			Deep-Minable			
County	**Original Resources**	**Remaining Resources**	**Mined Resources**	**Remaining Resources**	**Land-Use Restricted Resources**	**Available Resources**	**Remaining Resources**	**Technologically Restricted Resources**	**Land-Use Restricted Resources**	**Available Resources**
Athens	43,195	38,685	4,510	2,784	1,004	1,779	35,901	30,187	314	5,400
Belmont	641,361	641,361	-	-	-	-	641,361	476,741	2,605	162,016
Carroll	337,357	332,167	5,190	7,629	2,798	4,831	324,539	238,459	1,808	84,272
Columbiana	207,152	205,150	2,002	5,336	3,105	2,231	199,813	175,379	55	24,379
Coshocton	14,169	12,463	1,706	2,280	343	1,937	10,183	5,324	83	4,776
Gallia	139,251	139,251	-	1,502	654	848	137,749	117,970	80	19,699
Guernsey	451,883	450,742	1,141	4,644	2,122	2,522	446,098	391,849	1,327	52,922
Harrison	1,140,743	913,762	226,981	4,996	2,310	2,685	908,766	264,606	9,044	635,116
Hocking	41,698	32,863	8,835	5,091	1,034	4,057	27,771	26,349	116	1,306
Holmes	323	323	-	109	15	94	214	214	-	-
Jackson	25,365	25,365	1	6,337	1,411	4,926	19,028	15,737	-	3,291
Jefferson	1,023,401	894,235	129,166	15,181	8,509	6,671	879,054	251,901	8,583	618,570
Lawrence	120,797	120,713	84	4,124	2,133	1,991	116,589	94,255	99	22,235
Mahoning	42	42	-	7	-	7	35	35	-	-
Meigs	2,227	2,227	-	-	-	-	2,227	2,227	-	-
Monroe	726,779	726,779	-	-	-	-	726,779	493,018	10,445	223,316
Morgan	70,344	70,344	-	-	-	-	70,344	70,344	-	-
Muskingum	47,791	47,258	534	1,687	485	1,203	45,571	44,529	33	1,009
Noble	589,181	589,181	-	-	-	-	589,181	378,210	11,503	199,468
Perry	37,557	36,433	1,125	2,478	773	1,705	33,955	30,838	232	2,885
Stark	8,201	7,187	1,013	1,272	278	994	5,915	5,915	-	-
Tuscarawas	45,142	41,165	3,977	2,695	601	2,094	38,469	36,378	41	2,050
Vinton	4,341	4,192	149	1,025	213	812	3,168	3,168	-	-
Washington	436,150	436,150	-	-	-	-	436,150	320,290	5,931	109,928
OHIO TOTAL[2]	**6,154,452**	**5,768,038**	**386,415**	**69,178**	**27,789**	**41,389**	**5,698,860**	**3,473,922**	**52,301**	**2,172,637**

[1]Thousands of short tons.
[2]Any tally inconsistencies are due to rounding of tonnages to the nearest ton.

Lower Freeport coal bed has been mined in Ohio; an estimated 5.8 billion short tons of the 6.2 billion short tons of original resources remain.

Of the remaining resources, 5.7 billion short tons are deep-minable coal and 69 million short tons are surface-minable coal. Harrison County has the highest amount of remaining deep-minable Lower Freeport coal with 909 million short tons. Jefferson County has the highest amount of remaining surface-minable reserves with 15 million short tons.

Available Resources

Areas containing available resources were constructed by subtracting the areas restricted by land-use and technological factors from areas containing remaining resources. Approximately 2.2 billion short tons of the Lower Freeport are available for deep and surface mining.

Deep-minable coal

Plate 4 shows the extent and thickness of the available deep-minable coal for the Lower Freeport coal bed in Ohio and the extents of the restrictions. After removing 3.5 billion short tons of coal because of restrictions from the 5.7 billion short tons of remaining deep resources, an estimated 2.2 billion short tons are available for deep mining. Harrison County has the highest amount of available resources with 635 million short tons of deep minable reserves.

Surface-minable coal

Plate 5 shows the extent and thickness of the available surface-minable coal for the Lower Freeport coal bed in Ohio and the extents of the restrictions. After removing 28 million tons of coal because of restrictions from the 69 million tons of remaining surface resources, an estimated 41 million short tons are available for surface mining. Jefferson County has the highest amount of available resources with 7 million short tons of surface-minable reserves.

DISCUSSION

Uncertainty in the Methodology

Every effort was made to ensure that the methods used in the study resulted in an accurate estimation of the coal resources. However, deviations in the methodology from the previous studies potentially could have impacted the accuracy of the results.

Some outliers and miscorrelated points possibly were not removed from the dataset. This introduces some uncertainty into the estimate especially in areas of low data density where correlations are difficult to make.

The study area of this report encompasses a much larger area than most previous studies. This estimation covered 7,000 mi^2, while Olea and Luppens (2014) covered only an estimated 400 mi^2. Thus the methodology had to be adapted to deal with some of the issues that appear in such a large dataset, such as ArcGIS reaching its processing limitations at a cell size of 500 ft^2.

For this study, ArcGIS software was used to perform the estimations, whereas Olea and Luppens (2014) used the Stanford Geostatistical Modeling Software, a more robust statistical package. The advantages of ArcGIS include allowing for quickly calculating and removing restricted coal resources. However, ArcGIS had limitations in the processing capability for a large study area and lacked some interpolation techniques. For example, ArcGIS can perform sequential Gaussian simulation, though it cannot perform sequential indicator simulation. Therefore, one indicator kriging realization was used to remove data where coal had only a 15 percent probability, or less, to be greater than zero inches. Using only one realization instead of 100 realizations, as described by Olea and others (2011), should not have much effect on the estimation because all coal below 14 in is removed in subsequent processes. Thus even if the multiple realizations would more accurately model areas of coal presence or absence, most of these areas of low coal thickness would be removed from the estimate anyway.

Because of the size of the study area, the methods diverged from Olea and Luppens (2014), and all coal farther than 3 mi from a data point was removed. This corresponds to the area of hypothetical resources as described by Wood and others (1984). Several regions in the study area have few data points, and some of these data points show large thicknesses of coal. Removing any coal beyond the 3-mi radius of a data point prevents the estimation from including large areas of coal where data is lacking, although this process may remove resource areas that potentially are present in the real world. It is also important to remove areas beyond 3 mi because of the increased likelihood of miscorrelation in low data density areas. The 3-mi boundary limits the impact of mistakes in the dataset and limits interpolation in areas of no data.

Results

Original resources tonnage estimates are much larger than the previous estimate. This report estimates 6.2 billion short tons of Lower Freeport (No. 6a) coal, while Brant and Delong (1960) estimated 2.4 billion. This increase can be attributed to two factors. First, the 1960 estimate considered resources only in portions of four counties (fig. 3), while the new estimate is statewide and encompasses 24 counties. Secondly, more data has been collected in the past 55 years, revealing previously unknown deposits of Lower Freeport coal.

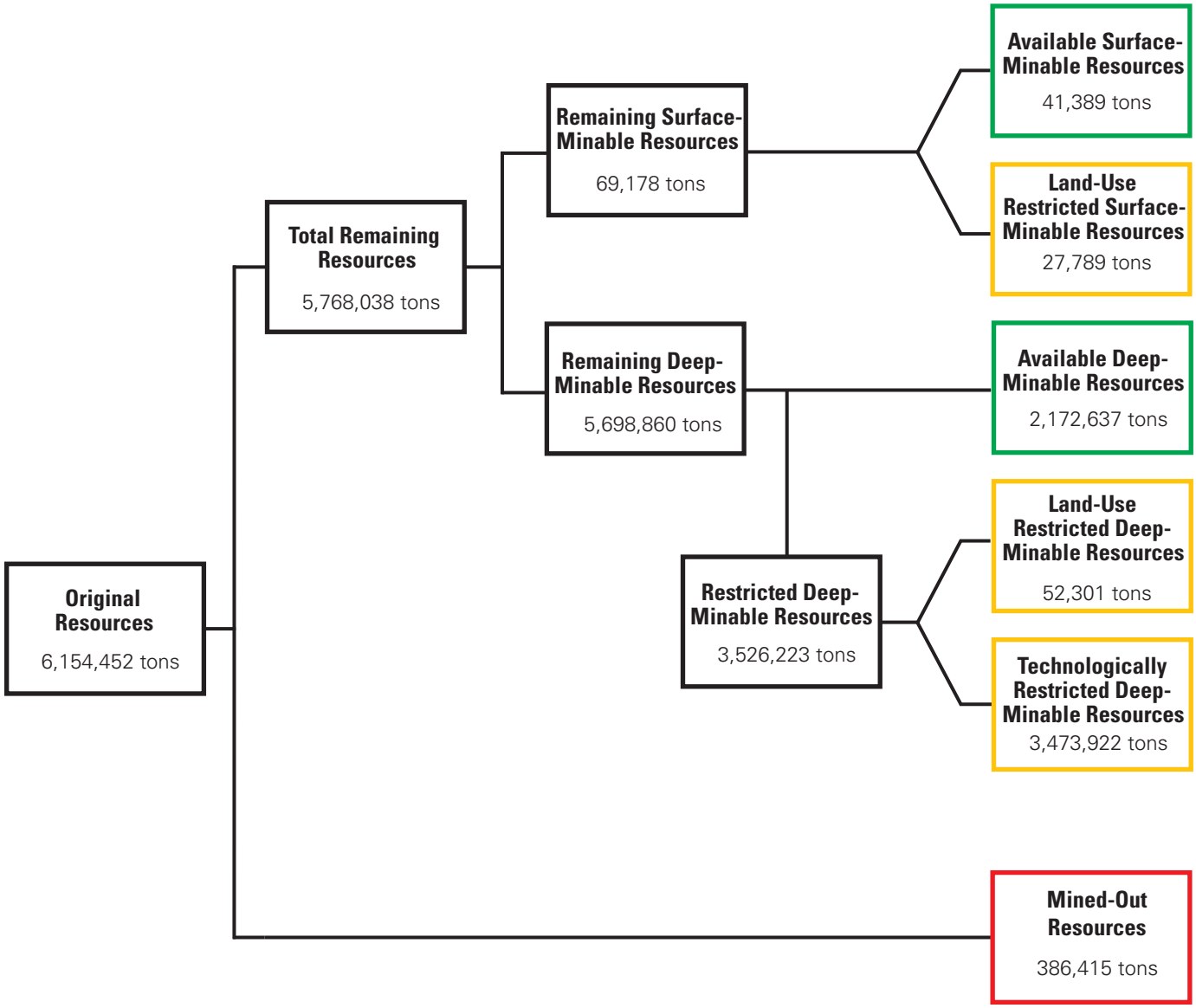

FIGURE 5. Summary of the median estimation of the coal resources (thousands of short tons) in the Lower Freeport (No. 6a) coal bed in Ohio.

In the Lower Freeport coal bed there are 5.7 billion short tons of remaining deep-minable resources, while there are only 69 million short tons of remaining surface-minable resources (fig. 5). In the future, land-use restrictions that impact the availability of surface mining could possibly increase because of urbanization and environmental regulations. However, technological restrictions could decrease the restrictions on deep-minable coal. Technological restrictions do not allow deep mining of coal thinner than 28 in. Sixty-one percent of the deep-minable Lower Freeport coal is less than 28 in thick. Future technologies may allow for deep mining of thin coal beds. Given that considerably more deep-minable coal remains than surface-minable coal, improvement in technology will allow for the Lower Freeport coal bed to become an even more economically viable resource for Ohio.

Data is sparse near the Ohio River where the Lower Freeport coal bed is overlain by more than 1,000 ft of cover. Data near the Ohio River are from geophysical logs from oil-and-gas wells and a few deep continuous cores drilled by the Ohio Geological Survey. Estimation of the coal resources in the Ohio River region could potentially be underestimated. Additional data points are necessary to better quantify the resources in areas where the overburden is greatest.

CONCLUSIONS

This report provides a resource evaluation of the Lower Freeport (No. 6a) coal bed in Ohio, the first statewide estimation of coal resources in 55 years for this coal. The Lower Freeport coal has 2.2 billion short tons of available resources.

The Lower Freeport coal bed is estimated to have contained approximately 6.2 billion short tons of coal in Ohio before mining. Of that amount, 400 million

short tons have been mined and approximately 5.8 billion short tons remain. Of the remaining resources, 41 million short tons are available to be mined through surface mining, and 2.2 billion short tons are available to be mined through underground methods. Given the current rate of mining for the Lower Freeport coal (Stucker, 2015), these resources will last for more than a century. The majority of the remaining reserves exist in Harrison and Jefferson Counties.

ACKNOWLEDGMENTS

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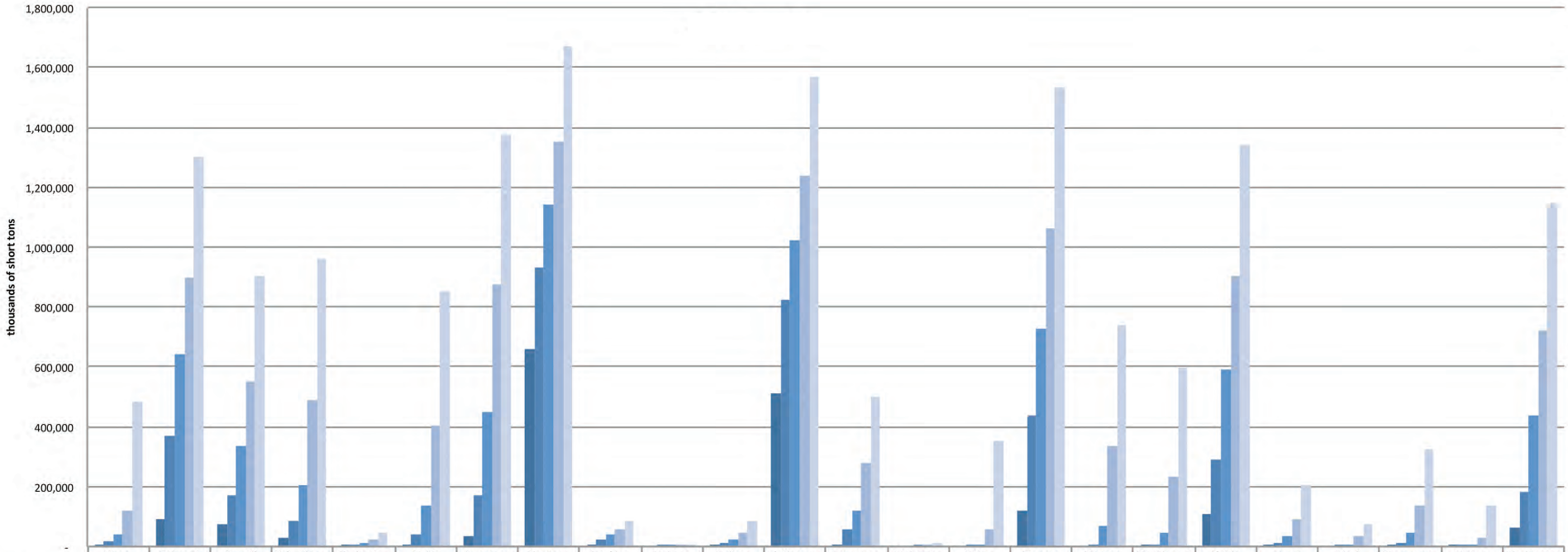
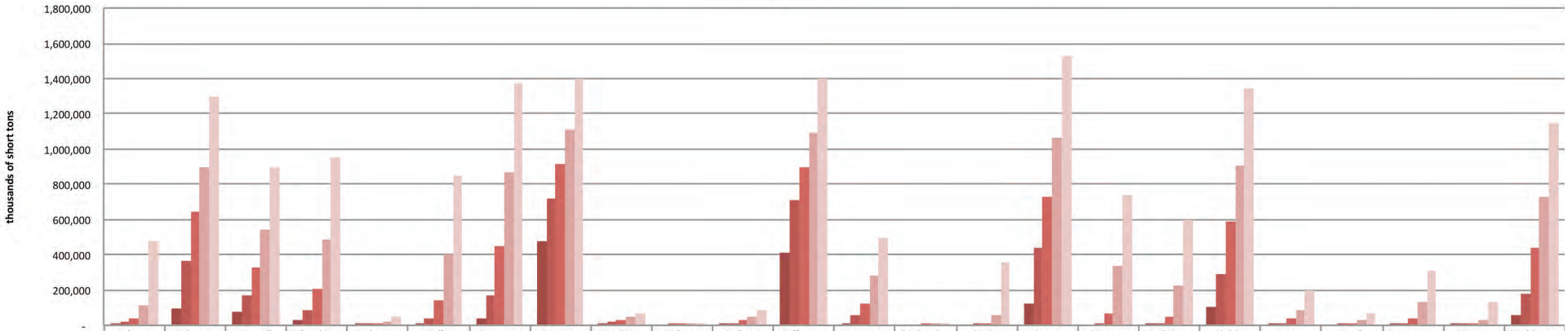
APPENDIX



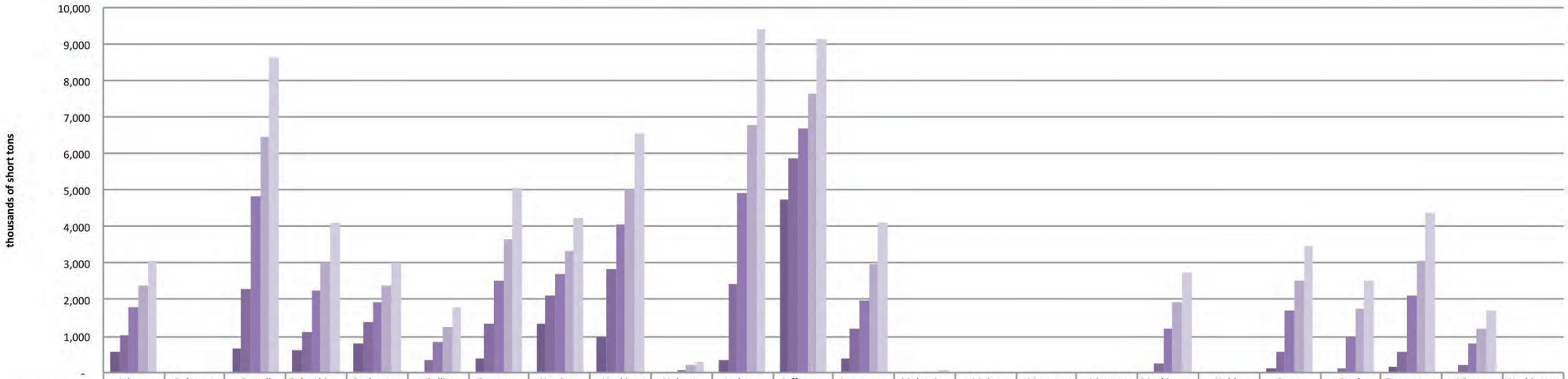
	Athens	Belmont	Carroll	Columbiana	Coshocton	Gallia	Guernsey	Harrison	Hocking	Holmes	Jackson	Jefferson	Lawrence	Mahoning	Meigs	Monroe	Morgan	Muskingum	Noble	Perry	Stark	Tuscarawas	Vinton	Washington
5th Percentile	8,619	93,459	73,808	31,194	4,028	6,531	37,020	659,294	7,754		963	511,728	6,287			122,045		316	107,141	3,614		4,317	33	61,382
25 Percentile	19,603	368,210	173,156	86,750	8,425	38,991	169,576	931,509	25,900	4	9,816	824,023	59,054		3	438,944	519	5,542	290,468	12,247	1,080	12,304	766	180,720
50 Percentile	43,195	641,361	337,357	207,152	14,169	139,251	451,883	1,140,743	41,698	323	25,365	1,023,401	120,797	42	2,227	726,779	70,344	47,791	589,181	37,557	8,201	45,142	4,341	436,150
75th Percentile	119,687	899,708	554,336	488,499	24,283	402,696	872,562	1,354,734	59,210	1,695	48,630	1,238,141	279,313	4,787	55,779	1,061,187	334,755	231,715	902,127	90,974	34,329	138,404	31,146	724,247
95th Percentile	481,469	1,300,834	905,397	959,512	47,506	849,921	1,377,674	1,671,347	83,366	3,482	84,344	1,569,458	499,574	14,766	353,970	1,533,425	739,140	599,375	1,339,556	206,899	71,763	321,884	136,432	1,147,122

FIGURE A1. Percentile estimations of original resources (in thousands of short tons) for the Lower Freeport (No. 6a) coal bed in Ohio, by county.



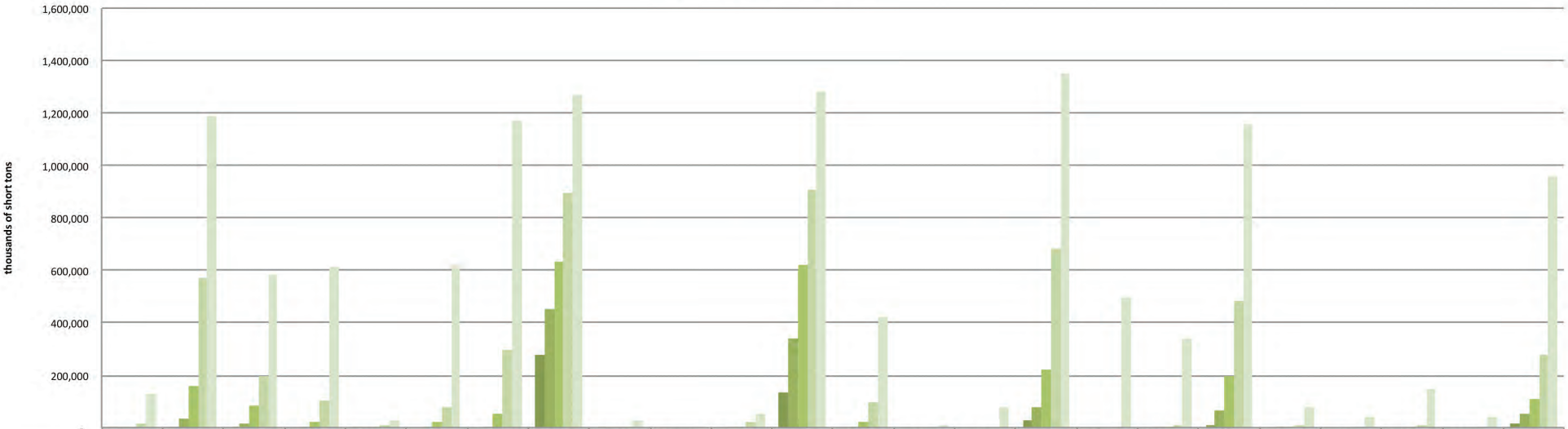
	Athens	Belmont	Carroll	Columbiana	Coshocton	Gallia	Guernsey	Harrison	Hocking	Holmes	Jackson	Jefferson	Lawrence	Mahoning	Meigs	Monroe	Morgan	Muskingum	Noble	Perry	Stark	Tuscarawas	Vinton	Washington
5th Percentile	7,447	93,459	72,078	30,749	3,295	6,531	36,436	472,776	5,382		963	413,194	6,286			122,045		288	107,141	3,547		3,936	33	61,382
25 Percentile	17,069	368,210	169,989	85,710	7,341	38,991	168,639	721,730	19,685	4	9,816	707,648	58,986		3	438,944	519	5,386	290,468	11,933	402	10,144	727	180,720
50 Percentile	38,685	641,361	332,167	205,150	12,463	139,251	450,742	913,762	32,863	323	25,365	894,235	120,713	42	2,227	726,779	70,344	47,258	589,181	36,433	7,187	41,165	4,192	436,150
75th Percentile	113,453	899,708	546,627	484,158	21,947	402,595	871,222	1,110,470	48,135	1,695	48,629	1,095,111	279,210	4,716	55,779	1,061,187	334,744	229,992	902,127	88,331	32,849	132,514	30,926	724,247
95th Percentile	473,274	1,300,834	895,300	951,276	44,208	849,755	1,376,049	1,401,416	68,937	3,482	84,343	1,404,460	499,435	14,629	353,970	1,533,425	739,114	595,735	1,339,556	202,028	69,759	313,748	136,112	1,147,122

FIGURE A2. Percentile estimations of remaining resources (in thousands of short tons) for the Lower Freeport (No. 6a) coal bed in Ohio, by county.



	Athens	Belmont	Carroll	Columbiana	Coshocton	Gallia	Guernsey	Harrison	Hocking	Holmes	Jackson	Jefferson	Lawrence	Mahoning	Meigs	Monroe	Morgan	Muskingum	Noble	Perry	Stark	Tuscarawas	Vinton	Washington
5th Percentile	553	-	641	596	814	-	393	1,325	964		336	4,733	400			-		17	-	137		176	31	-
25 Percentile	1,036	-	2,279	1,122	1,404	360	1,321	2,098	2,823	-	2,441	5,855	1,214		-	-	-	264	-	556	128	561	207	-
50 Percentile	1,779	-	4,831	2,231	1,937	848	2,522	2,685	4,057	94	4,926	6,671	1,991	7	-	-	-	1,203	-	1,705	994	2,094	812	-
75th Percentile	2,370	-	6,466	3,027	2,364	1,267	3,635	3,315	4,997	196	6,793	7,631	2,982	35	-	-	-	1,919	-	2,513	1,759	3,077	1,204	-
95th Percentile	3,060	-	8,623	4,089	3,007	1,807	5,056	4,226	6,554	286	9,396	9,154	4,090	50	-	-	-	2,743	-	3,475	2,533	4,398	1,701	-

FIGURE A3. Percentile estimations of available surface-minable resources (in thousands of short tons) for the Lower Freeport (No. 6a) coal bed in Ohio, by county.



	Athens	Belmont	Carroll	Columbiana	Coshocton	Gallia	Guernsey	Harrison	Hocking	Holmes	Jackson	Jefferson	Lawrence	Mahoning	Meigs	Monroe	Morgan	Muskingum	Noble	Perry	Stark	Tuscarawas	Vinton	Washington
5th Percentile	224	3,089	1,523	-	591	-	-	278,411	9		-	136,421	-			28,709		-	8,678	-		-	-	16,676
25 Percentile	1,952	35,195	17,657	414	2,031	2,062	1,315	454,591	511	-	135	340,990	20		-	81,358	-	10	68,316	601	-	-	-	53,005
50 Percentile	5,400	162,016	84,272	24,379	4,776	19,699	52,922	635,116	1,306	-	3,291	618,570	22,235	-	-	223,316	-	1,009	199,468	2,885	-	2,050	-	109,928
75th Percentile	14,950	568,389	197,436	101,139	9,293	79,643	299,476	892,745	6,181	-	19,671	910,134	97,360	-	-	685,035	6,252	12,512	481,161	11,184	1,447	9,557	35	278,740
95th Percentile	128,085	1,190,108	582,159	615,037	26,568	629,458	1,169,558	1,268,366	28,777	2,357	55,506	1,282,360	419,736	8,497	80,664	1,349,097	494,195	340,850	1,154,574	75,928	40,224	145,712	39,283	956,192

FIGURE A4. Percentile estimations of available deep-minable resources (in thousands of short tons) for the Lower Freeport (No. 6a) coal bed in Ohio, by county.

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STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Thomas J. Serenko, Chief

STRUCTURE MAP OF THE LOWER FREEPORT (NO. 6a) COAL BED IN OHIO

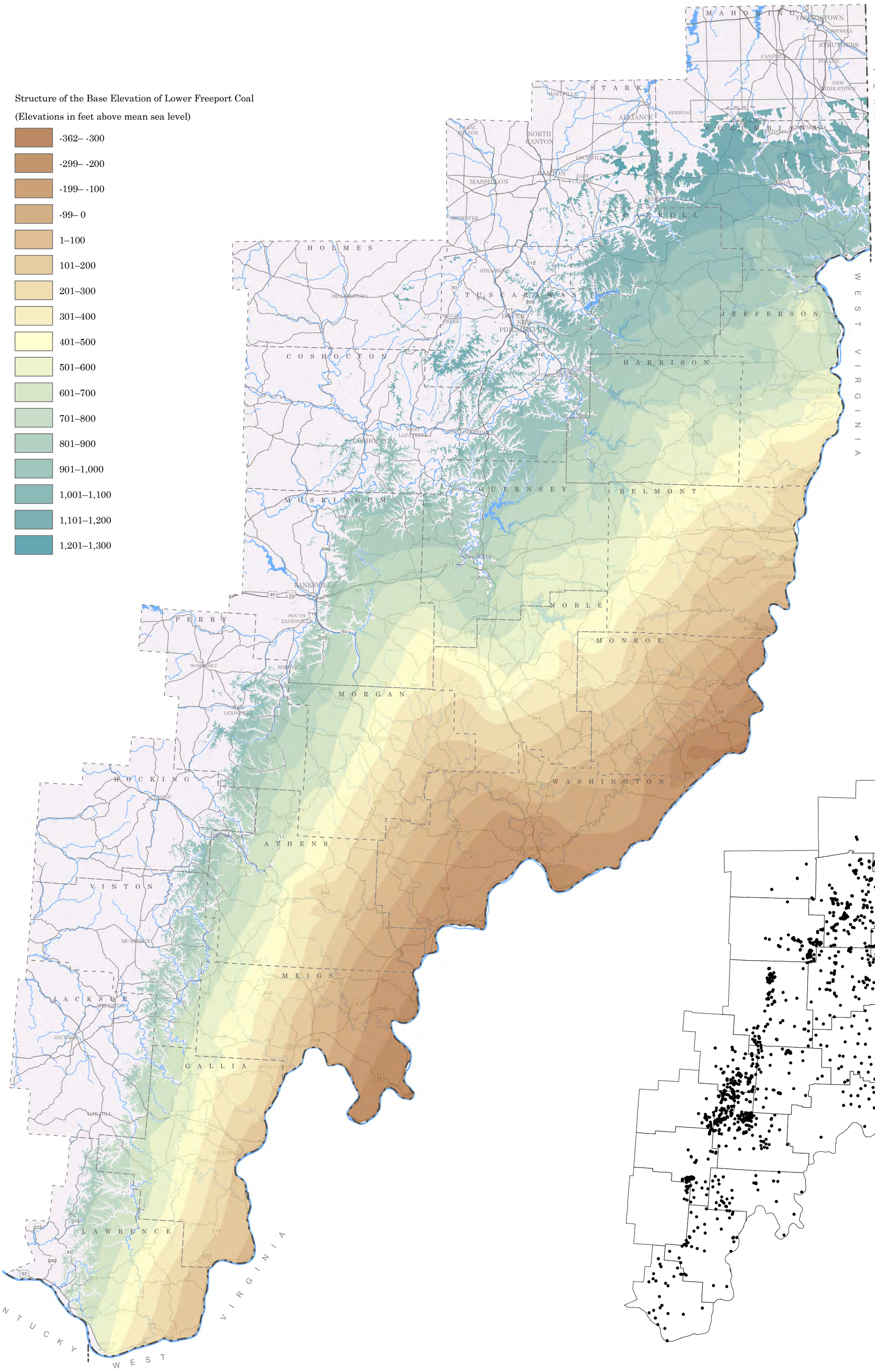
by
Lee M. Sorrell and Paul N. Spahr

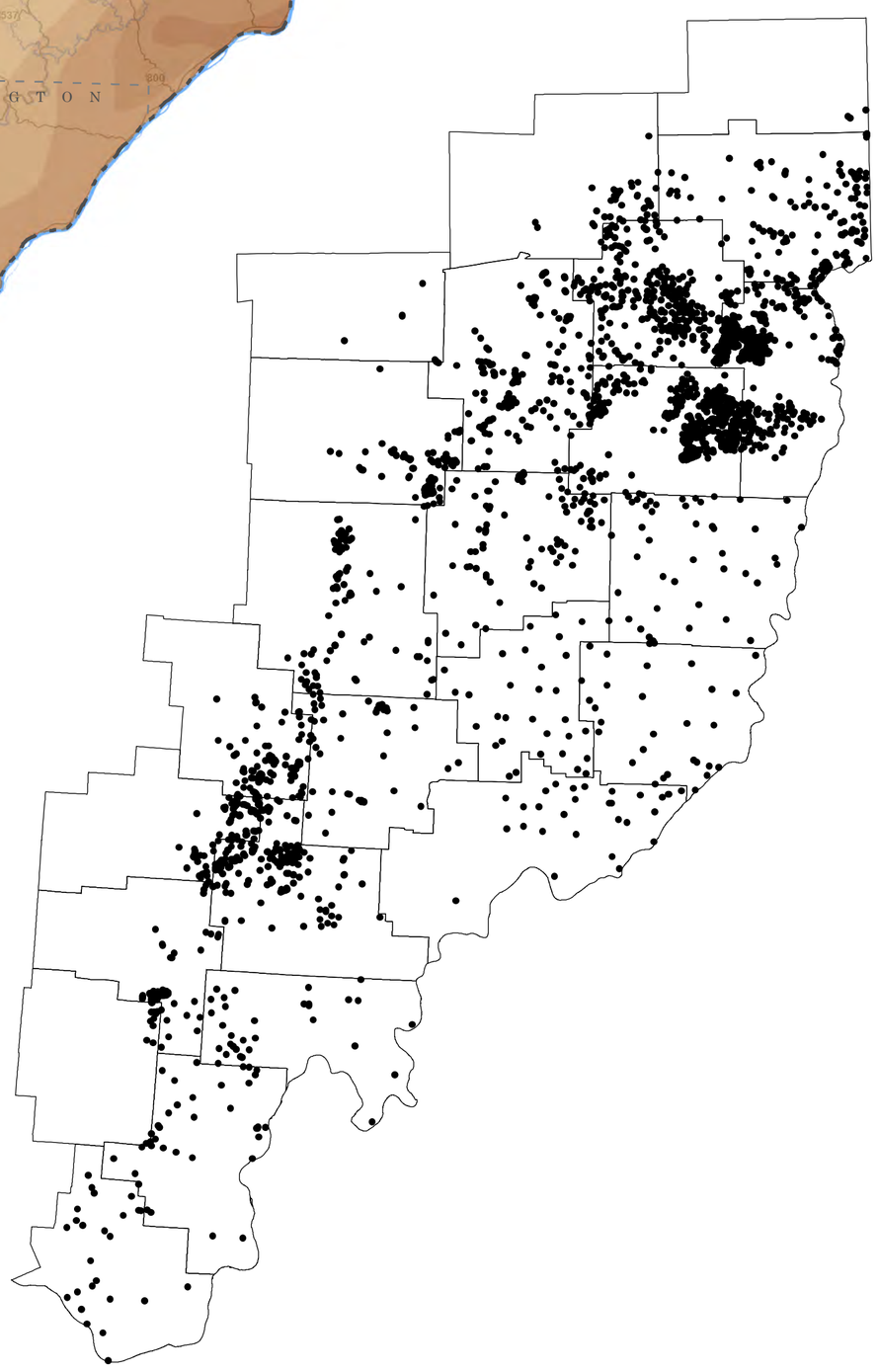
PLATE 1
Open-File-Report 2016-1

Structure of the Base Elevation of Lower Freeport Coal

(Elevations in feet above mean sea level)

- -362– -300
- -299– -200
- -199– -100
- -99– 0
- 1–100
- 101–200
- 201–300
- 301–400
- 401–500
- 501–600
- 601–700
- 701–800
- 801–900
- 901–1,000
- 1,001–1,100
- 1,101–1,200
- 1,201–1,300





ELEVATION DATA POINTS

STUDY AREA

N

10 5 0 10 20 30 40 Miles

10 5 0 10 20 30 40 50 Kilometers

SCALE 1:500,000

Projection is Ohio coordinate system,
south zone. North American Datum 1983.

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STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Thomas J. Serenko, Chief

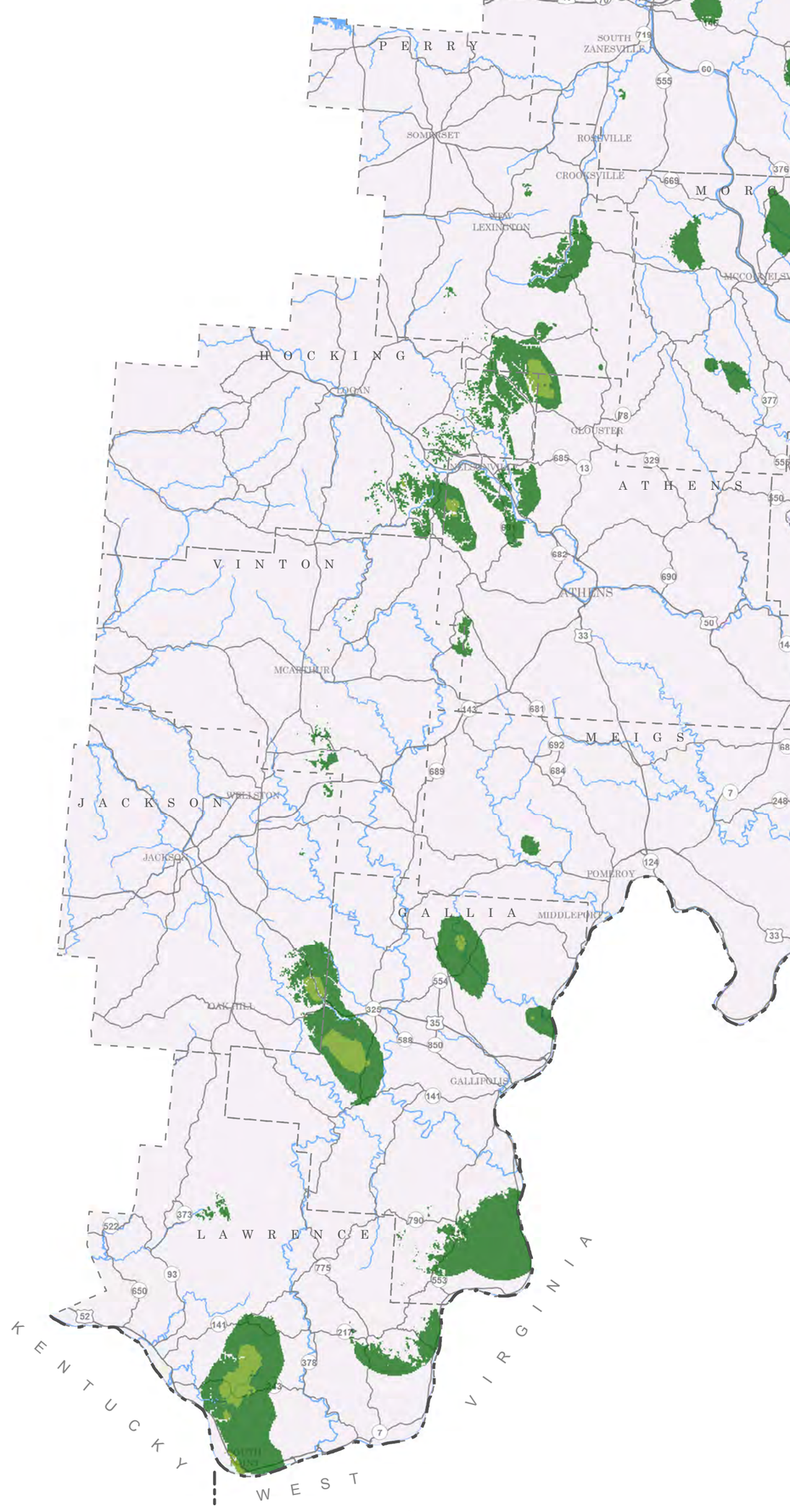
ORIGINAL RESOURCES ISOPACH OF THE LOWER FREEPORT (NO. 6a) COAL BED IN OHIO

by
Lee M. Sorrell and Paul N. Spahr

PLATE 2
Open-File Report 2016-1

Coal Thickness
(inches)

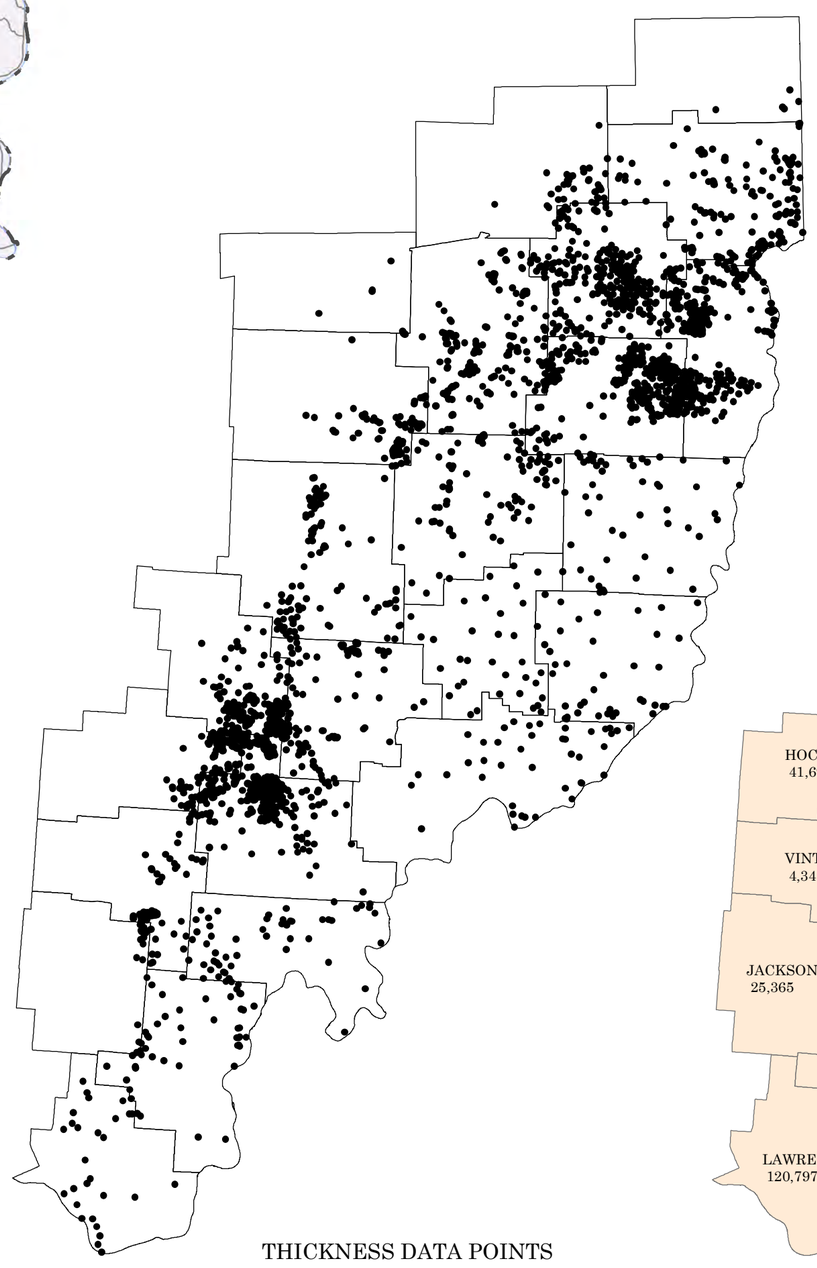
- 14–28
- 29–42
- 43–56
- 57–70
- 71– 84
- 85–98



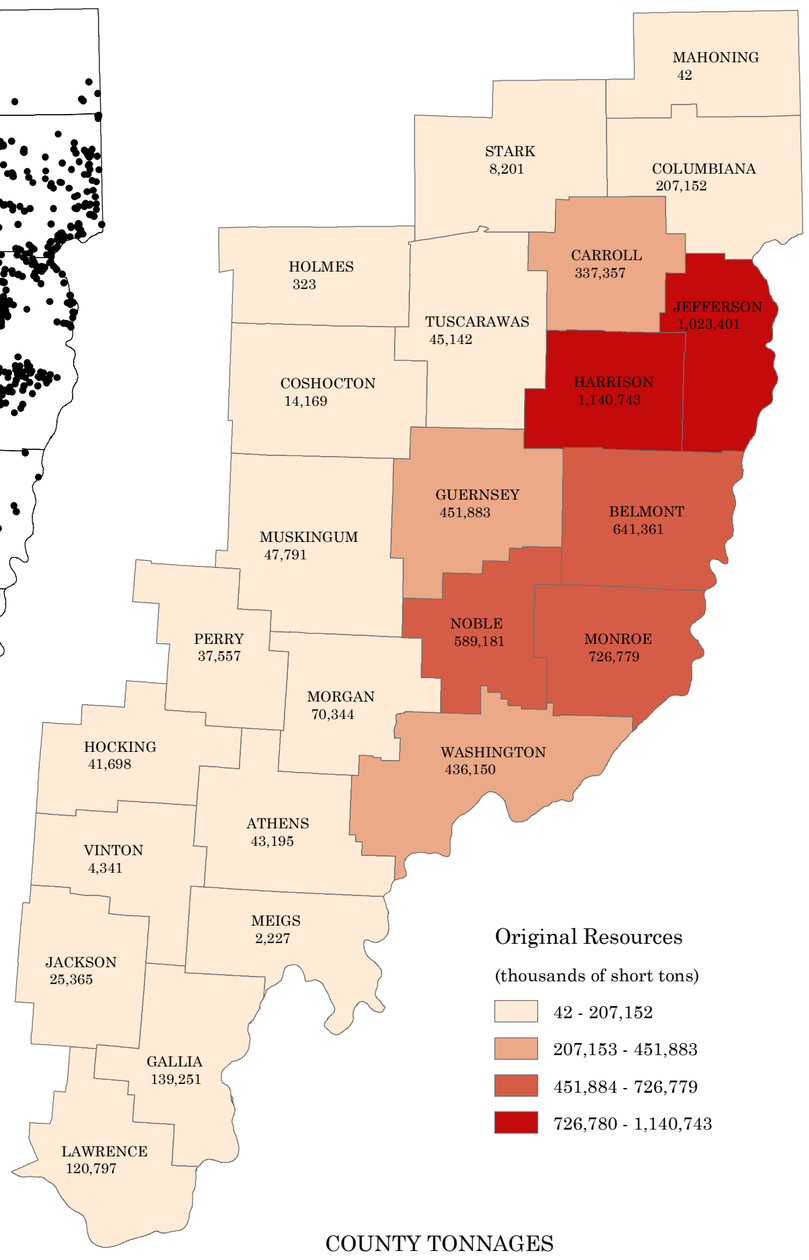
SCALE 1:500,000

Projection is Ohio coordinate system,
south zone. North American Datum 1983.

STUDY AREA



THICKNESS DATA POINTS



COUNTY TONNAGES

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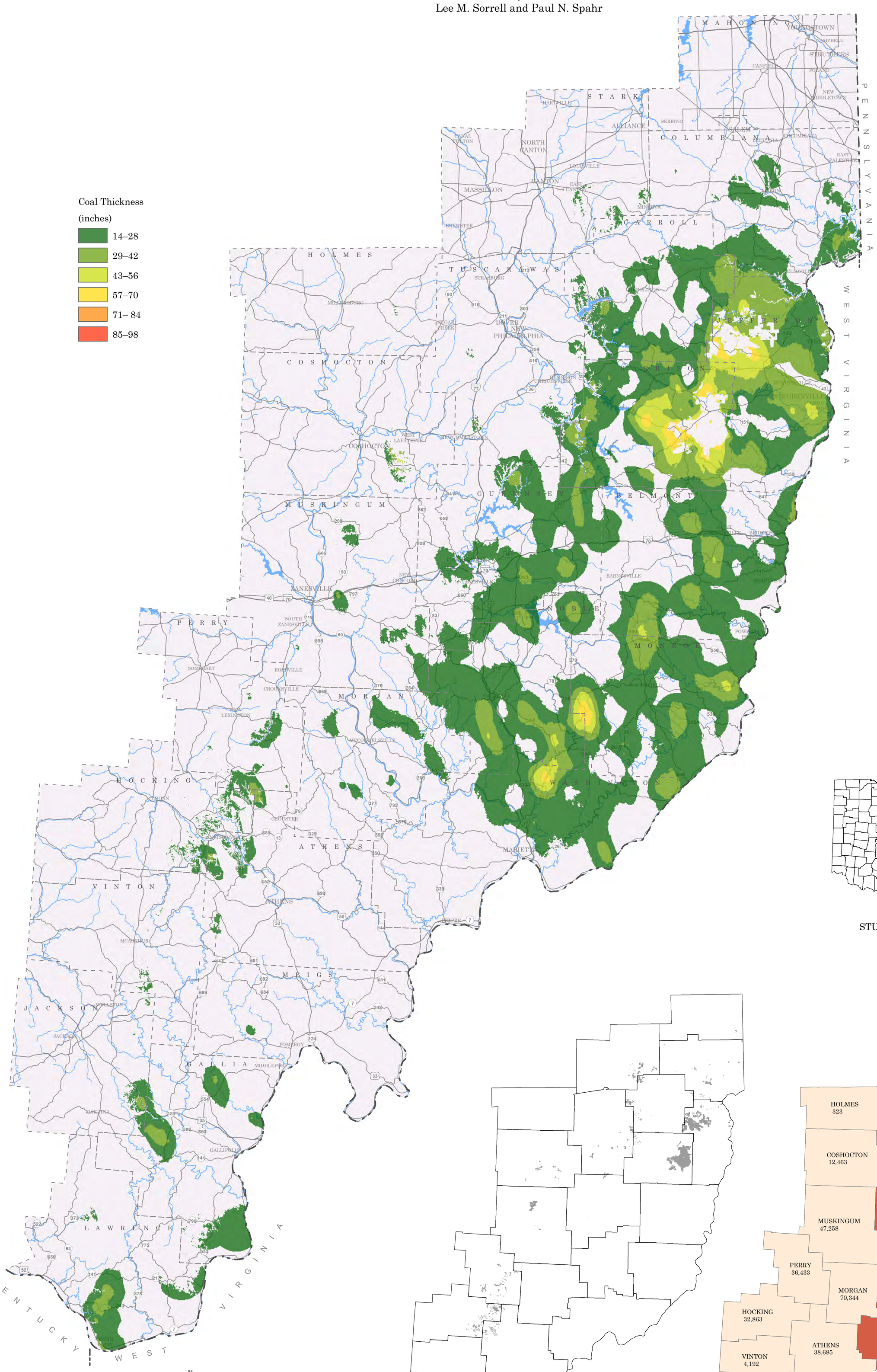
STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Thomas J. Serenko, Chief

REMAINING RESOURCES ISOPACH OF THE LOWER FREEPORT (NO. 6a) COAL BED IN OHIO

by
Lee M. Sorrell and Paul N. Spahr

PLATE 3
Open-File Report 2016-1



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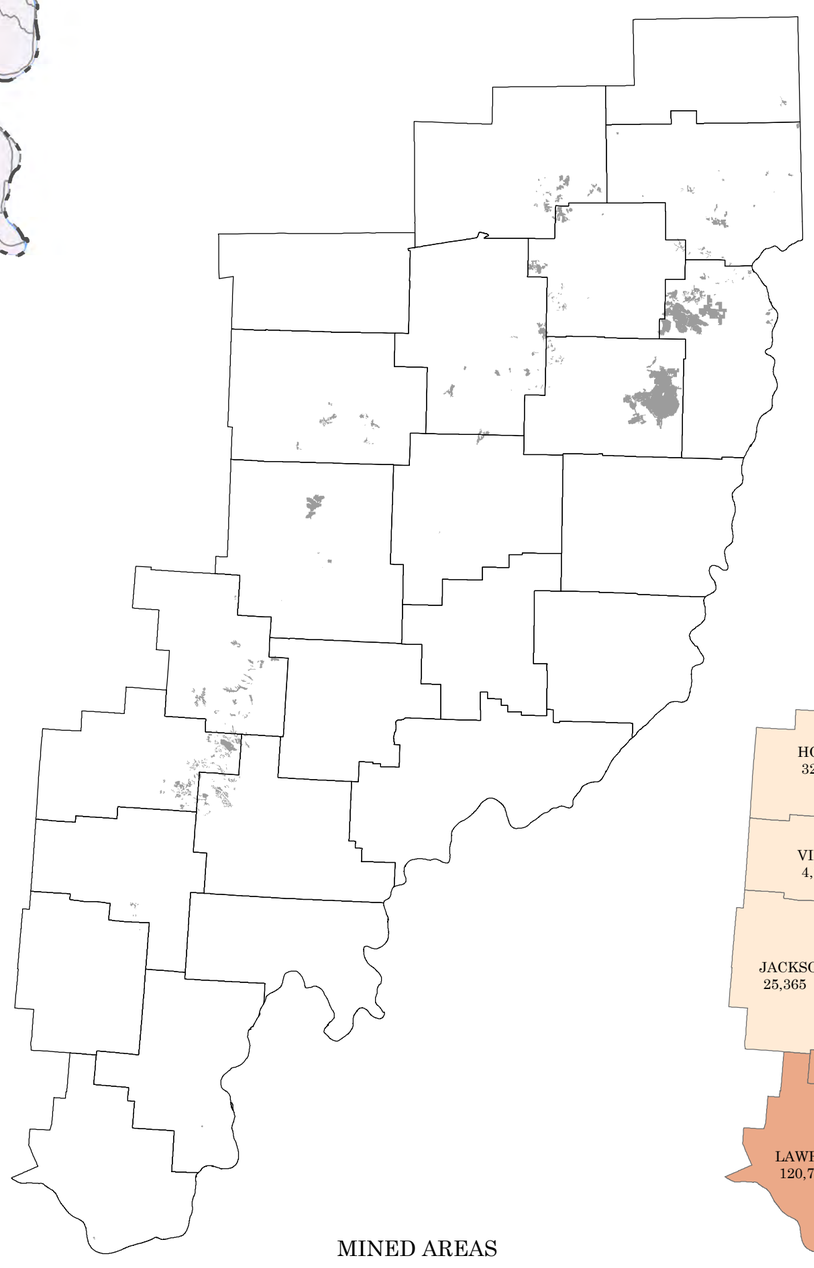
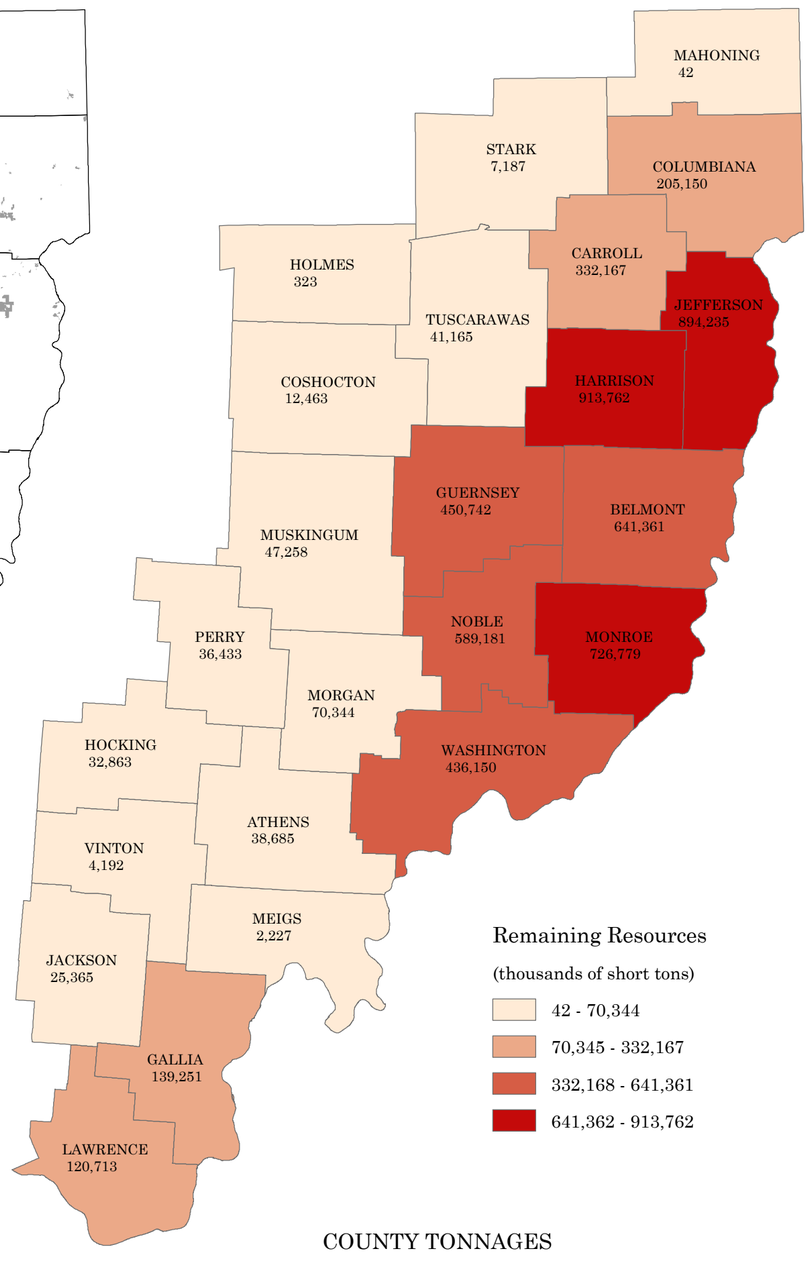
Projection is Ohio coordinate system,
south zone. North American Datum 1983.

STUDY AREA



MINED AREAS



COUNTY TONNAGES

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STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Thomas J. Serenko, Chief

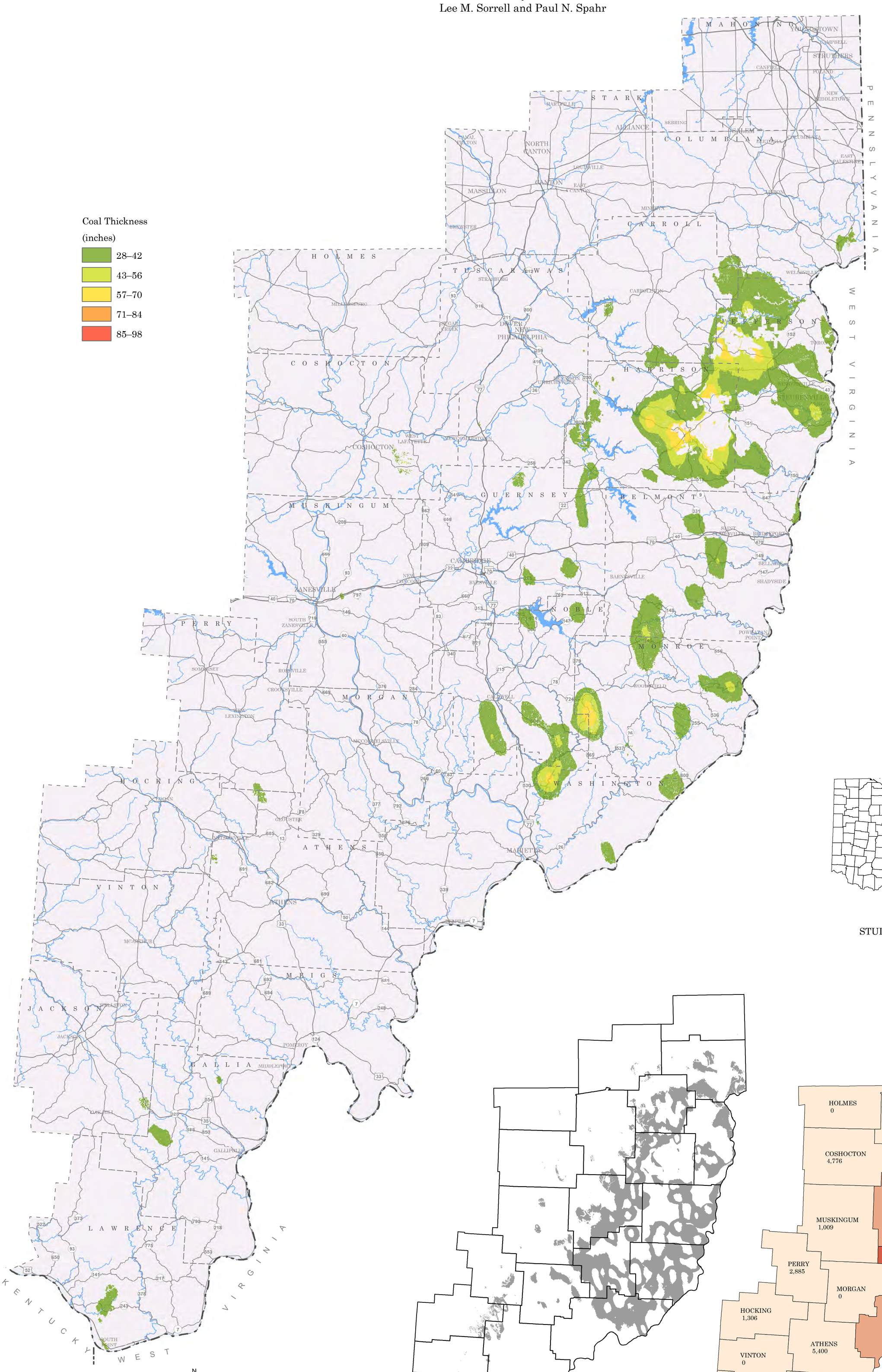
AVAILABLE DEEP-MINABLE RESOURCES ISOPACH OF THE LOWER FREEPORT (NO. 6a) COAL BED IN OHIO

by
Lee M. Sorrell and Paul N. Spahr

PLATE 4
Open-File Report 2016-1

Coal Thickness
(inches)

- 28–42
- 43–56
- 57–70
- 71–84
- 85–98



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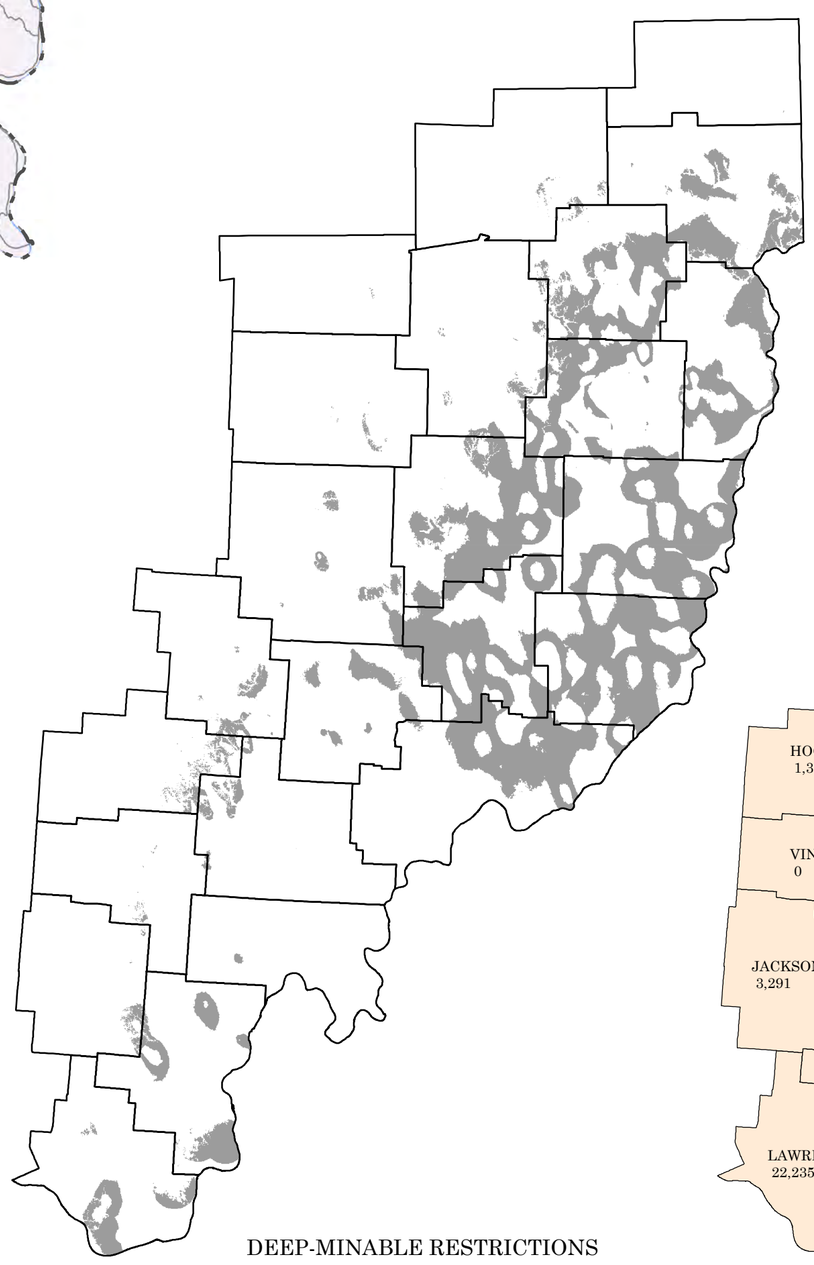
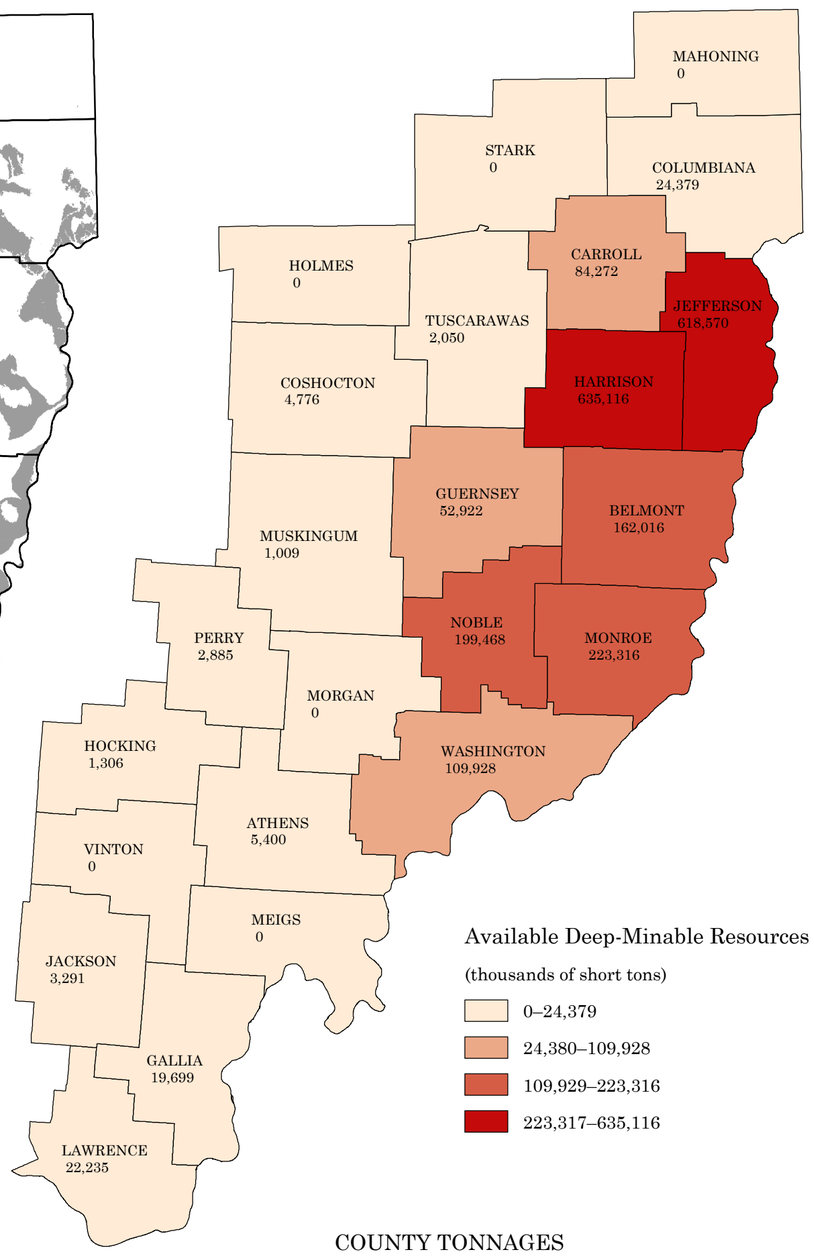
Projection is Ohio coordinate system,
south zone. North American Datum 1983.

STUDY AREA



DEEP-MINABLE RESTRICTIONS



COUNTY TONNAGES

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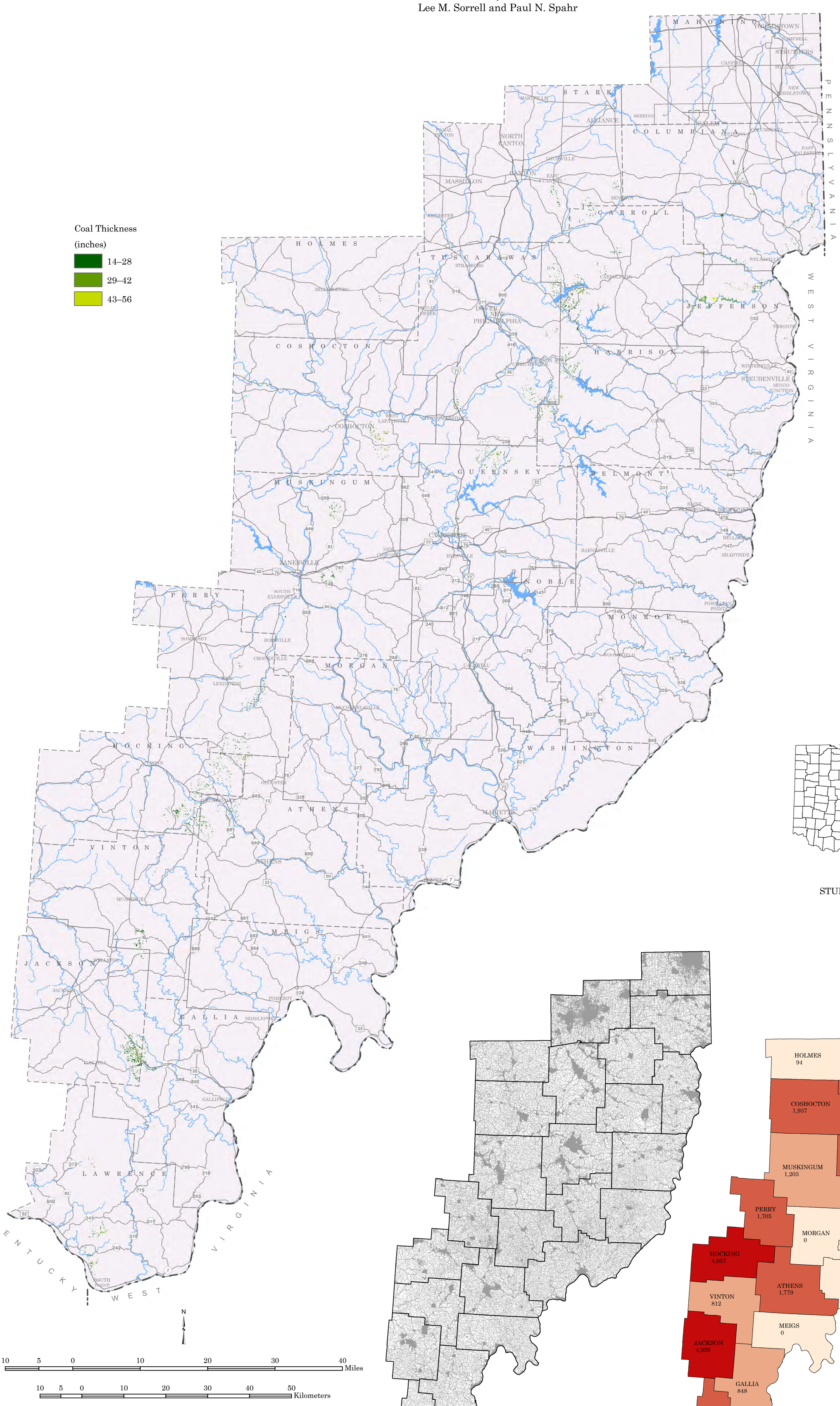
Thomas J. Serenko, Chief

AVAILABLE SURFACE-MINABLE RESOURCES ISOPACH OF THE LOWER FREEPORT (NO. 6a) COAL BED IN OHIO

by
Lee M. Sorrell and Paul N. Spahr

PLATE 5
Open-File Report 2016-1



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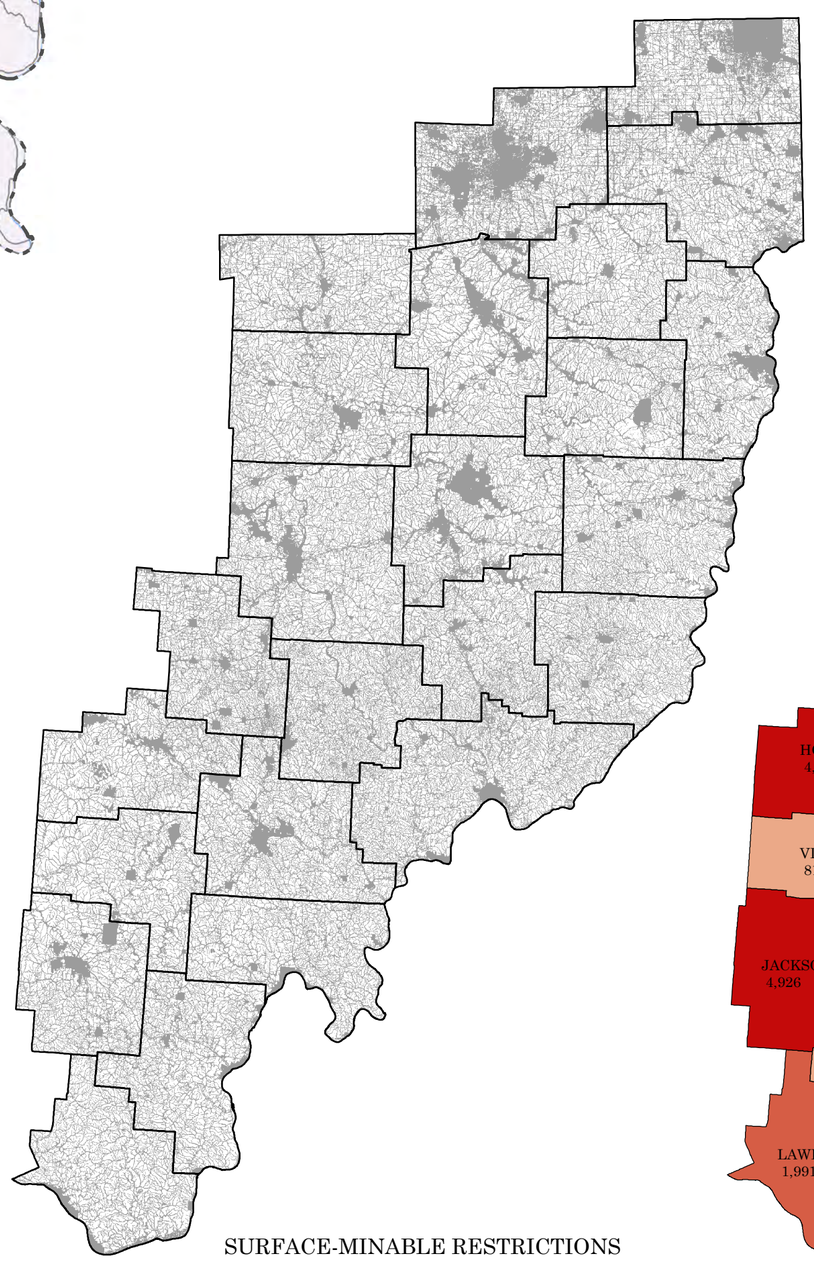
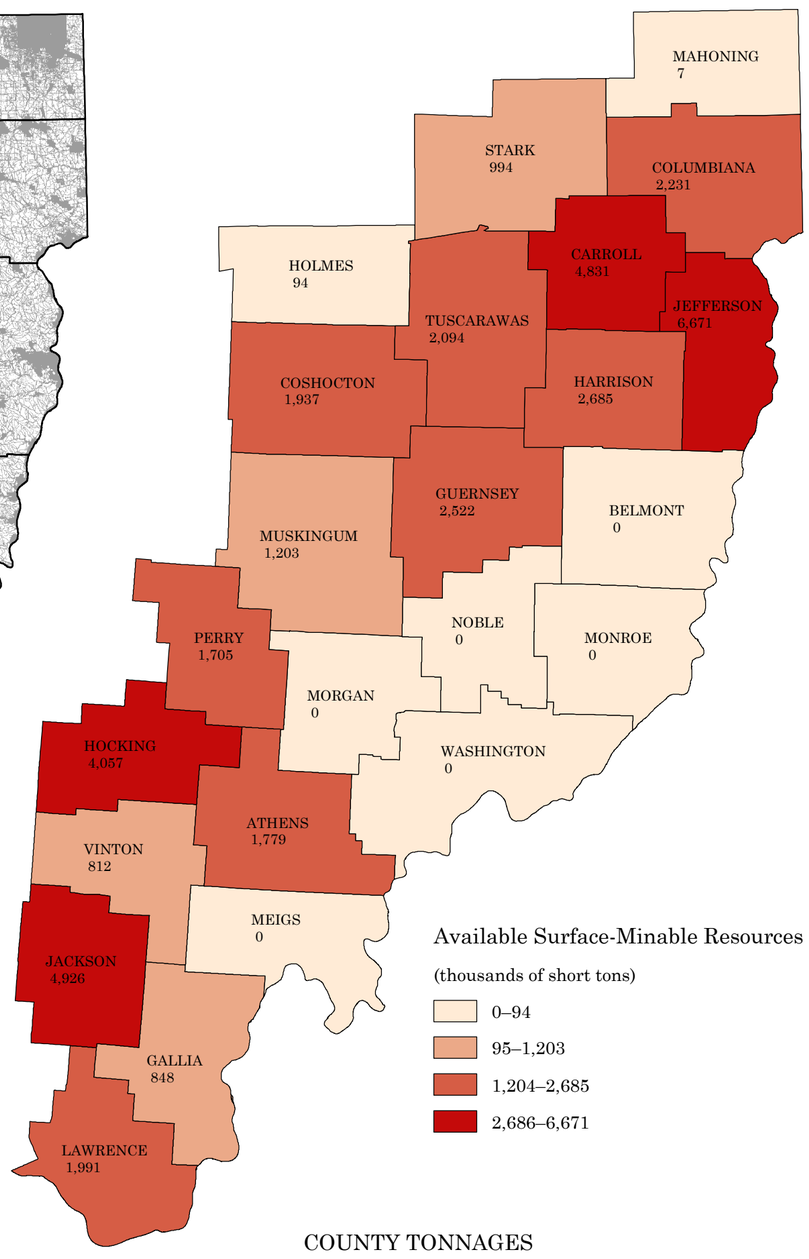
Projection is Ohio coordinate system,
south zone. North American Datum 1983.

STUDY AREA



SURFACE-MINABLE RESTRICTIONS



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