

The Servant Coal Member of the Linton Formation (Pennsylvanian) in Indiana: Geometry, Resources, and Properties

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Erratum: Table 3 has some incorrect values listed; see replacement Table 3 at the end of this article.



ABSTRACT

This study attempts to advance the understanding of the geometry of the Servant Coal Member of the Linton Formation (Pennsylvanian) in Indiana. We documented variability in the thickness and lateral extent of the coal beds present between the Mecca Quarry Shale Member of the Linton Formation and the Excello Shale Member of the Petersburg Formation—two transgressive traceable marine horizons. Our study was based on the detailed examination of 1,240 petroleum geophysical logs and coal test borehole logs throughout Indiana and on previously collected data. The presence of multiple coal beds in the Servant Coal Member and variable thickness of the clastic partings create mapping challenges and difficulties in reliably evaluating coal resources, as well as stratigraphic uncertainties and confusion related to the nomenclature used for this coal.

Because one to four coal beds occur between the Mecca Quarry Shale Member and the Excello Shale Member (namely, between the Colchester and Houchin Creek Coal Members of the Linton and Petersburg Formations), it is unclear which seams should be included in the Servant Coal Member. To better depict the complexity of the Servant Coal Member, we suggest that two additional locations be considered as reference sections. The first auxiliary reference section is Indiana Geological and Water Survey drill core SDH-366 (Petroleum Database Management System [PDMS] #150359) from Vanderburgh County (PDMS, 2018). This reference section represents the more southern part of Indiana where two coal benches are separated by a thick clastic interval. The second auxiliary reference section is drill hole SDH-235 (PDMS #157302) in Greene County, representative of the central part of Indiana where two distinct coal benches are separated by a relatively thin clastic parting. These two additional sections together with the current reference section (SDH-306 [PDMS #115871] located in Pike County in southern Indiana) capture the complexity of the Servant Coal Member more comprehensively than the current reference section alone.

This study provides new data on the geometry of the coal beds within the Servant Coal Member that will allow more reliable future resource and reserve evaluation of this coal. In addition, we have also compiled information about mining, resources, and properties of this coal to provide a comprehensive reference for the Servant Coal Member in Indiana.

INTRODUCTION

The Survant Coal Member (Burger and Wier, 1970; Ault and Harper, 1986) marks the top of the Linton Formation, and it is overlain by sandstone or gray shale at the base of the Petersburg Formation (Burger and Wier, 1970; Ault and Harper, 1986) (fig. 1). The type section for this coal is located in SW¼NE¼ sec. 2, T. 2 S., R. 7 W., at the southern edge of the abandoned village of Survant along the Patoka River in Pike County, Indiana (Burger and Wier, 1970; Ault and Harper, 1986). A reference section for the Survant Coal Member was designated as Indiana Geological Survey Drill Hole (SDH) 306 (Petroleum Database Management System [PDMS] #115871) (IGNIS, 2018) where the coal occurs at the depth of 83.3 to 85.2 ft (25.3–

26.0 m) (Hasenmueller and Ault, 1991, p. 6). The drill site is located in SE¼NE¼NW¼ sec. 2, T. 2 S., R. 7 W., near the type section in Pike County (Hasenmueller and Ault, 1991).

The Survant Coal Member has been correlated throughout the Illinois Basin based on subsurface data and palynology (Jacobson and others, 1985; Ault and Harper, 1986). In Illinois, it had long been correlated with the Shawneetown and Lowell coals. In 1985, the Illinois State Geological Survey formally adopted the name “Survant” for use in eastern and southern Illinois (Jacobson and others, 1985). In Illinois, the Survant is known to be mostly absent, thin, or to contain multiple rock partings (Jacobson and Bengal, 1981); but, in eastern Edgar County, Illinois, for example, where the

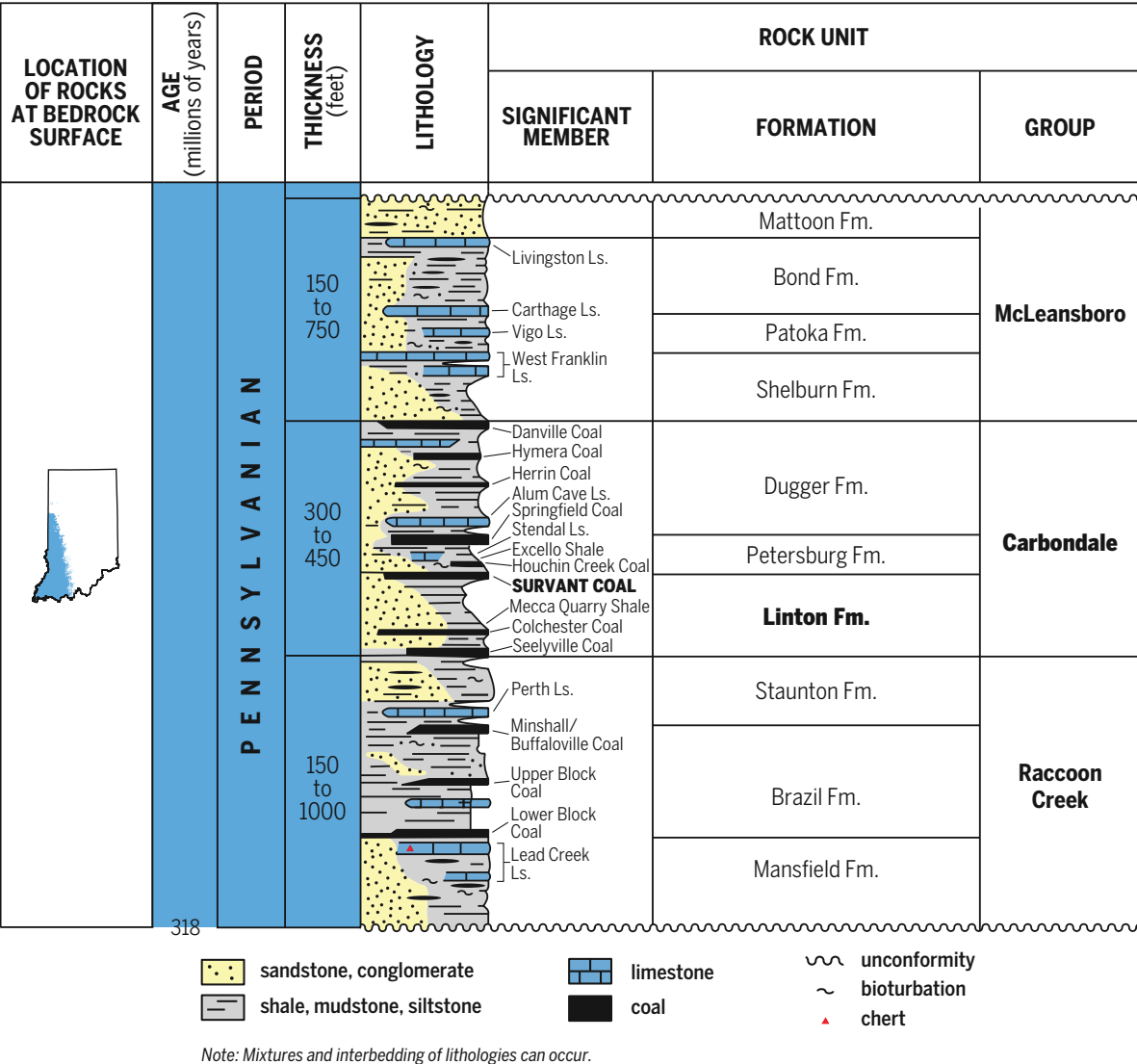


Figure 1. Stratigraphic position of the Survant Coal Member on the background of Pennsylvanian stratigraphy in Indiana (modified from Thompson and others, 2013).

two benches of the Survant have merged, this coal has been reported to be up to 6 ft (1.8 m) thick (Jacobson and others, 1985) and up to 8 ft (2.4 m) thick in Saline County in southern Illinois (Willman and others, 1975).

The name “Survant” was recommended to replace the name “Well coal” in Kentucky by Jacobson and others (1985, fig. 2). In Indiana, the Survant Coal Member is highly variable in thickness (0.2–8 ft [0.1–2.4 m]), and has one, two, or more benches separated by partings. The main shale parting is commonly less than a few feet thick but is known to be up to 20 ft thick (6 m) in southwestern Greene County and southeastern Clay County, and 30 ft thick (9 m) in northwestern Vigo County (Burger and Wier, 1970; Ault and Harper, 1986). In some places, this coal seam is absent (Ault and Harper, 1986).

HISTORY OF INVESTIGATIONS OF THE SURVANT COAL MEMBER IN INDIANA

The Survant Coal Member was recognized in Indiana by David Dale Owen at least as early as 1859. He stated that a coal of “superior quality” was mined near Seelyville, Indiana (Owen, 1859, p. 50). The coal was formally recognized by Cox in 1876 when he introduced a system of designating coal seams by letter, beginning with A for the lowest seam, through N for the highest (Cox, 1876). In that designation, the Survant was called “Coal N.” Ashley (1899), having recognized problems with the lettering system and resultant misidentification and miscorrelations of coal beds, introduced a new system for coal beds using Roman numerals I through VIII to name the main recognized seams, and Roman numerals followed by a lowercase letter (for example, IIIa) to designate thinner or less persistent seams occurring in the Pennsylvanian System in southwestern Indiana. Using his numerical classification scheme, Ashley (1899) initially designated the Survant as Coal VII but used the name “Survant” in describing exposures near the town of Survant in Pike County, Indiana (Burger and Wier, 1970). This and other early errors in seam identification were promptly recognized and corrected, including renaming the Survant “Coal IV.” By 1909 the general stratigraphic scheme of coals in Indiana was established (Ashley, 1909). Since that time, the only substantial change in naming coal seams was introduced in the 1960s, when the Indiana Geological Survey (now Indiana Geological and Water Survey [IGWS]) designated coal seams as members of formations, replacing formerly used divisions. Ashley’s Coal IV became the Survant Coal Member of the Linton Formation.

During the first half of the twentieth century, the Survant Coal Member was drilled and mined in

Greene, Sullivan, and Clay Counties; the area between Terre Haute and Clinton, Indiana; a smaller area between Terre Haute and Seelyville, Indiana; and a small area in northeast Knox County, Indiana (fig. 2). These operations generated data about this coal, but most of the information was proprietary and was lost, with the exception of some mine maps. Later during the 1950s and 1960s, new information on coal in Indiana became available as a result of field work carried out by researchers of the Indiana Geological Survey and graduate students. The results were published in a series of Preliminary Coal Maps, County Coal Maps, geologic maps of select quadrangles, graduate dissertations, and bulletins and circulars (Frielinghausen, 1950; Friedman, 1954; Hutchison, 1956, 1958, 1961, 1964, 1967; Kottowski, 1954; Powell, 1968; Wier, 1952, 1953, 1957; and others). These maps and publications focused on the distribution, structure, and mined areas of coals in various counties and quadrangles in southwestern Indiana, and they addressed the occurrence and characteristics of the Survant Coal Member where it was encountered.

Few studies have specifically focused on the Survant Coal Member. Guennel (1952) analyzed fossil spores of Desmoinesian Series coals in Indiana and determined that the dominant miospores of this coal belonged to *Laevigatosporites* and *Lycospora*. Of note, however, is that all the Survant coal samples studied by Guennel (1952) were from the mining districts well to the north of the type section; no Survant samples from southern Indiana counties were studied palynologically. Neavel (1961) examined petrographic and chemical characteristics of one section of the Survant coal north of Linton, Indiana. He divided the 39.5-inch-thick (1-m) section into 30 layers of different brightness and analyzed each layer petrographically and chemically. The results of the chemical analysis showed wide variation among these layers. On a dry, ash-free basis, fixed carbon ranged from 45.8 to 62.0 percent; heating value (dry basis) ranged from 11,110 to 14,680 Btu per pound. Ash content on an as-received basis ranged from 1.6 to 44.7 percent.

Hutchison (2008) drilled 13 holes in the Survant coal at the Coal, Inc. IVth Vein Mine at Vicksburg, Indiana, to document additional reserves for the operating mine. The Coal, Inc. holdings comprised a north-south-trending body of coal approximately 1 mile (1.6 km) wide and 3 miles (4.8 km) long where the coal was more than 4 ft (1.2 m) thick. He cored and examined 15 ft (4.6 m) of roof rock, the coal, and 5 ft (1.5 m) of floor. Megascopically, the coal was bright banded with no partings. The floor was a massive, sandy, well-developed paleosol or a fine-grained, slightly rooted, light

gray sandstone. In the minable area, the coal ranged from 3.8 to 4.4 ft (1.15–1.3 m) in thickness, but thinned rapidly and split outside the minable areas. Coal quality was good, having heating values from 11,340 to 11,560 Btu/pound (on an as-received basis), ash content ranging from 7.1 to 8.2 percent, moisture from 12.0 to 13.6 percent, and a low sulfur content, from 0.95 to 1.3 percent, averaging 1.13 percent. Based on limited data, we believe that the Survant in this area was deposited in a freshwater deltaic environment along a north-south-trending distributary channel, removed from marine influence.

Harper (1985) detailed mining activities in Vigo County, Indiana. He addressed the major coal seams in Vigo County, the history of mines in those seams, and associated geologic conditions and engineering problems encountered during mining. He published maps and discussed the Saxton group of mines in the Survant Coal Member northwest of Terre Haute, the Glen Ayr group, also in the Survant, east of Terre Haute, as well as a complete survey of Vigo County mines in the other major seams (Harper, 1985). Similar reports followed on Sullivan County (Harper, 1988a) and Knox County (Harper and Eggert, 1995). Harper (1988b) summarized available information regarding geologic conditions encountered during underground mining in the Survant coal. He based the work on information from mine maps and mine literature, while focusing on mapping past mines and geologic conditions encountered during mining.

Friedman (1989), while discussing the Pennsylvanian and coal stratigraphy in northern Vigo and southern Vermillion Counties, provided 50 thickness measurements of the Survant and briefly discussed the split in the Survant Coal Member in the western part of the study area. Three proximate analyses were included, two from the Saxton Mine that operated from 1923 to 1954, and one from an outcrop in T. 15 N., R. 8 W., sec. 31, 4 miles (6.4 km) northeast of Clinton, Indiana. Friedman (1989) also calculated original resources, reserves mined and lost in mining, and remaining reserves by township, based on average weighted thicknesses.

Mastalerz and others (2004) provided a comprehensive summary of coal data publicly available in Indiana, and included statewide maps of the extent, depth, thickness, availability for mining, and areas unavailable for mining owing to technological or land use restrictions for the Survant coal, as well as other Indiana coals. The study also estimated total resources and summarized geochemical data for as many as 55 Survant samples statewide. An update to that publication can be found in Mastalerz and others (2009).

Hutchison (2008) discussed stratigraphic, geochemical, petrographic, and depositional characteristics of the Survant Coal Member in an area in Vermillion County, Indiana, and Edgar County, Illinois. That work was based on 16 holes drilled during the study combined with existing information about the Survant. The study shows that, in that area, the Survant is of high-volatile bituminous C rank, as indicated by vitrinite reflectance measurements and heating value analysis. It is a low-sulfur, low-ash, high-Btu/lb, and high-fusion-temperature coal with good slagging characteristics. Hutchison also provided trace element data including Hg, Cd, Co, Cu, Pb, Se, and V, all comparable to Illinois Basin averages. Hutchison (2008) noted that Hg and Pb content was significantly reduced by washing, similar to other Indiana coals (Mastalerz and others, 2009).

This literature review points out that Survant Coal Member data are rather spotty and limited to areas of mining interest. In these studies, it is well documented that the Survant has variable thickness and often contains clastic particles. However, the data are limited to isolated areas and cannot easily be extrapolated to the entire state of Indiana. The presence of clastic intervals of varying thickness splitting the seam makes it difficult to obtain a reliable distribution of the thickness of the coal and, consequently, to reliably evaluate its resources and reserves. The frequent presence of sandstones above and below the coal and the absence of the coal in some areas complicate the reconstruction of geometric relationships. Therefore, the main objective of this study is to advance the understanding of the geometry of the Survant Coal Member based on detailed examination of 1,240 petroleum geophysical logs and coal test borehole logs throughout Indiana; this will provide a more even and reliable data distribution for evaluating the future resources and reserves of this coal. We have also compiled information about the mining, resources, and properties of this coal to provide a comprehensive up-to-date reference for the Survant Coal Member in Indiana.

To better understand the geometry of the Survant Coal Member, we studied its stratigraphic position relative to the underlying Mecca Quarry Shale Member and the marine black shale overlying the Houchin Creek Coal Member. In Indiana, this shale has not been formally named. We propose that the formal name “Excello Shale Member” for this widely mappable stratigraphic unit be extended into Indiana’s part of the Illinois Basin as the “Excello Shale Member of the Petersburg Formation.” We designate SDH-306 (PDMS #115871) at the depth of 21.5 to 26.8 ft (6.5–8.2 m) in Pike County and SDH-366 (PDMS #150359) at the

depth of 439.6 to 444.7 ft (134–135.5 m) in Vanderburgh County as reference sections for this horizon in Indiana. These cores are available for inspection in the IGWS sample archive. Similar to its character in Illinois, in Indiana the Excello Shale Member is a black fissile shale ranging from 1 to 5 ft (0.30–1.5 m) thick. It directly underlies the Stendal Limestone Member and immediately overlies the Houchin Creek Coal Member, except locally where 1 to 3 ft (0.30–0.9 m) of gray shale separates them.

RESOURCES AND MINING OF THE SURVANT COAL MEMBER IN INDIANA

While calculating coal resources in west-central Indiana, Friedman (1989) also provided assessments of the Survant Coal Member with regard to original resources, coal mined and lost in mining, remaining resources, and recoverable reserves. Specifically, as of 1985 he mentioned 119,980,000 short tons of remaining resources and 60,490,000 short tons as recoverable reserves in Vermillion County and 33,175,000 short tons of remaining resources (with 16,589,000 short tons of recoverable reserves) in Vigo County.

On a statewide scale, the original resources of the Survant Coal Member in Indiana are estimated at 8.48 billion short tons and available resources at 1.30 billion short tons, 0.23 billion short tons of which are available from surface mining and 1.11 billion short tons from underground mining (Mastalerz and others, 2009) (Table 1). The available surface-minable resource accounts for 11 percent of the total original surface-minable resource, and the available underground resource accounts for 14 percent. We note, however, that because of the poorly known geometry of this seam, this calculation of resources on a statewide scale does not have a high confidence level.

As of 2016, one mine (surface mine) was active in the Survant Coal Member (fig. 2) at the Pike/Dubois

County boundary. The majority of past mining used underground mining methods, and it was concentrated primarily in two areas—southern Vermillion County to northern Vigo County and eastern Sullivan County to western Greene County—where that coal was thick (>4.5 ft [1.37 m]). Mining terminated when these thick coal reserves were exhausted (Harper, 1988b). Past surface-mining operations were also concentrated in two areas—western Greene and Pike Counties (fig. 2). Historically, the greatest amount of coal was produced from the Survant from 1910 to 1930 (fig. 3); since 1955, underground mining has been minimal. The Survant has been mined by surface extraction techniques since 1990, with the sole exception of one short-lived underground mine in western Greene County (fig. 2).

Hutchison (2008) estimated, based on drilling in Vermillion County, Indiana, and Edgar County, Illinois, that about 15.5 million tons of the Survant were recoverable by underground mining methods in that area. He estimated that roof and floor conditions generally would be favorable for mining, although, locally, problems could be expected because of the presence of a paleosol or slickensided shale and sandstone above the coal. Hutchison (2008) concluded that the main mining-related issue for the Survant coal is the relatively small size of the reserve and that the future viability of its extraction is a question of economics. He further stated that given the characteristics of the Survant coal and the decreasing demand for low-sulfur coal (attributable to the installation of scrubbers at most power plants), the prospect for substantial renewed interest in the Survant coal was minimal. We concur with Hutchinson's assessment that the Survant coal will not be a primary target of future mining operations except for a few remaining, relatively small surface minable reserves, primarily in Pike County. However, the Survant coal could be a good mining target as a secondary seam in larger surface mines where the principal targets are thick pods of the underlying Seelyville Coal Member of the Linton Formation. In like

Table 1. Summary of the Survant Coal Member resources in Indiana (in billion short tons) (Mastalerz and others, 2009)

Survant Coal Member	Potential mining method*		Total
	Surface	Underground	
Original	2.10	7.68	8.48
Mined	0.06	0.25	0.31
Remaining	2.04	7.43	8.17
Technological restrictions	1.72	5.98	6.44
Land-use restrictions	0.09	0.34	0.43
Available	0.23	1.11	1.30

*Values of potential surface and underground mining do not add up to total because some resources can be mined by both surface and underground methods.

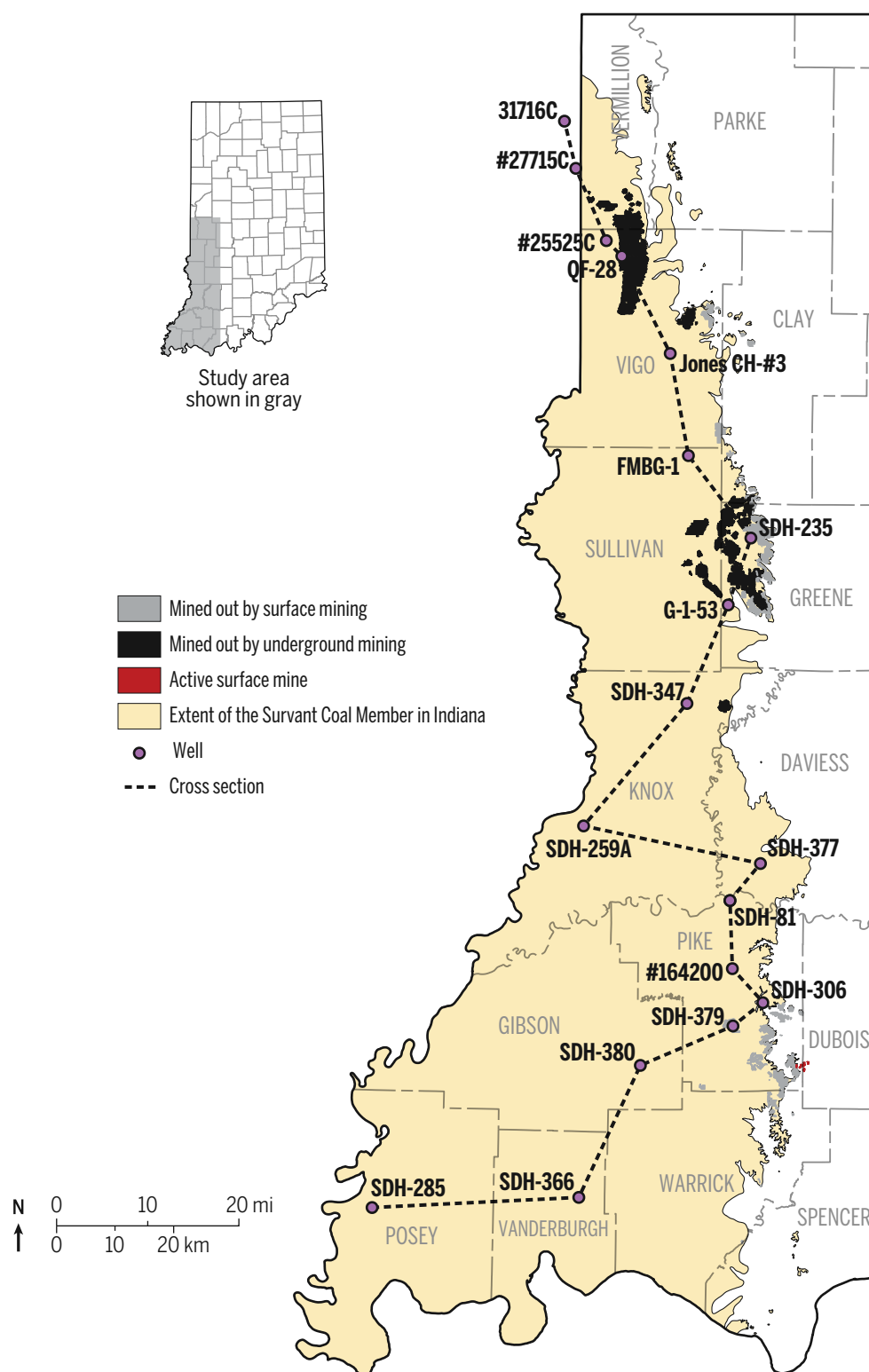


Figure 2. Map of southwestern Indiana showing mining data for the Survant Coal Member (2015 data for areas mined out by underground mining; 2016 data for areas of active mining and areas mined out by surface mining). Locations of wells used for cross section (fig. 6) are indicated. For wells that are available in the Petroleum Database Management System (PDMS), ID numbers are indicated in the text.

manner, deeper pods of thicker (>4 ft [1.2 m]) Survant Coal could conceivably be mined from slopes or shafts extending to deep minable reserves of the Seelyville Coal Member; this could maximize a mine’s reserve base or be used for blend coal to enhance the quality of the final mine product, should the economics of multi-seam materials handling and ground control issues prove favorable.

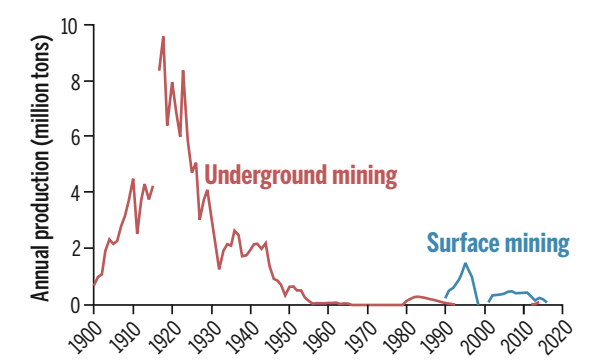


Figure 3. Annual production from the Survant Coal Member (1900–1983 data from Harper, 1988b; no data for 1916; 1983–2016 data estimated from Indiana Coal Council, 2017).

COAL PROPERTIES

The coal quality parameters of the Survant are based on data from the Indiana Coal Quality Database (Drobniak and Mastalerz, 2012). The average ash yield is 11.5 percent and sulfur content is 2.6 percent, on a dry basis. An average heating value of 12,648 Btu/lb is typical of Indiana coals, but the Survant ranges from 5,202 to 13,943 Btu/lb, reflecting its variable mineral matter content. Major and trace element data are compiled in Table 3 (Drobniak and Mastalerz, 2012). We note that only a limited number of analyses are available for these elements; the same is true for the analyses for oxides in coal ash (Table 4).

Data about the petrographic composition of the Survant Coal Member are limited. Neavel (1961) examined one section of the Survant north of Linton, Indiana, and found that the coal was composed of abundant anthraxylon and moderately bright or moderately dull attritus. Hutchison (2008) analyzed several samples from Vermillion County (Table 5). These limited data suggest that, on a mineral-containing basis, the coal has variable vitrinite and inertinite content, from ~60 to 80 percent and ~5 to 18 percent by volume, respectively. This variability is illustrated in photomicrographs of this coal (fig. 4). Vitrinite reflectance ranges from 0.44 to 0.57 percent, placing the coal mostly in the high-volatile bituminous C rank.

Table 2. Survant Coal Member quality (raw coal) (Hutchison, 2008; Drobniak and Mastalerz, 2012) (ar - as received basis)

Parameter	Number of samples	Average	Minimum	Maximum	Standard deviation
Moisture (ar, %)	76	11.2	1.0	22.2	3.8
Ash (dry, %)	78	11.5	5.5	58.8	6.6
Total sulfur (dry, %)	31	2.6	1.0	5.3	1.0
Heating value (dry, Btu/lb)	76	12,648	5,202	13,943	1,102.6
Volatile matter (dry, %)	65	39.4	21.8	46.9	3.9
Fixed carbon (dry, %)	65	49.2	19.4	68.3	6.0
Ultimate carbon (dry, %)	47	69.4	28.7	76.1	7.4
Ultimate hydrogen (dry, %)	47	6.1	2.9	7.8	1.1
Ultimate oxygen (dry, %)	46	18.1	5.6	41.0	7.1
Ultimate nitrogen (dry, %)	46	1.6	0.8	2.2	0.2
Ultimate sulfur (dry, %)	56	2.6	0.6	11.9	1.9

Table 3. Elements in ppm (raw whole coal) in Survant Coal Member samples (Drobnik and Mastalerz, 2012)

Element symbol	Element	Number of samples	Average	Minimum	Maximum	Standard deviation
Ag	Silver	12	0.14	0.03	0.36	0.11
Al	Aluminum	7	9,828.57	7,900.00	13,000.00	1,978.82
As	Arsenic	12	29.12	0.89	58.40	19.75
Au	Gold	9	0.84	0.60	1.46	0.31
B	Boron	9	99.63	84.68	150.00	20.64
Ba	Barium	9	46.70	13.00	121.00	34.53
Be	Beryllium	12	3.88	2.78	6.42	0.96
Bi	Bismuth	9	1.25	0.24	2.30	0.64
Br	Bromine	7	3.43	1.00	7.00	2.23
Ca	Calcium	7	1,571.43	310.00	2,900.00	1,115.83
Cd	Cadmium	12	0.30	0.04	1.63	0.44
Ce	Cerium	7	14.71	9.00	21.00	5.15
Cl	Chlorine	1	0.01	-	-	-
Co	Cobalt	12	6.99	2.80	24.82	6.15
Cr	Chromium	12	15.85	9.30	25.00	5.64
Cs	Cesium	9	1.31	0.80	2.54	0.52
Cu	Copper	12	15.69	7.80	31.46	6.75
Dy	Dysprosium	7	2.26	1.90	3.40	0.54
Er	Erbium	7	0.79	0.60	1.20	0.23
F	Fluorine	7	0.32	0.19	0.51	0.12
Fe	Iron	10	101.20	0.01	232.00	74.33
Ga	Gallium	7	24,428.57	19,000.00	32,000.00	4,276.18
Gd	Gadolinium	9	4.84	3.40	7.30	1.25
Ge	Germanium	7	2.29	0.70	4.50	1.18
Hf	Hafnium	9	13.65	3.90	18.00	3.92
Hg	Mercury	7	0.49	0.40	0.60	0.09
Ho	Homium	7	0.48	0.41	0.72	0.11
In	Indium	7	0.48	0.41	0.72	0.11
Ir	Iridium	7	12.37	0.91	24.00	10.58
K	Potassium	7	1,300.00	1,000.00	1,900.00	382.97
La	Lanthanum	7	8.14	4.00	12.00	3.39
Li	Lithium	12	15.52	5.40	33.50	9.59
Lu	Lutetium	7	0.10	0.08	0.12	0.01
Mg	Magnesium	7	528.57	330.00	690.00	135.70
Mn	Manganese	9	23.49	8.70	35.09	8.82
Mo	Molybdenum	12	2.90	1.10	7.30	1.77
Na	Sodium	7	352.86	170.00	610.00	140.20
Nb	Niobium	9	2.90	0.74	5.20	1.21
Nd	Neodymium	7	12.17	3.20	18.00	6.24
Ni	Nickel	12	23.27	9.50	51.10	12.86

Table 3 (cont.). Elements in ppm (raw whole coal) in Survant Coal Member samples (Drobniak and Mastalerz, 2012)

Element symbol	Element	Number of samples	Average	Minimum	Maximum	Standard deviation
Os	Osmium	7	0.70	0.60	1.00	0.14
P	Phosphorus	7	262.43	33.00	740.00	297.91
Pb	Lead	12	35.90	8.23	105.12	24.58
Pd	Palladium	7	0.11	0.09	0.16	0.02
Pr	Praseodymium	7	5.80	4.10	12.00	2.82
Pt	Platinum	7	0.48	0.41	0.72	0.11
Rb	Rubidium	9	15.37	10.00	24.20	4.52
Re	Rhenium	7	0.70	0.60	1.00	0.14
Rh	Rhodium	7	0.07	0.06	0.10	0.01
Ru	Ruthenium	7	0.23	0.19	0.34	0.05
S	Sulfur	7	961.43	630.00	1,400.00	285.10
Sb	Antimony	12	1.73	0.69	4.30	1.04
Sc	Scandium	9	3.85	2.50	6.86	1.45
Se	Selenium	12	3.04	1.80	5.50	1.19
Si	Silicon	7	14,428.57	12,000.00	19,000.00	2,878.49
Sm	Samarium	5	1.88	0.90	2.70	0.66
Sn	Tin	9	0.77	0.41	1.46	0.38
Sr	Strontium	9	101.22	14.00	314.60	97.20
Ta	Tantalum	7	0.11	0.07	0.14	0.03
Tb	Terbium	7	0.24	0.15	0.39	0.08
Te	Tellurium	2	0.27	0.24	0.29	0.04
Ti	Titanium	7	528.57	420.00	740.00	114.52
Th	Thorium	9	1.60	1.10	2.90	0.56
Tl	Thallium	9	0.83	0.51	2.04	0.47
Tm	Thulium	7	0.33	0.28	0.49	0.08
U	Uranium	9	1.53	0.71	3.94	1.04
V	Vanadium	12	25.54	7.10	50.82	13.33
W	Tungsten	7	0.43	0.36	0.57	0.09
Y	Yttrium	9	7.49	3.60	9.70	1.97
Yb	Ytterbium	7	0.59	0.50	0.70	0.08
Zn	Zinc	12	50.77	7.90	231.00	65.66
Zr	Zirconium	9	31.87	7.70	71.00	18.28

Table 4. Oxides in coal ash (in weight %) (Drobniaak and Mastalerz, 2012)

Parameter	Number of samples	Average	Minimum	Maximum	Standard deviation
Ash Al ₂ O ₃	12	21.16	15.00	28.70	4.34
Ash BaO	3	0.12	0.09	0.14	0.03
Ash CaO	12	2.67	0.50	6.60	1.96
Ash Fe ₂ O ₃	12	29.65	6.42	49.00	14.36
Ash K ₂ O	12	1.76	1.20	2.60	0.47
Ash MgO	12	0.82	0.37	1.10	0.23
Ash MnO	7	0.02	0.01	0.03	0.01
Ash Na ₂ O	12	0.79	0.24	2.22	0.60
Ash P ₂ O ₅	12	0.80	0.08	2.49	0.80
Ash SiO ₂	12	36.42	25.00	47.90	8.13
Ash SO ₃	9	2.40	0.42	4.15	1.01
Ash SrO	3	0.23	0.03	0.44	0.21
Ash TiO ₂	12	0.98	0.65	1.40	0.23

Table 5. Petrographic characteristics of the Survant Coal Member samples (Hutchison, 2008; Drobniaak and Mastalerz, 2012) (ICQD - Indiana Coal Quality Database; MM - mineral matter; VR_o - vitrinite reflectance)

ICQD ID	County	Sample source	Vitrinite (vol %)	Liptinite (vol %)	Inertinite (vol %)	MM (vol %)	VR _o (%)
ICQD-AB-342	Sullivan	Core T-31	80.4	5.6	4.8	9.2	0.55
ICQD-AD-521	Posey	IGWS SDH - 384	74.4	8.7	7.2	9.8	0.44
ICQD-AD-529	Posey	IGWS SDH - 383	77.4	10.0	6.7	6.7	0.58
ICQD-AD-659	Vermillion	Hutchison, 2008	61.0	3.0	13.0	23.0	0.53
ICQD-AD-661	Vermillion	Hutchison, 2008	60.0	8.7	18.3	13.0	0.51
ICQD-AD-663	Vermillion	Hutchison, 2008	64.0	3.6	17.2	15.2	0.57

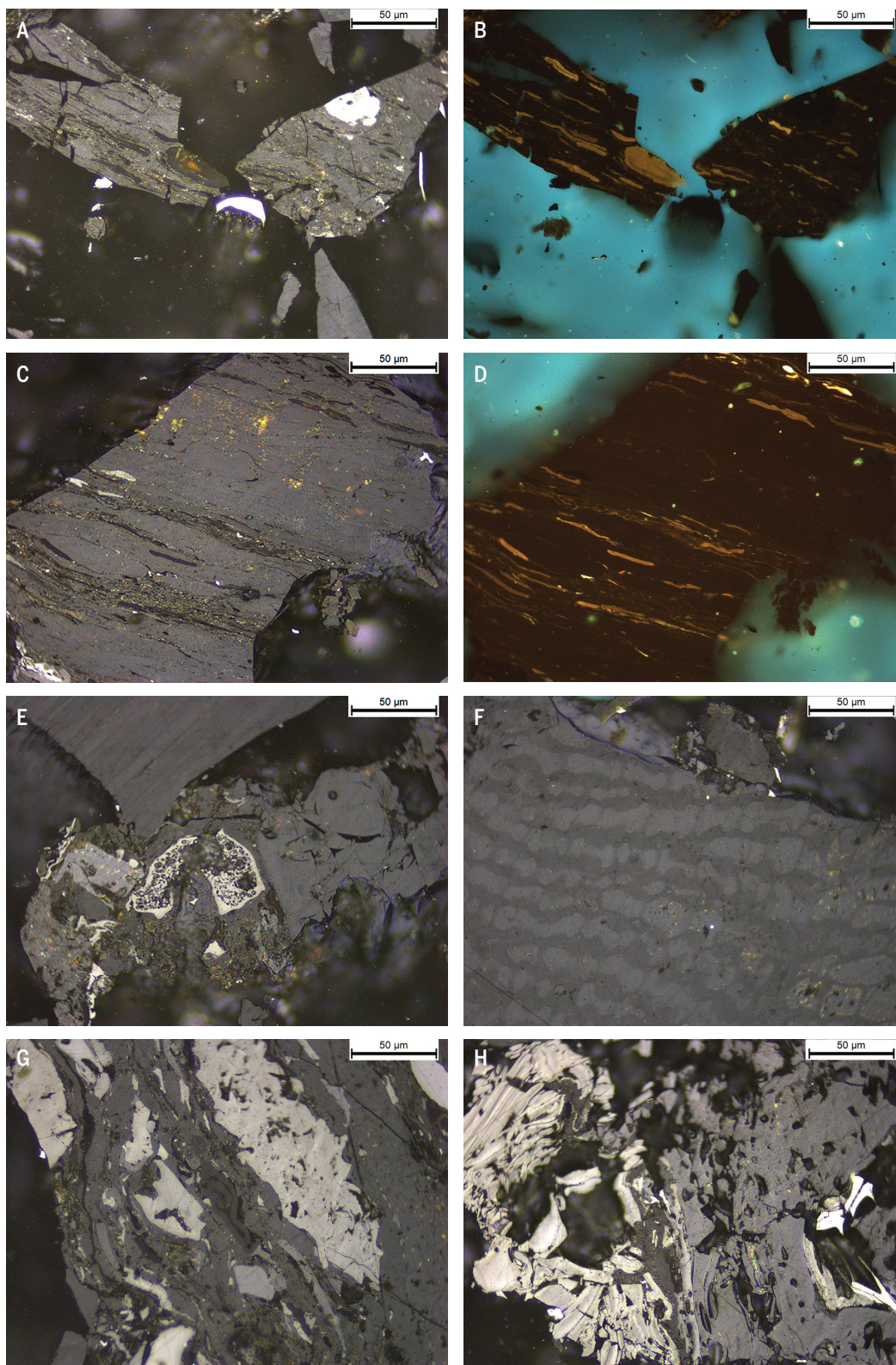


Figure 4. Photomicrographs of the Survant Coal Member from Vermillion County, Indiana. Reflected (A, C, E–H) and fluorescent (B, D) light. Oil immersion. A–D: vitrinite-rich coal with fluorescent liptinite (sporinite); E: inertinite (white) and vitrinite (gray) in coal; F: liptinite (cutinite) in coal; G: inertinite (white) surrounded by vitrinite and liptinite; H: inertinite-rich coal.

GEOMETRY OF THE SURVANT COAL MEMBER

Our analysis of the geometry of the Survant Coal Member is based on: a) cross sections generated through the Indiana portion of the Illinois Basin from Edgar County in the north (two wells from Illinois are included to better understand the correlations across the Indiana/Illinois border) to Posey County in the south (figs. 2, 5, 6), and b) mapping of the Survant Coal Member. Informal nomenclature is used in this study to distinguish the multiple coal benches of the Survant Coal Member (fig. 5). Specifically, the main seam is given a designation of upper bench of the Survant Coal—SV (UB); the underlying bench is designated the lower bench of the Survant Coal Member—SV (LB); and, locally, where one or two lenticular, discontinuous coal benches are present, they are given the designations of rider coal of the Survant Coal Member—SV (R1)—and upper rider coal of the Survant Coal Member—SV (R2).

Analysis of cross sections

In this study we carefully analyzed cores and geophysical logs to cover geometric variability of the coal seams identified as the Survant Coal Member. We examined 1,240 petroleum geophysical logs and coal test

borehole logs throughout Indiana to obtain a good data distribution so that we could understand the extent and stratigraphy of the two main Survant Coal seams and determine their relationship to the type section of the Survant Coal Member in Pike County (Hasenmueller and Ault, 1991). In our cross sections, we use the overlying Excello Shale Member (fig. 1) above the Houchin Creek Coal Member as a datum time horizon (fig. 6), because it is a transgressive marine shale (Coveney and others, 1991) and easily traceable on both geophysical and borehole logs throughout the basin. The underlying Mecca Quarry Shale Member (that overlies the Colchester Coal Member), another well-defined transgressive marine horizon (Coveney and others, 1987), is used as the base of our cross sections. We compiled a master north-south cross section, which incorporates mostly IGWS cores (signified by “SDH”) related to the observation of the geometry of the Survant Coal Member (fig. 6).

In the northernmost part of the section in eastern Illinois (fig. 6), there are four coal beds of the Survant Coal Member enclosed in fine-grained sediments. Lack of data to the north and west prevented us from determining whether these multiple coal benches occur proximal to a distributary channel. Within a short

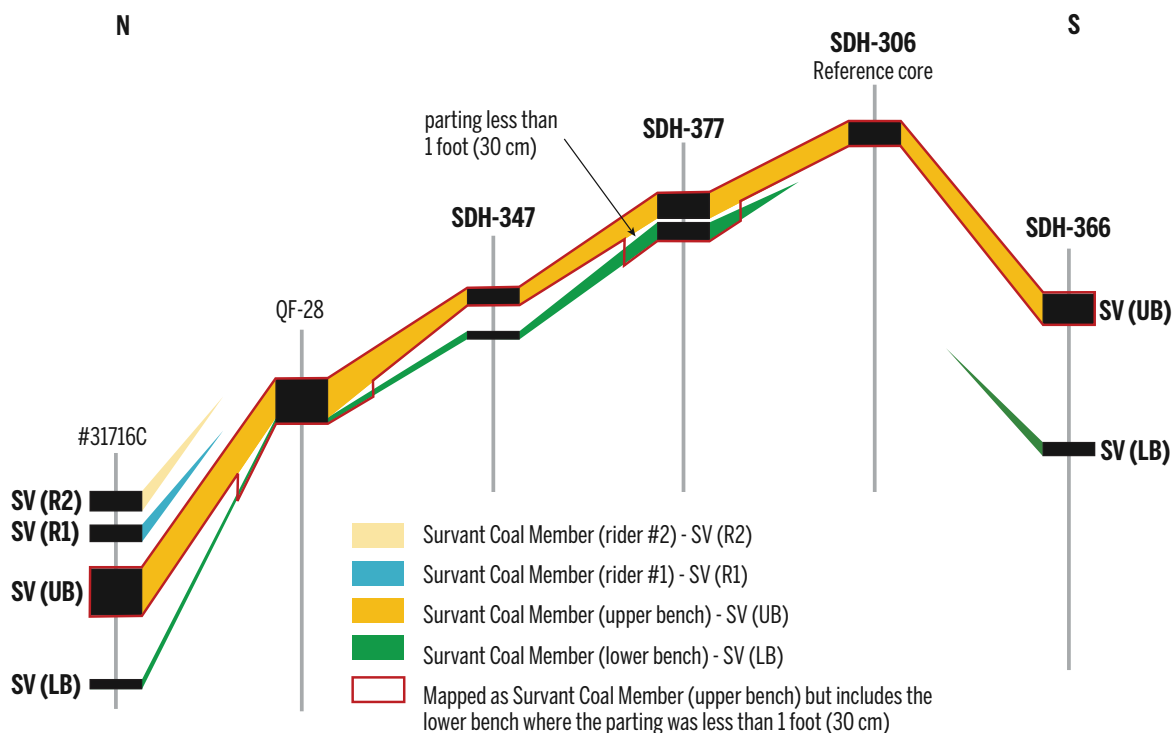


Figure 5. Schematic representation of the nomenclature of the Survant Coal Member used in this study. When mapping the upper bench, we added the thickness of lower bench to the upper bench if the thickness of the parting separating them was less than 1 ft (30.48 cm), as shown in SDH-377 or QF-28.

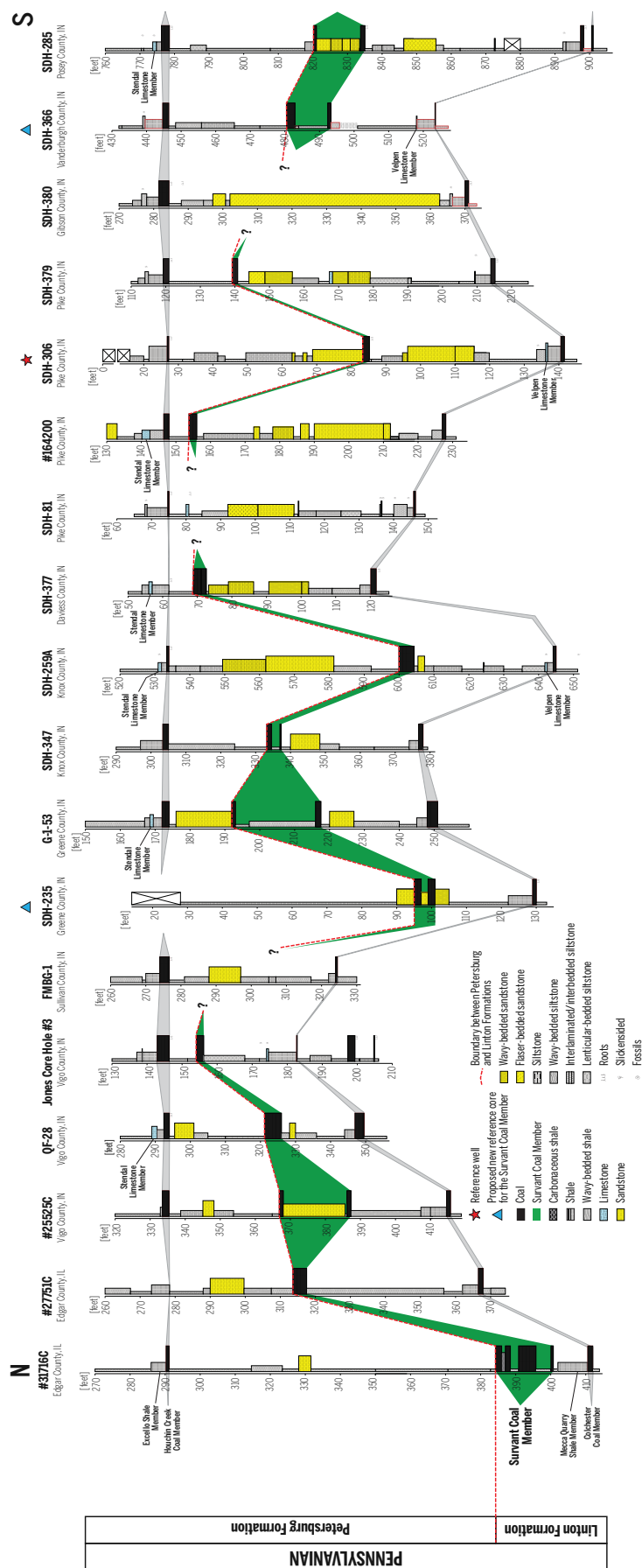


Figure 6. Cross section from well #31716C to well SDH-285; see well locations on Figure 2. Note that coal beds may not be present between two adjacent wells; lines shown on the section are for correlation purposes.

distance, only one thick coal seam is present (fig. 6, 27751C), and the enclosing sediments are coarser grained. Further south, in northern Vigo County, Indiana, two seams in that zone (fig. 6, 25525C), are separated by a 15-ft-thick (4.6-m) sandstone of local nature; nearby in QF-28, the two seams appear to have coalesced into one thick coal at the northern end of underground mining district in Vigo and Vermillion Counties. The coal thins in central Vigo County (Jones Core Hole #3) and disappears at the Vigo-Sullivan County boundary. The presence of a 10-ft-thick (3-m) sandstone in FMBG-1 suggests either a thin coal was eroded or was not deposited in this location. In a few areas of southern Vigo and northern Sullivan Counties near borehole FMBG-1, the thin interval between the Houchin Creek and Survant Coal Members suggests that the Survant Coal Member may have been eroded subaerially prior to Houchin Creek deposition. In Greene County, again, two coal seams in the Survant Coal Member are associated with sandstones in SDH-235 (fig. 6) and sandstones and siltstones in G-1-53 (fig. 6). The thick coal area west of Linton and Jasonville was the historic underground mining district of western Greene and eastern Sullivan Counties (fig. 2). One thick coal occurs in SDH-259A in Knox County and SDH-377 in Daviess County (fig. 6); however, in some areas between them no coal occurs, likely because of overlying sandstone cutouts (see fig. 7).

In Pike County, one discontinuous coal seam and a prominent sandstone component occur in the Excello Shale Member/Mecca Quarry Shale Member interval (fig. 6). SDH-306 in Pike County—the reference core for the Survant Coal Member (Hasenmueller and Ault, 1991)—shows one coal seam overlain by sandstone. In the Gibson County core (fig. 6, SDH-380), the Survant Coal Member is absent, and the interval between the Excello Shale and Mecca Quarry Shale Members is dominated by sandstone. It is difficult to resolve whether the coal was originally present and eroded or not deposited. In the southernmost part of the state (Vanderburgh and Posey Counties), two coal seams may be present in the Survant Coal Member (fig. 6). However, the lowest seam is discontinuous, likely because it was deposited in isolated localized basins, thus, only the upper seam is present in some areas (figs. 7, 8).

The presence of one to four coal seams (benches) and the variable thickness of the clastic partings create mapping challenges and cause stratigraphic uncertainties and problems with nomenclature used for this coal seam. As discussed above, the type section of the Survant Coal Member is only a single seam between the Colchester and Houchin Creek Coal Members

(figs. 5, 6), yet in other locations, two and, locally, as many as four seams are present. Consequently, it is not obvious whether those additional seams should be included in the Survant Coal Member. To better depict the complexity of this coal, we suggest adding two more locations as reference sections for the Survant Coal Member. The first is SDH-366 (PDMS #150359) in Vanderburgh County at a depth of 480.5 to 493.3 ft (146–150 m), which represents the southern part of Indiana where two benches are separated by a thick clastic interval (fig. 6). The second is SDH-235 (PDMS #157302) in Greene County at a depth of 85 to 91 ft (25.9–27.7 m), representative of the central part of the area studied where two distinct benches are separated by a relatively thin clastic parting (fig. 6). These two additional sections, together with the current reference section SDH-306 (PDMS #115871) (fig. 6), capture the complexity of the Survant Coal Member better than the current single reference section.

Mapping the benches of the Survant Coal Member

After carefully examining the data available in several databases, we generated maps of the depth and thickness of the upper and lower benches and the thickness of the clastic interval between the lower and upper bench. Note that, for the purpose of mapping the upper bench, where the lower bench was close to the upper bench and the thickness of the parting separating them was less than 1 ft (30.48 cm), we added the thickness of lower bench to the upper (fig. 5). The upper bench is clearly dominant (fig. 7), and its thickness ranges from less than 1 ft (30.48 cm) to more than 6 ft (1.8 m) locally. Past underground mining in this seam targeted those areas where the upper seam thickened or coalesced with the lower seam. The lower bench is more localized but appears to be thicker than the upper bench in the southernmost part of Indiana (fig. 8). The thickness of the interval between the upper and lower benches of the Survant Coal Member ranges from 0 to 4 ft (0–1.21 m) (fig. 9). There is no split in the underground mining districts of Vigo and Vermilion Counties and Greene and Sullivan Counties where the two benches merged to form the thick coal exploited by mining.

The depth of the Survant Coal Member (upper bench) increases progressively from less than 100 ft (30.48 m) at the basin margin to more than 900 ft (274.3 m) in Posey County (fig. 10), and the elevation of the coal bed ranges from +500 ft to -500 ft (+152.4–-152.4) (fig. 11). To better understand the depositional setting of the Survant Coal Member, we generated a thickness map of the interval between the Excello Shale Member and Mecca Quarry Shale Member (fig. 12), two well-defined transgressive marine shales in Indiana that occur above and below the Survant Coal Member,

respectively (fig. 1). In addition, we generated two maps: one covering the interval between the Excello Shale and the upper bench of the Survant Coal Member (fig. 13) and the other the interval between the upper bench of the Survant Coal Member and the Mecca Quarry Shale (fig. 14). Comparing the clastic intervals above and below the Survant Coal, there is a major shift in the location of the thickest zones; below (before the deposition of the Survant), the thickest interval occurs in the southern part of the state and thins to the northern part of the state by an average of about 20 ft (6 m) (fig. 14). The clastic interval above the Survant Coal (after its deposition) is considerably more variable in thickness. Thicker clastic zones are located throughout southwestern Indiana, separated by the zones of a much thinner interval (fig. 13). The variability of the thickness of the clastic interval above the Survant Coal Member appears to be a primary component in the variability of the total thickness of the entire Mecca Quarry Shale Member/Excello Shale Member interval (fig. 12). Inspection of the available core samples and geophysical logs shows that both the subjacent and superjacent Survant Coal Member clastic intervals are normally upward-coarsening, progradational sequences that occasionally show minor oscillations. Fining-upward channel-fill sequences are also present in both intervals, but are more common and generally thicker in the Excello/Survant (upper) interval, thus accounting for the increased variability of this interval noted above.

CONCLUSIONS

Our detailed analysis of the thickness and the extent of the two main benches of the Survant Coal Member within the framework of the Mecca Quarry Shale Member/Excello Shale Member interval suggests the following:

- 1) The Survant Coal Member is very discontinuous. Although it is difficult to determine whether this discontinuity resulted from erosion (subaqueous or subaerial) or nondeposition, the pattern of noncoal intervals suggests that both processes contributed. The upper bench of the Survant is much more extensive than the lower bench. This is, most likely, the part of the Survant that was described from the type section of this coal, although further detailed biostratigraphic analysis and depositional systems mapping are required to verify this. The vast majority of the mining to date has exploited the upper bench of the Survant. The lower bench was probably also mined where the two benches coalesced to form a thick seam.
- 2) The thickest areas of the upper bench of the Survant Coal Member seem to coincide with the zones of the thin underlying clastic interval between this coal and the Mecca Quarry Shale Member. In the southern part of the state where the interval is thickest, the coal is thin. This suggests that topography affected coal deposition, namely, that the thickest coal was deposited in the topographic low points. Variable pre-peat topography is also indicated by the presence of small coal zones of the lower bench that were probably deposited in isolated topographic lows.
- 3) The change in the thickness patterns between the Mecca Quarry/Survant and Survant/Excello clastic intervals is intriguing and not only related to sediment compaction. We suggest that some tectonic activity followed deposition of the Survant, perhaps along fault lines (major faults are marked on figs. 7–14), that modified the topography and caused the change in depositional patterns. Both clastic intervals above and below the Survant Coal Member are dominantly upward-coarsening, progradational sequences with some upward-fining channel-fill sequences. The channel-fill sequences are more common and generally thicker in the clastic interval above the Survant Coal Member.
- 4) The presence of one to four coal benches and the variable thickness of clastic partings create mapping challenges and cause stratigraphic uncertainties and problems with the nomenclature used for this coal seam. Because from one to four coal beds occur between the Colchester and Houchin Creek Coal Members, it is unclear which and how many seams should be included within the Survant Coal Member (*sensu stricto*). Therefore, to better depict the complexity of the Survant Coal Member, we suggest adding two locations as reference sections: one (SDH-366 in Vanderburgh County) represents the more southern part of Indiana where two benches are separated by a thick clastic interval; the second (SDH-235 in Greene County) represents the central part of the study area where two distinct benches are separated by a relatively thin clastic parting. These two additional sections, together with the current reference section (SDH-306), capture the complexity of the Survant Coal Member and create a much more representative view of this seam than the current single reference section alone.
- 5) The Survant Coal Member is limited as a resource for conventional mining. The main limiting issue is the relatively small sizes of the potential reserve blocks, especially for underground mining. Any future mining of this coal is contingent upon whether the economics of any given reserve block are favorable at the time of assessment.

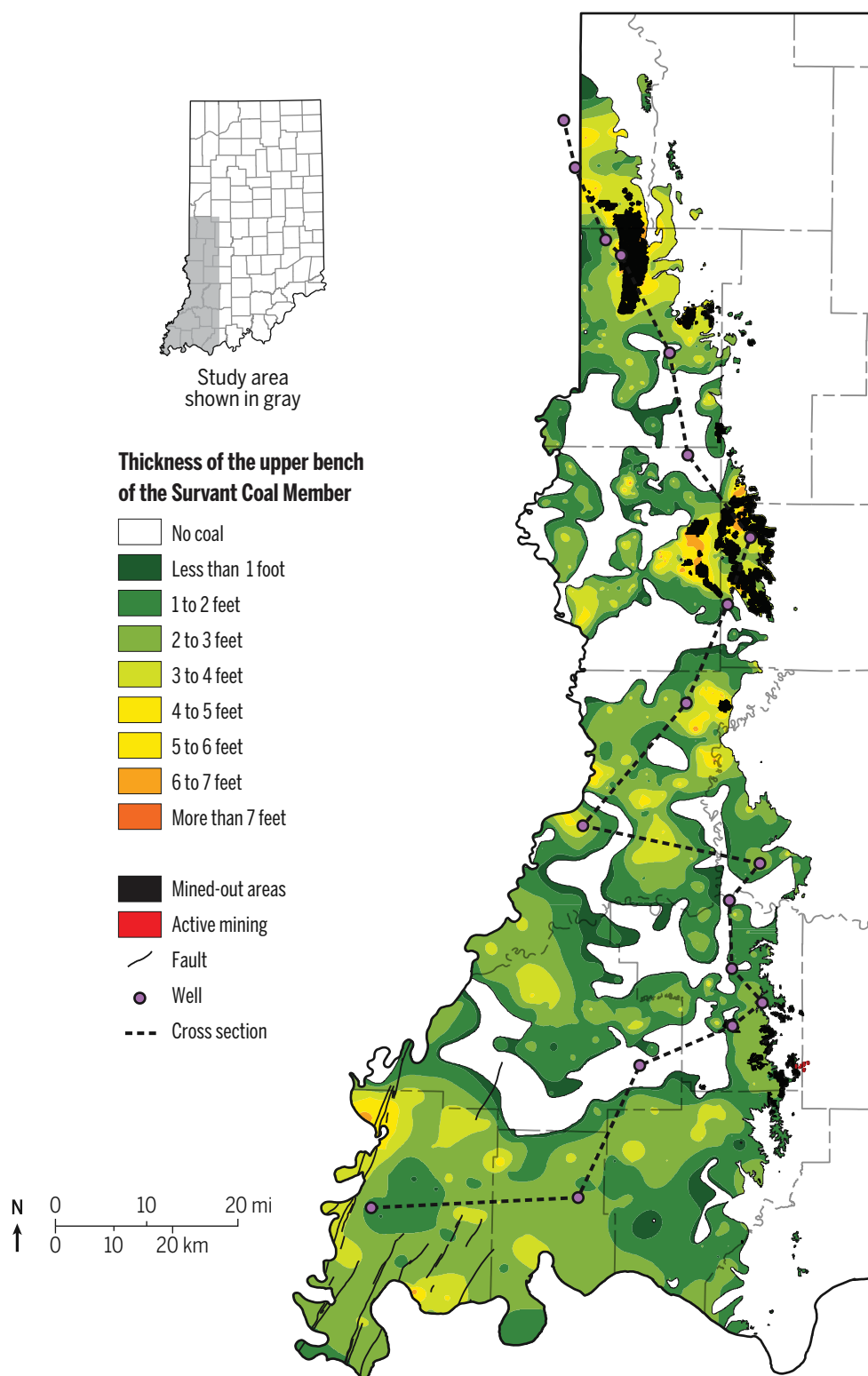


Figure 7. Thickness of the upper bench of the Survant Coal Member. See Figure 2 for names of wells used in the cross section (fig. 6).

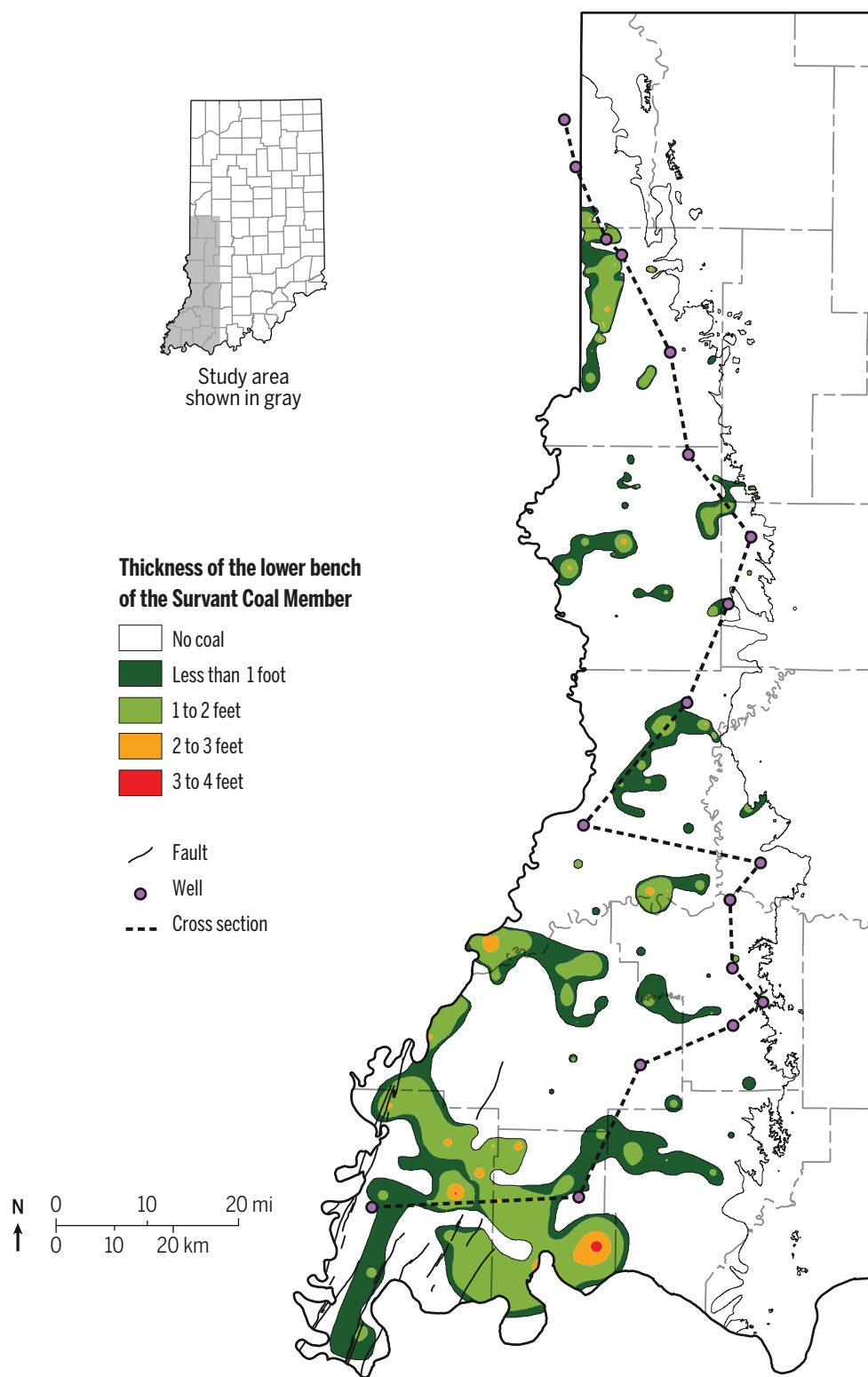


Figure 8. Thickness of the lower bench of the Survant Coal Member. See Figure 2 for names of wells used in the cross section (fig. 6).

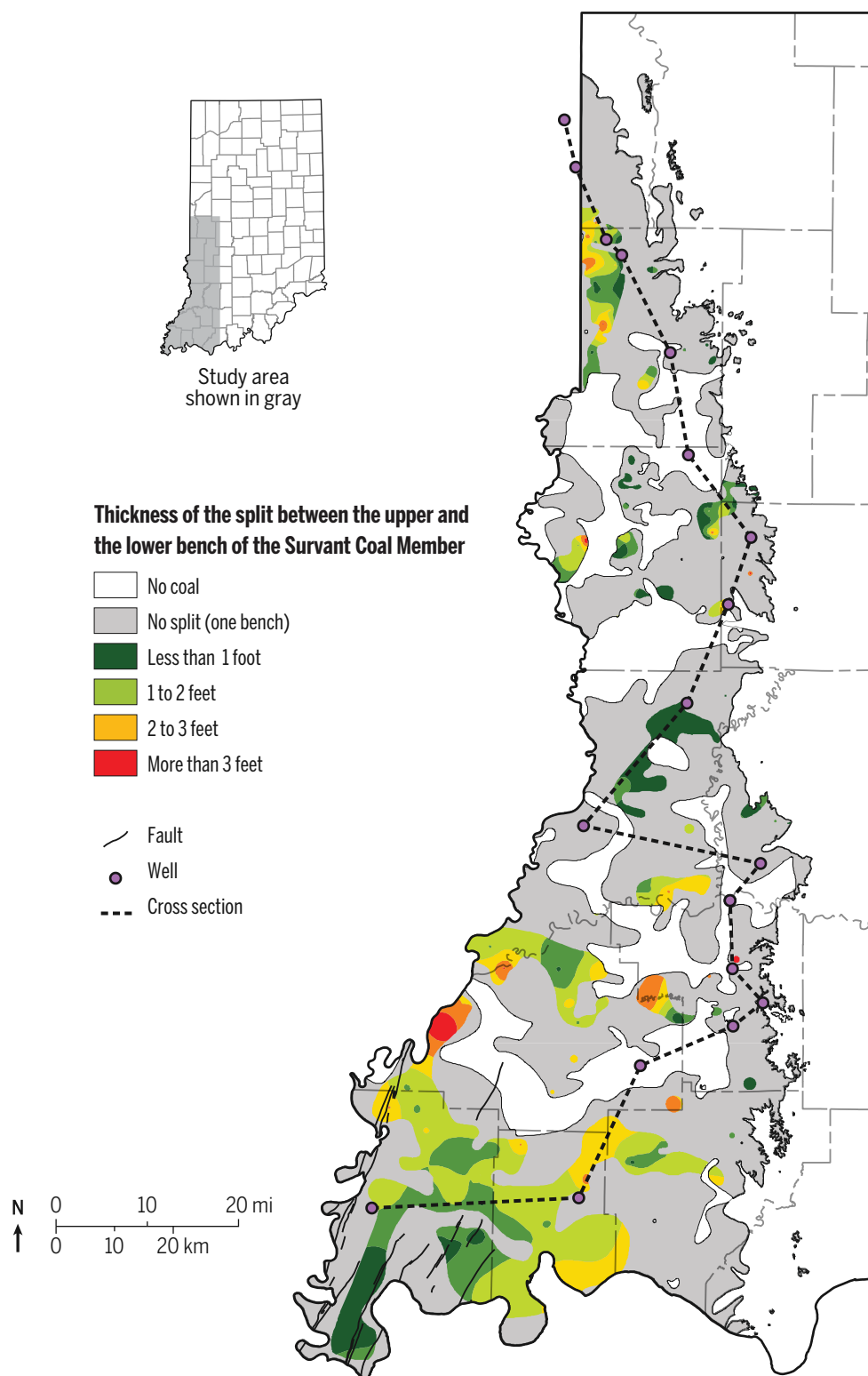


Figure 9. Thickness of the split between the upper and the lower bench of the Servant Coal Member. See Figure 2 for names of wells used in the cross section (fig. 6).

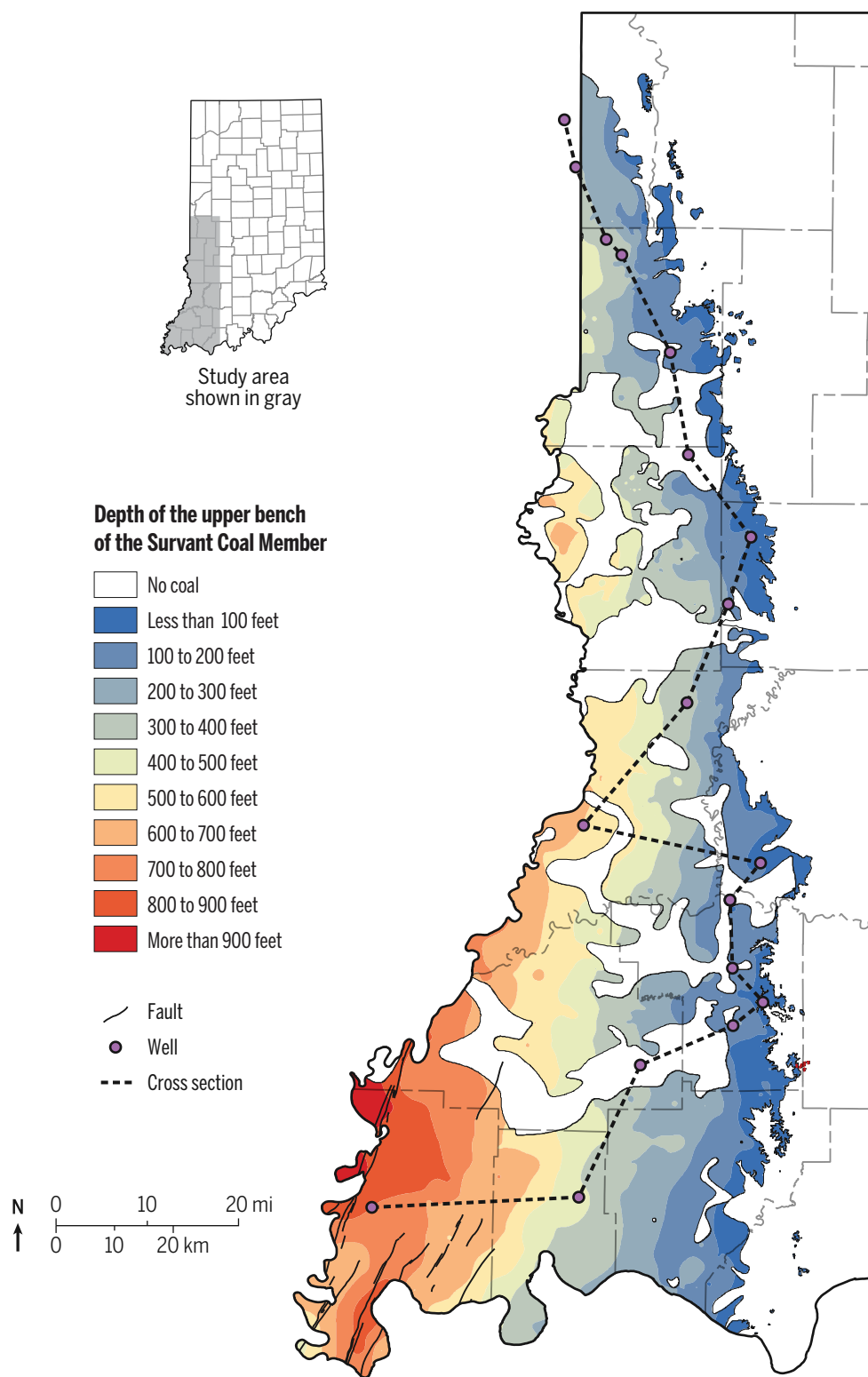


Figure 10. Depth of the upper bench of the Survant Coal Member. See Figure 2 for names of wells used in the cross section (fig. 6).

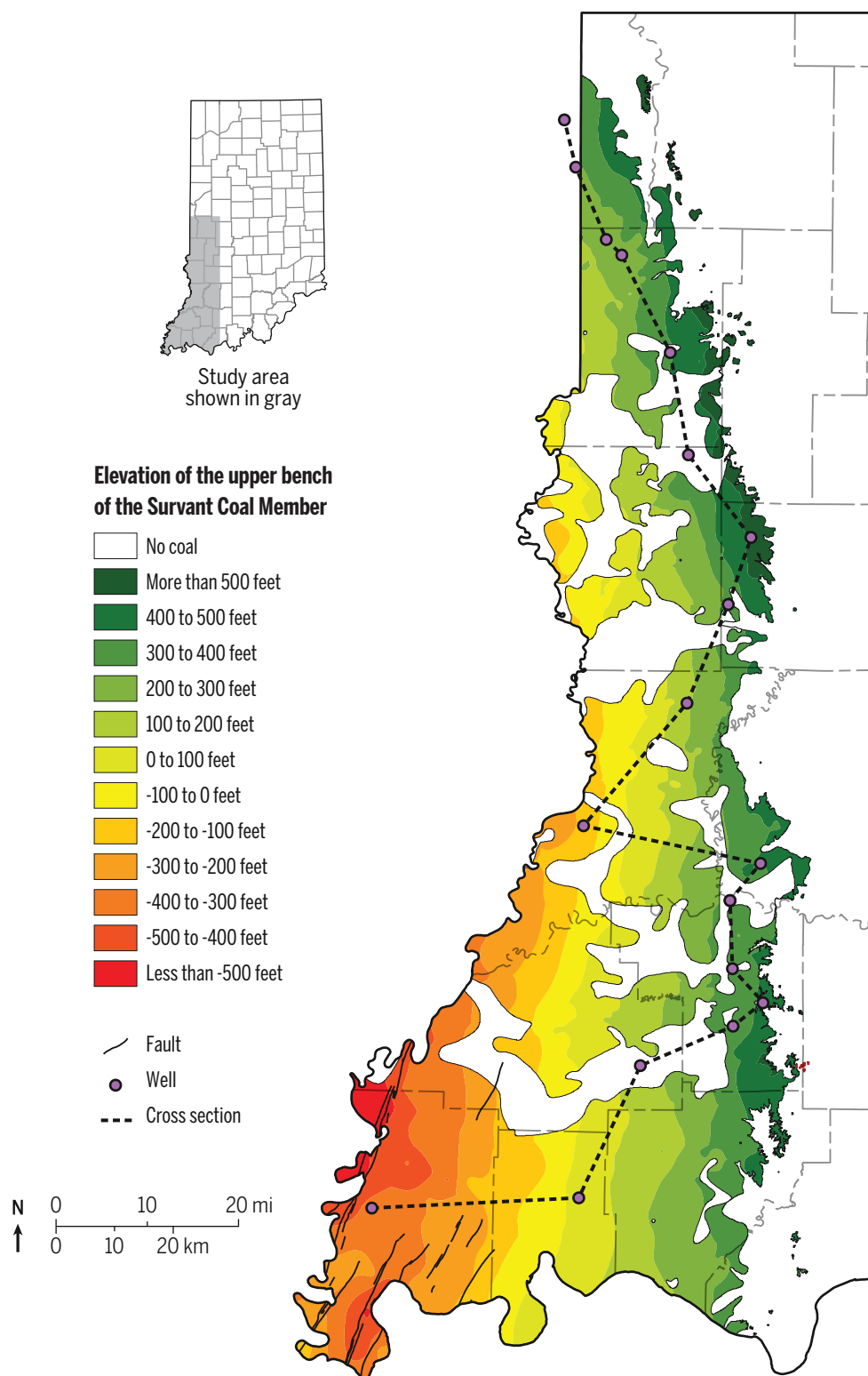


Figure 11. Elevation of the upper bench of the Servant Coal Member. See Figure 2 for names of wells used in the cross section (fig. 6).

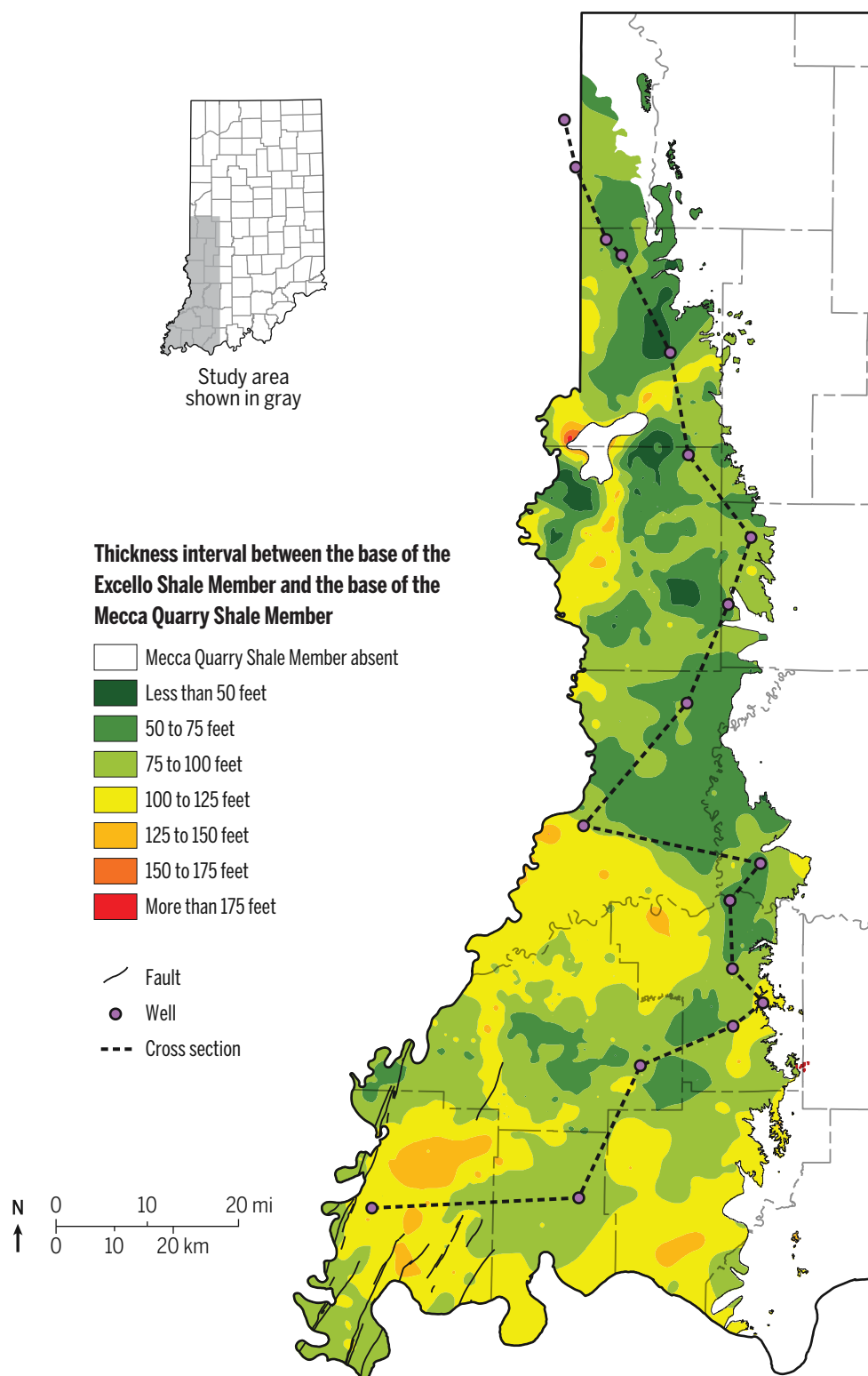


Figure 12. Thickness interval between the base of the Excello Shale Member and the base of the Mecca Quarry Shale Member within the extent of the Survant Coal Member in Indiana. See Figure 2 for names of wells used in the cross section (fig. 6).

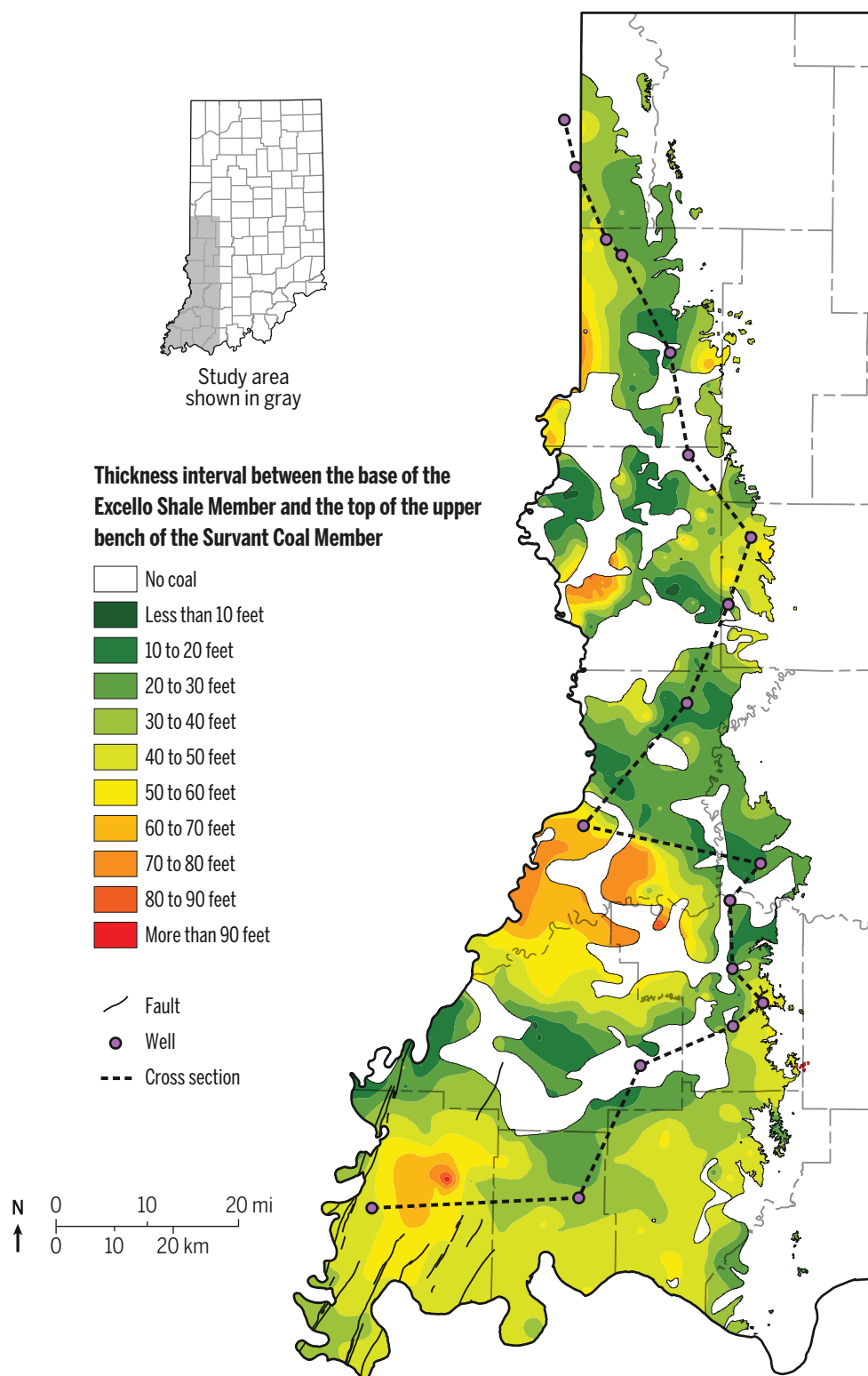


Figure 13. Thickness interval of the base of the Excello Shale Member and the top of the upper bench of the Survant Coal Member. See Figure 2 for names of wells used in the cross section (fig. 6).

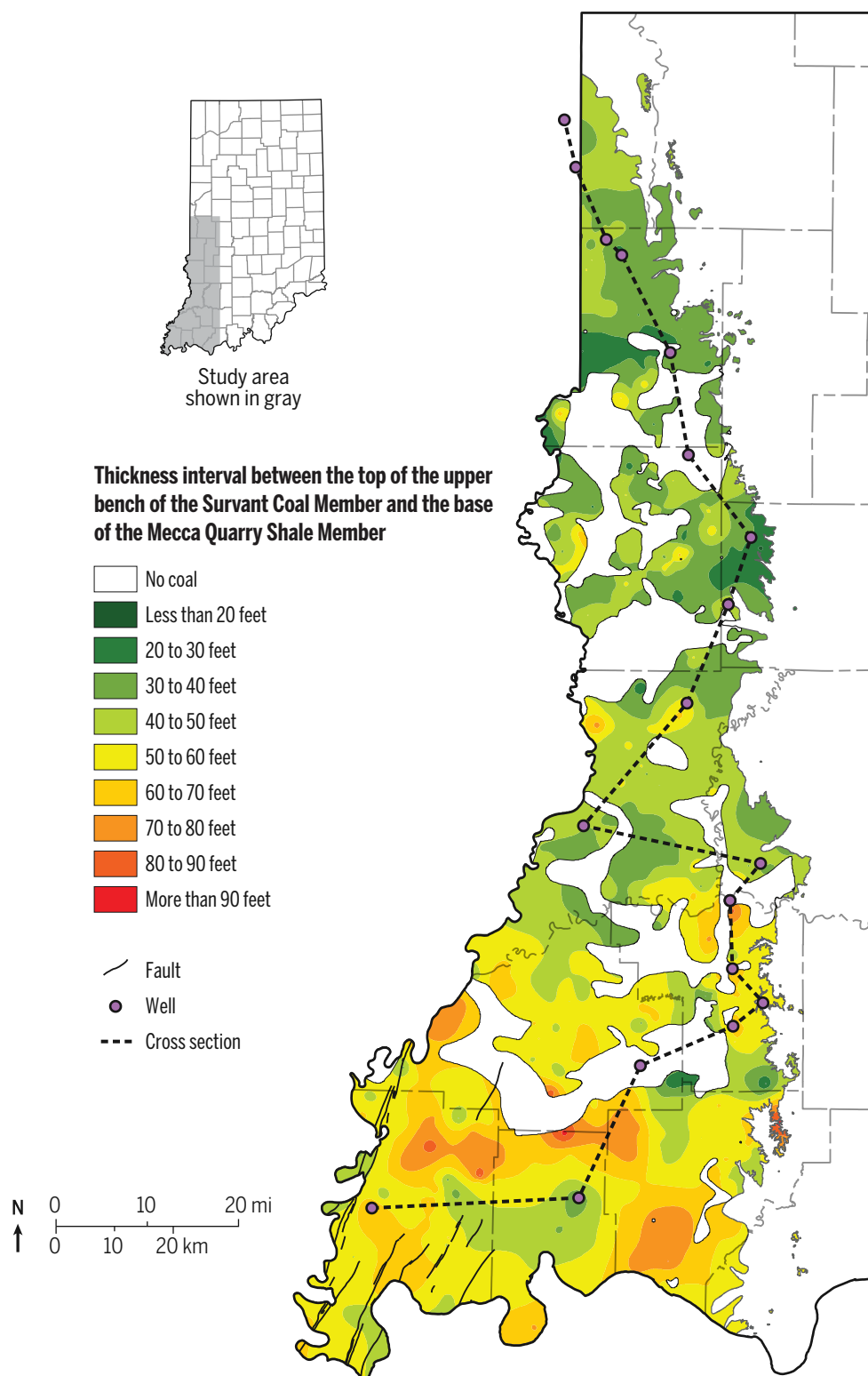


Figure 14. Thickness interval between the top of the upper bench of the Servant Coal Member and the base of the Mecca Quarry Shale Member. See Figure 2 for names of wells used in the cross section (fig. 6).

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Table 3. Elements in ppm (raw whole coal) in Survant Coal Member samples (Drobniak and Mastalerz, 2012)

Parameter symbol	Parameter	Number of samples	Average	Minimum	Maximum	Standard deviation
Ag	Silver	12	0.14	0.03	0.36	0.11
Al	Aluminum	7	9,828.57	7,900.00	13,000.00	1,978.82
As	Arsenic	12	29.12	0.89	58.40	19.75
Au	Gold	9	0.84	0.60	1.46	0.31
B	Boron	9	99.63	84.68	150.00	20.64
Ba	Barium	9	46.70	13.00	121.00	34.53
Be	Beryllium	12	3.88	2.78	6.42	0.96
Bi	Bismuth	9	1.25	0.24	2.30	0.64
Br	Bromine	7	3.43	1.00	7.00	2.23
Ca	Calcium	7	1,571.43	310.00	2,900.00	1,115.83
Cd	Cadmium	12	0.30	0.04	1.63	0.44
Ce	Cerium	7	14.71	9.00	21.00	5.15
Cl	Chlorine	1	0.01	0.01	0.01	-
Co	Cobalt	12	6.99	2.80	24.82	6.15
Cr	Chromium	12	15.85	9.30	25.00	5.64
Cs	Cesium	9	1.31	0.80	2.54	0.52
Cu	Copper	12	15.69	7.80	31.46	6.75
Dy	Dysprosium	7	2.26	1.90	3.40	0.54
Er	Erbium	7	0.79	0.60	1.20	0.23
Eu	Europium	7	0.32	0.19	0.51	0.12
F	Fluorine	10	101.20	0.01	232.00	74.33
Fe	Iron	7	24,428.57	19,000.00	32,000.00	4,276.18
Ga	Gallium	9	4.84	3.40	7.30	1.25
Gd	Gadolinium	7	2.29	0.70	4.50	1.18
Ge	Germanium	9	13.65	3.90	18.00	3.92
Hf	Hafnium	7	0.49	0.40	0.60	0.09
Hg	Mercury	12	0.19	0.05	0.35	0.10
Ho	Homium	7	0.48	0.41	0.72	0.11
Ir	Iridium	7	12.37	0.91	24.00	10.58
K	Potassium	7	1,300.00	1,000.00	1,900.00	382.97
La	Lanthanum	7	8.14	4.00	12.00	3.39
Li	Lithium	12	15.52	5.40	33.50	9.59
Lu	Lutetium	7	0.10	0.08	0.12	0.01
Mg	Magnesium	7	528.57	330.00	690.00	135.70
Mn	Manganese	9	23.49	8.70	35.09	8.82
Mo	Molybdenum	12	2.90	1.10	7.30	1.77
Na	Sodium	7	352.86	170.00	610.00	140.20
Nb	Niobium	9	2.90	0.74	5.20	1.21
Nd	Neodymium	7	12.17	3.20	18.00	6.24
Ni	Nickel	12	23.27	9.50	51.10	12.86

Table 3 (cont.). Elements in ppm (raw whole coal) in Survant Coal Member samples (Drobniak and Mastalerz, 2012)

Parameter symbol	Parameter	Number of samples	Average	Minimum	Maximum	Standard deviation
Os	Osmium	7	0.70	0.60	1.00	0.14
P	Phosphorus	7	262.43	33.00	740.00	297.91
Pb	Lead	12	35.90	8.23	105.12	24.58
Pd	Palladium	7	0.11	0.09	0.16	0.02
Pr	Praseodymium	7	5.80	4.10	12.00	2.82
Pt	Platinum	7	0.48	0.41	0.72	0.11
Rb	Rubidium	9	15.37	10.00	24.20	4.52
Re	Rhenium	7	0.70	0.60	1.00	0.14
Rh	Rhodium	7	0.07	0.06	0.10	0.01
Ru	Ruthenium	7	0.23	0.19	0.34	0.05
S	Sulfur	7	961.43	630.00	1,400.00	285.10
Sb	Antimony	12	1.73	0.69	4.30	1.04
Sc	Scandium	9	3.85	2.50	6.86	1.45
Se	Selenium	12	3.04	1.80	5.50	1.19
Si	Silicon	7	14,428.57	12,000.00	19,000.00	2,878.49
Sm	Samarium	5	1.88	0.90	2.70	0.66
Sn	Tin	9	0.77	0.41	1.46	0.38
Sr	Strontium	9	101.22	14.00	314.60	97.20
Ta	Tantalum	7	0.11	0.07	0.14	0.03
Tb	Terbium	7	0.24	0.15	0.39	0.08
Te	Tellurium	2	0.27	0.24	0.29	0.04
Ti	Titanium	7	528.57	420.00	740.00	114.52
Th	Thorium	9	1.60	1.10	2.90	0.56
Tl	Thallium	9	0.83	0.51	2.04	0.47
Tm	Thulium	7	0.33	0.28	0.49	0.08
U	Uranium	9	1.53	0.71	3.94	1.04
V	Vanadium	12	25.54	7.10	50.82	13.33
W	Tungsten	7	0.43	0.36	0.57	0.09
Y	Yttrium	9	7.49	3.60	9.70	1.97
Yb	Ytterbium	7	0.59	0.50	0.70	0.08
Zn	Zinc	12	50.77	7.90	231.00	65.66
Zr	Zirconium	9	31.87	7.70	71.00	18.28