SITE EVALUATION OF SUBSIDENCE RISK, HYDROLOGY, AND CHARACTERIZATION OF INDIANA COALS FOR UNDERGROUND COAL GASIFICATION (UCG)

FINAL REPORT TO CCTR

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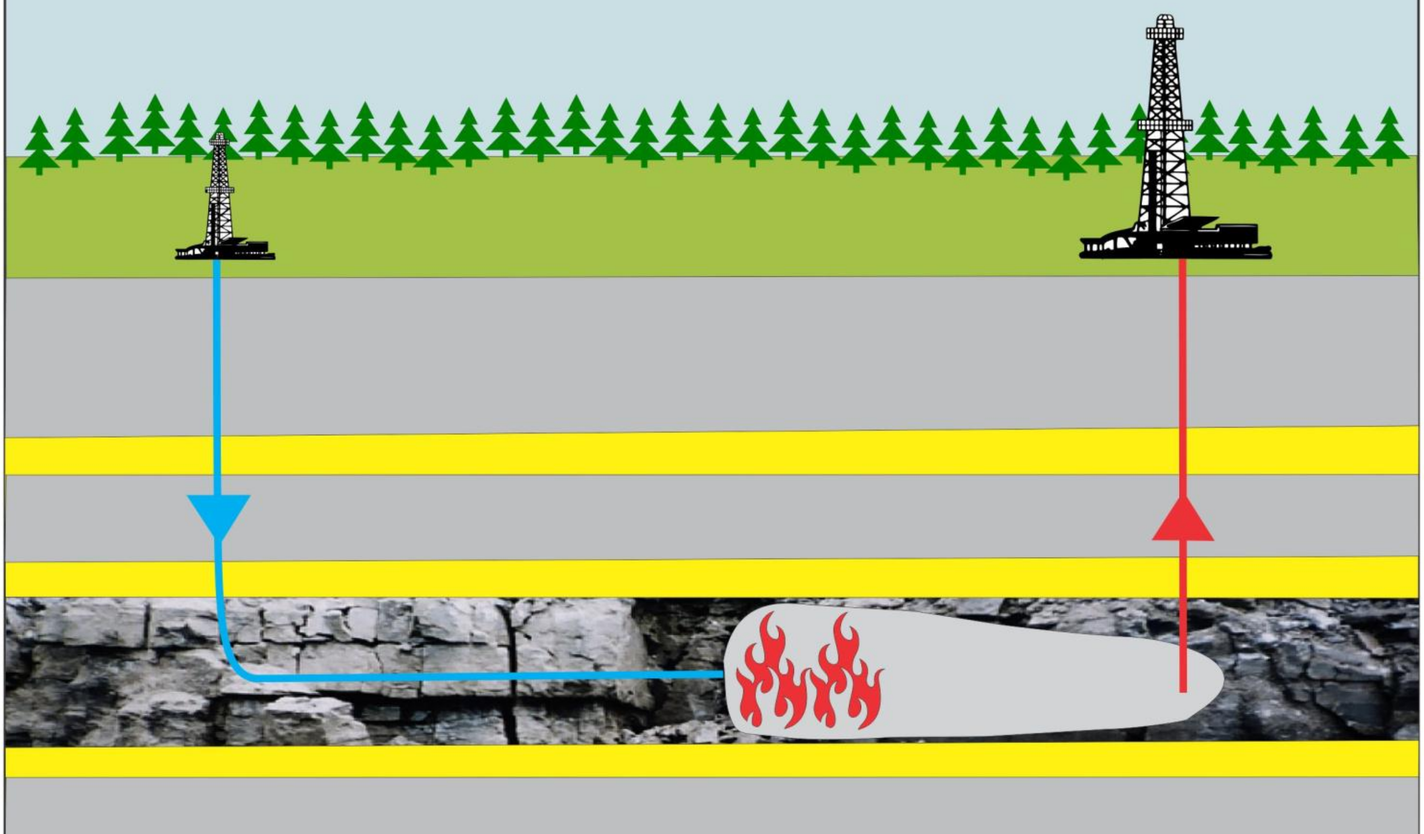

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1.0 Introduction

Underground coal gasification (UCG) is a technology that has potential to complement or even replace traditional methods for coal mining and surface gasification. New commercial UCG projects have started recently in several countries such as Australia, China, and India, and more projects are being considered. Appropriate site selection and application of the best UCG technology is a complex process, and a variety of technical and geological factors must be taken into consideration to evaluate each site being considered. Some of these factors and the parameter ranges are listed in Table 1.

A review of the UCG technologies worldwide and their possible application for use in the in-situ gasification Indiana coals was the subject of a recent preliminary assessment (Shafirovich et al., 2009) sponsored by the Indiana Center for Coal Technology Research (CCTR). Taking into account both the operational experiences of UCG projects and the geological characteristics of Indiana coals, the thickness and depth of target coal seams were recommended to be used as the primary screening criteria in selecting the areas that have the most potential for further evaluation for UCG. The Springfield and the Seelyville Coal Members were selected as the primary targets for assessment. For these coals, maps were generated that show thickness, depth, and other characteristics, such as moisture and heating value. Based on these maps, several of the most promising zones were identified; these zones are shown in Figure 1 for the Springfield and in Figure 2 for the Seelyville, and they are shown jointly in Figure 3. Based on these maps and other geological and infrastructure data, preliminary recommendations on the future selection of a suitable location for UCG operations were made. That study emphasized, however, that the available information on the coals and overlying rock characteristics was insufficient for use in selecting individual sites for engineering and design studies for the construction of a UCG plant. Consequently, additional follow-up site evaluation of the areas determined in the initial assessment would be required.

The intent of this evaluation is to provide more detailed geological analysis of the potential areas or sites that were derived in the previous assessment. Some modifications of the proposed areas were made to make best use of data coverage and to account for the changes in land use. This geological analysis includes: (1) a detailed characterization of coal properties in order to better predict the nature of the produced syngas and the kinetics of the underground gasification process; (2) a generalized investigation of the lithological characteristics of the overlying rock strata in an effort to understand the risk to underground sources of drinking water as well as the availability of water for the gasification process; and (3) a preliminary general evaluation of the overlying rock characteristics in an effort to understand their influence on potential roof collapse and on the subsidence of the ground surface. The resulting data and characterizations from these areas of investigation will provide the information that is essential for the planning and modeling of the performance of an underground gasification project.

Table 1. Desired geologic and hydrologic characteristics for UCG (based on Oliver and Dana, 1991). Note: FSI – Free Swelling Index.

Parameter	Desired value	Imperial units and comments
Coal thickness (m)	1.5-15.0	5-50 ft
Thickness variation (% of seam thickness)	<25	
Depth (m)	92 -460	300-1,500 ft
Dip (degrees)	0-70	Technology dependent
Dip variation (degrees/31m, 100 feet)	<2	For directionally drilled wells
Single parting thickness (m)	<1	<3 ft
Total parting thickness (% of seam thickness)	<20	
Fault displacement (% of seam thickness)	<25	
Fault density (Number of faults/31 m)	<1	number of faults/100 ft
Coal rank	≤bituminous	If bituminous, FSI should be low
Coal moisture (wt %)	<15	
Ash content (wt %)	<50	
Coal sulfur (wt %)	<1	
Thickness of consolidated overburden (m)	>15	>50 ft
Seam permeability (mD)	50-150	
Immediate overburden permeability (mD)	<5	15 m (50 ft) above the seam
Distance to nearest overlying water-bearing unit (m)	>31	>100 ft
Coal aquifer characteristics	confined	
Nearest producing well completed in coal seam (km)	>1.6	>1 mile
Available coal resources (10^6 m^3)	15.4	~543×10^9 cubic ft for 20-year-long operation

2.0 Characterization of coal beds

2.1 Importance of coal and seam characteristics for UCG

2.1.1. Thickness of coal seam

Generally for UCG purposes, the thicker the coal seams the better, because more coal is available for gasification. Thicker seams also may require fewer wells for extraction of the produced gas. However, there is no agreement on the minimum seam thickness for UCG. ErgoExergy (http://www.ergoexergy.com) states that UCG can be used in coal seams as thin as 0.5 m. Oliver and Dana (1991) give 1.5 m as a cut-off value (Table 1). However, it has been demonstrated that the heating value of the produced gas decreases significantly in coal seams thinner than 2 meters (Kreinin and Shifrin, 1993), partly because a relatively larger portion of energy is lost to the surrounding rock formations (Gunn, 1977). In our study, we consider 2 meters or more as the most suitable seam thickness (Shafirovich et al., 2009) (Table 2).

In addition to the seam thickness, a consistent thickness is desirable for UCG (Table 1). Seams that change thickness over short distances may cause complications during the drilling of directional wells as part of the extraction process. Oliver and Dana (1991) state that a commercial operation will require approximately 2.6 km^2 (~1 square mile) of a fairly continuous 6-meter-thick coal seam to operate a moderate sized plant for about 20 years.

Table 2. Coal seam thickness values used for determining the suitability of Indiana coals for UCG (after Shafirovich et al., 2009).

Thickness	**Suitability**
>2.0 m	High
1.5 – 2.0 m	Medium
1.0 – 1.5 m	Low
<1.0 m	Unacceptable

2.1.2. Partings

The presence of horizontal partings within the coal seam may cause operational problems if they occur near ignition points or along a path that links the injection and production wells. Single partings should be thinner than 1 meter (Table 1); partings thicker than 1 meter not only can substantially decrease gas quality but can totally stop gasification. If the coal seam contains more than 20% parting material, the quality of gas may be decreased to the point that gasification of that seam would be economically infeasible (Oliver and Dana, 1991).

2.1.3 Depth of coal seam

Depth of the coal is another parameter of key concern for UCG. In general, the greater the depth of the seam, the safer it is for the environment because it significantly reduces the chances for detrimental impacts on potable groundwater, surface subsidence issues, and the possibility of releasing emissions from the gasification process into the air. However, to date, UCG operations have targeted coals at a variety of depths. The depth varied from 30 to 350 m in both the former Soviet Union (FSU) developments and U.S. experiments, while Western European trials were conducted in coals as deep as 600 to 1,200 m. Burton et al. (2006) indicate that the minimum depth should be 12 m but no explanation for this recommendation is provided. Oliver and Dana (1991) give 92 m (300 ft) as the desirable depth. In general, shallow seams provide lower potential for UCG for several reasons. At shallow depths, coals that are possible candidates for UCG would have to compete with surface and subsurface mining. Additionally, the proximity of potable and potentially potable groundwater supplies (underground sources of drinking water, USDWs) at shallow depths also discourages the consideration of shallower coals for UCG.

Another problem with the use of shallower depths for UCG is the risk of subsidence. To decrease the risk of subsidence, Burton et al. (2006) recommend operational depths of >200 m. Depths greater than 300 m require, on one hand, more complicated and expensive drilling technologies but, on the other hand, greater depths minimize the risk of subsidence and offers the possibility to conduct the UCG process at higher pressure, which increases the heating value of the produced gas. Also, deeper seams are less likely to be linked with potable aquifers, thus avoiding drinkable water contamination problems. Finally, if the product gas is to be used in gas turbines, additional compression of gas produced from greater depths may not be necessary. Seams deeper than 460 m (1,500 ft) are not desirable for UCG either (Table 1). At the current technological level, very deep seams cause operational problems because of high lithostatic pressure, which restricts gas flow (Oliver and Dana, 1991).

Taking the above-mentioned considerations and Indiana's geologic conditions into account, in which coal seams range in depth from zero to 300 m, Shafirovich et al. (2009) formulated depth criteria for the state (Table 3) in which depths of >200 m present the highest suitability for UCG.

Table 3. Coal seam depth values used for determining the suitability of Indiana coals for UCG (after Shafirovich et al., 2009).

Depth	**Suitability**
>200 m	High
60-200 m	Adequate
<60 m	Unacceptable

2.1.4. Dip of coal seam

Sury et al. (2004) indicate that slightly dipping coal seams are preferable. Such seams facilitate drainage and the maintenance of hydrostatic balance within the gasifying area and minimize potential damage to the down-dip production well from material that is moved in association with the UCG process. Sloping seams also encourage water and ash to move away from the oxidation zone. A common recommendation is dip angles of zero to 20 degrees (GasTech, 2007). We note, however, that UCG has been successfully carried out in steeply dipping seams (Kreinin, 2004). ErgoExergy gives a dip of 0^o to 70^o as the preferred range (see also Table 1). Within the state of Indiana, all coal seams dip at an approximate rate of 5^o and therefore meet the required value for this parameter.

2.1.5. Coal properties

In general, lignite, sub-bituminous and low-rank high volatile bituminous coals are preferable. UCG may work better on lower ranks coals because they tend to shrink upon heating, enhancing the permeability and connectivity between the injection and production wells (Jennings, 1976). In contrast, higher rank coals swell upon heating, potentially reducing permeability. On the other hand, the higher the rank and corresponding heating value of coal, the higher the heating value of the UCG gas. Therefore, such coal properties as the calorific value and free swelling index (FSI) are important for UCG.

Swelling of coal upon heating is often mentioned as a prohibitive feature for UCG. For example, Sury et al. (2004) states that the reverse combustion process works well in shallow nonswelling coal seams but it is not a recommended process for use at significant depths and in swelling coals. In contrast, Burton et al. (2006) note that the methods used in the former Soviet Union demonstrated minimum sensitivity to coal swelling and that the large-dimension channels formed in the linkage process employed in that operation did not appear to be plugged by coal swelling even though the gasified coals were of a rank that generally swell upon combustion. Volatile matter content, to a large extent, is related to the ability of coal to swell upon heating, an undesirable effect for UCG. Usually coal swells when volatile matter is between 15% and 40%, with the maximum swelling occurring in the range of 25% to 30%. This range corresponds to low volatile, medium volatile, and a portion of high volatile bituminous rank.

UCG can use coals having a wide range of ash contents up to 60%, but in coals having ash contents above 50% one can expect lower heating values, because a substantial portion of the thermal energy is taken up by the mineral matter (Gunn et al., 1976). Sulfur content is important because excessive sulfur emissions will require additional clean-up of the produced syngas. Moisture content in coal is another important parameter that must be considered. The gasification process requires water, and coal moisture is one of the sources of the water. Generally, a moisture content of less than 15% is preferred (Table 1).

Porosity and permeability within the coal seam are also important parameters that must be considered because these influence the ability to connect an injection and a production well and also influence kinetics of the gasification. More porous, better cleated, and more permeable seams allow for more effective connection between the injection and production wells, leading to faster transport of reactants and a higher rate of gasification. Bulk permeability values of 50 to 150 mD for coals is preferred (Oliver and Dana, 1991; Table 1). On the other hand, higher porosity and permeability increase the influx of water, and increase product gas losses. However, at this point there is scarcity of this type of data and, consequently, the influence of these parameters on UCG is difficult to assess.

2.2 Springfield Coal sites

For the Springfield Coal, four small areas (denoted as zones 1 to 4) have been selected for further examination (Figures 3, 4, and 5). A single area that includes all four zones is called Area A in this report (Figure 3). Thickness of the coal and the depth to the seam is projected in Figures 6 and 7, respectively. Within each of these four zones, the seam thicknesses are greater than 2 m, and depths are in the 60 to 200 m range. Coal quality parameters compiled for this area include: moisture, ash and sulfur content, heating value, sulfur content, petrographic composition, vitrinite reflectance (R_o), carbon content, hydrogen content, fixed carbon, and volatile matter content and they are shown in Figures 8 through17. In addition, the ranges and averages of the values for Area A are listed in Table 4. For individual zones (1 to 4) of the Springfield Coal, these and other parameters were compiled previously and are included in this report as Table 5.

One of the important characteristics for UCG is the presence and thickness of clastic partings that occur within the coal seam (Table 1). Figures 18 through 21 document the distribution of clastic partings in the Springfield Coal in zones 1 through 4. In zones 1 and 2, clastic partings are sporadic, and when present their thickness is less than 1 m and accounts for much less than 20% of the seam (Figures 18 and 19). In zone 3 (Figure 20) clastic partings are frequent, sporadically thicker than 1 meter, and in several places their thickness accounts for more than 20% of the seam thickness. In zone 4, few data points are available (Figure 21), and it is difficult to evaluate this aspect.

Table 4**.** Ranges and average values of parameters in the studied areas.

PARAMETER	**SPRINGFIELD IN AREA A**			**SEELYVILLE IN AREA A**			**SEELYVILLE IN AREA B**		
	MIN	MAX	AVERAGE	MIN	MAX	AVERAGE	MIN	MAX	AVERAGE
Moisture [%, ar]	1.6	17.9	9.3	0.8	9.7	5.2	1.8	9.3	6.0
Ash [%, dry]	4.9	32.0	12.4	10.9	34.3	17.7	7.0	23.0	15.0
Heating value [Btu/lb, dry]	9,506	15,202	13,086	8494	12262	11386	10,073	13,271	11,901
Sulfur [%, dry]	0.33	5.89	2.61	4.07	9.84	6.55	4.07	5.81	4.91
Vitrinite reflectance [%]	0.56	0.72	0.62	0.59	0.61	0.60	0.50	0.61	0.57
FSI	-	-	-	-	-	-	-	-	-
Ultimate carbon [%, dry]	51.49	75.27	69.07	47.56	68.27	61.68	54.18	68.27	62.51
Ultimate hydrogen [%, dry]	4.01	6.88	5.77	4.19	5.45	4.84	4.38	5.45	5.04
Fixed carbon [%, dry]	39.10	58.30	48.77	33.20	50.70	43.73	40.80	61.10	49.58
Volatile matter [%, dry]	30.00	51.30	39.70	31.20	41.00	37.26	31.60	37.90	35.75

Table 5. Characteristics of the Springfield Coal in zones 1 through 4 (see Figure 3 for zone locations).

	Zone 1	Zone 2	Zone 3	Zone 4
Coal bed	**Springfield**	**Springfield**	**Springfield**	**Springfield**
Area [km^2]	8.67	30.36	14.11	9.83
Area [ft^2]	93,285,125	326,752,816	151,906,925	105,774,118
Area [acres]	2,141	7,501	3,487	2,428
Volume [m^3]	18,192,618	67,844,800	34,901,024	21,339,823
Volume[ft^3]	642,466,257	2,395,916,517	1,232,518,036	753,608,728
Metric tons	**25,105,813**	**93,625,825**	**48,163,413**	**29,448,955**
Short tons	**27,674,138**	**103,203,747**	**53,090,531**	**32,461,584**
Thickness range [ft]	6.56-7.9	6.56-8.6	6.56-10.3	6.56-7.9
Thickness range [m]	2-2.4	2-2.6	2-3.1	2-2.6
Depth range [ft]	196.85-656.17	196.85-656.17	196.85-656.17	196.85-656.17
Depth range [m]	60-200	60-200	60-200	60-200
Moisture range [ar,%]	5-10	5-10	5-7.5	7.5-12.5
Ash range [dry, %]	7.5-12.5	10-15	10-15	5-10
S [total, dry, %]	3-4	2-4	3-5	1-3
Btu [dry, lb/Btu]	12,500-13,000	12,000-13,000	11,500-12,500	13,000-14,000
Distance to nearest power plant [miles]	14	9.5	10	3
Distance to nearest pipeline [miles]	1	0	0	7
Distance to nearest town [miles]	3	0	6.7	5.5

2.3 Seelyville Coal sites

For the Seelyville Coal, two general areas have been considered: one covering the same region as that of the Springfield Coal (Seelyville in Area A), and the other, a more southern portion of the state, includes zones 5 through 9 (Area B, Figure 3). Maps of seam geometry and coal characteristics for the Seelyville in Area A are presented in Figures 22 through 34, and the ranges and average values of selected parameters are listed in Table 4. There are no available data on the presence of clastic partings in zones 1 and 2 for the Seelyville Coal (Figure 35). In zone 3 (Figure 36), there are thick clastic partings (greater than 1 m), and they occupy more than 20% of the seam thickness. These are very limited data available in zone 4 (Figure 37).

For the Seelyville Coal in Area B, a similar set of maps showing various coal characteristics are presented in Figures 38 through 51. For individual zones (5-9) of the Seelyville Coal, these and other parameters were compiled earlier and they are included in this report as Table 6. The Seelyville Coal in zones 5 to 9 of Area B is thicker than 2 m, and the coal occurs at depth range of 60 to 200 m, except zone 7 where the depth is greater than 200 m.

With regard to clastic partings, zones 5 and 6 (Figure 52), have splits but they are thinner than 1 m. Their total contribution to the seam thickness varies from 30% to 10%. Zones 7, 8 and 9 (Figures 53 and 54) have few data points available to characterize clastic partings.

Table 6. Characteristics of the Seelyville Coal in zones 5 through 9 (see Figure 3 for zone locations).

	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
Coal bed	**Seelyville**	**Seelyville**	**Seelyville**	**Seelyville**	**Seelyville**
Area [km^2]	10.56	21.48	11.68	6.56	44.88
Area [ft^2]	113,666,894	231,208,828	125,722,474	70,611,252	483,084,300
Area [acres]	2,60	5,307	2,886	1,621	11,090
Volume [m^3]	23,548,810	49,618,092	30,369,915	15,491,992	120,256,072
Volume[ft^3]	831,618,367	1,752,246,390	1,072,503,422	547,094,529	4,246,803,094
Metric tons	**32,497,357**	**68,472,967**	**41,910,483**	**21,378,949**	**165,953,379**
Short tons	**35,821,837**	**75,477,752**	**46,197,925**	**23,566,015**	**182,930,410**
Thickness range [ft]	6.56-9.4	6.56-9.2	6.56-11.4	6.56-9.4	6.56-11.3
Thickness range [m]	2-2.9	2-2.8	2-3.5	2-2.9	2-3.4
Depth range [ft]	196.85-656.17	196.85-656.17	Greater than 656.17	196.85-656.17	196.85-656.17
Depth range [m]	60-200	60-200	Greater than 200	60-200	60-200
Moisture range [ar,%]	Less than 7.5	5-7.5	5-7.5	7.5-10	7.5-10
Ash range [dry, %]	10-15	10-15	7.5-12.5	12.5-15	12.5-20
S [total, dry, %]	3-5	2-4	3-4	3-4	2-4
Btu [dry, lb/Btu]	11,500-12,000	11,500-12,000	12,000-13,000	11,500-12,500	11,500-12,000
Distance to nearest power plant [miles]	18	17	18	17	17
Distance to nearest pipeline [miles]	0	2	3	5	0
Distance to nearest town [miles]	3	2.5	2.2	1.6	2.5

2.4 Data limitations

In general, there are several major deficiencies associated with available coal-related data. First, for all sites and both coal beds, there are no direct data indicating swelling properties of the coal, such as free swelling index (FSI), maximum fluidity, temperature of maximum fluidity, plastic range, etc. As discussed earlier, coal swelling may cause serious problems while connecting an injection well to the production well. On one hand, the coal in the proposed locations is predominantly high volatile bituminous C and B rank (R_o of 0.50 to 0.56% in the Seelyville Area B, 0.59 to 0.61% in the Seelyville Area A, and 0.56 to 0.72% in the Springfield), which is low enough not to expect appreciable swelling of the coal. However, direct plasticity and fluidity measurement data are needed to confirm this general statement. Secondly, several zones have very limited data on clastic partings, and new boreholes would be needed to supply more clastic-parting-related information. Additionally, the basic petrophysical properties of coals, specifically bulk porosity and permeability, are unknown for the areas being evaluated within Indiana. There is also little information documenting the distribution and density of fracture porosity and permeability that is present as a result of the cleating found in coals. The complexity of cleats with regard to their distribution and origin as shown in a recent study by Solano-Acosta et al. (2007) clearly demonstrates that detailed site-specific information is needed to for reliable evaluation of the cleating systems.

3.0 Characterization of hydrologically and geomechanically important rock units associated with coal seams

3.1 Overburden and UCG

For UCG it is important to have a sequence of competent, well-consolidated rock or “overburden” above the coal seam to provide a rigid container for the gasification modules to operate without collapse and associated surface subsidence (Oliver and Dana, 1991). As estimated based on the extent of the roof collapses above the seams in UCG trials, the consolidated overburden should be at least 15 m (50 ft) thick (Oliver, 1986; Oliver et al., 1987). The overburden immediately overlying the coal should be relatively impermeable to inhibit water influx and gas loss. To prevent possible connection between the gasified seam and water-bearing strata, no water-bearing zone should be present within 31 m (100 ft) above the target seam. It is also desirable to have impermeable strata below the gasified seam (Oliver et al., 1987).

Because water is an essential component of the UCG process, its availability from either within a coal seam or from a source adjoining the seam is an important characteristic. In UCG-favorable circumstances, the coal itself serves as the principle aquifer within the stratigraphic section and is bounded by impermeable shales or other low permeability rock. In some cases, permeable sandstones form the roof rock and therefore are in hydrological connectivity with strata outside the coal seam. Sury et al. (2004) recommend using coal seams having no overlying potable aquifers within a distance 25 times the seam thickness. If the coal seam is saturated with water, the amount of water available is likely to be sufficient to support a UCG operation. For example, in the Rocky Mountain 1 UCG site, approximately 2% of the water available in the coal seam aquifer was consumed during the test (Beaver et al., 1991). Within southwestern Indiana, generally the deepest potable groundwater is found at depths of 300 ft or less (Fenelon and others, 1994). The general nature of the middle Pennsylvanian rocks of the region is that the lithofacies are dominated by fine-grained, low permeability sediments and therefore more often function as aquicludes rather than aquifers (Table 7).

As much as the availability of water is important for UCG, too much water creates problems for UCG operations. Field tests and commercial operations (Gregg et al., 1976; Gunn et al., 1976) as well as mathematical model calculations (Gunn et al., 1976) and experimental results (Fischer et al., 1977) all verify that excessive water influx can result in major deterioration of the gasification process, resulting in reduced gas quality. With too much water, it is difficult to adjust air or oxygen injection rates to maintain an optimal air/water ratio (Gunn, 1977).

Table 7. Average lithological composition in the 50-ft-interval overlying the coals in individual zones

UCG zone	Target coal	Well/Core Calibration (IGS ID)	Overburden Composition (%)									Ave K
			Lithology 1	%	K (md)	Lithology 2	%	K (md)	Lithology 3	%	K (md)	
1	Springfield	162538	shale	81	2	silt	12	25	sand	9	250	27.1
1	Seelyville	162538	shale	46	2	sand	29	250	silt	19	25	78.2
2	Springfield	162538	shale	81	2	silt	12	25	sand	9	250	27.1
2	Seelyville	162538	shale	46	2	sand	29	250	silt	19	25	78.2
3	Springfield	163506	silt	44	25	sand	30	250	shale	26	2	86.5
3	Seelyville	163506	silt	50	25	sand	28	250	shale	22	2	82.9
4	Springfield	128686	silt	90	25	shale	10	2				22.7
4	Seelyville	128686	sand	50	250	silt	40	25	shale	10	2	135.2
5	Seelyville	133039	shale	80	2	sand	10	250	coal	10	40	30.6
6	Seelyville	130831	shale	50	2	sand	28	250	coal	12	40	75.8
7	Seelyville	109086	shale	79	2	sand	15	250	coal	4	40	40.7
8	Seelyville	102162	sand	60	250	shale	32	2	coal	8	40	153.8
9	Seelyville	101859	shale	84	2	silt	16	25				5.7

3.2 Hydrological considerations for the selected sites

Table 7 includes the average composition of the lithologies that overlie the coals (“overburden”) in each of the nine zones identified in southern Indiana. These lithological interpretations are based on the interpretation of geophysical logs and one core (SDH-302 in zone 7). In the other eight zones, there were no cores available for observations. In general, the coals are overlain by a sequence of fine-grained to very fine grained clastic rocks (shales and clay-rich siltstones). The presence of coarser-grained clastic material – generally sandstone – within the overlying rock column is limited to two isolated occurrences, primarily in zone 4 and 8 above Seelyville (Table 7). Figure 55 (and Appendix 1) shows the set of geophysical logs (Gamma Rays) that were chosen as examples to show the general lithological distributions over the coals of interest in each of the nine zones evaluated or in their closest proximities. The permeabilities of the rock sequences are dependent on the lithologies present, with the highest values found in sandstones and decreasing in value as finer grained rocks are encountered. The permeability of overburden in each zone was calculated based on average permeability values for the three dominant lithologies that are present within the 50 ft immediately overlying the target coal (Table 7). Where present, the higher permeability sandstones are assumed to be water saturated based on the resistivity measurements. In most cases, the sandstone-rich zones do not directly overlie the coal seams. The sandstone bodies range from 10 to 20 ft in thickness and are highly discontinuous depositional features, having limited vertical and horizontal continuity. Figure 55 shows that of the five zones assessed above the Seelyville Coal (zones 5-9), there may be sandstone bodies in zones 8 and 9 that could be water-saturated. Out of four zones assessed above the Springfield Coal (zones 1-4), there may be sandstone bodies within 50-ft-interval above the coal in zones 2 and 3. Because the aquifers that contain fresh water generally only extend to depths of 300 feet in southwestern Indiana, those sandstone bodies that occur above the target coals probably contain non-potable water and are, therefore, not potential underground sources of drinking water. However, because of the general nature of this hydrological evaluation, a careful assessment of petrophysical nature of these sand bodies and the character of the water that they contain should be undertaken to carefully identify the extent of potential aquifers that overlie each zone.

In addition to geophysical log interpretations, core material available in the proximity of individual zones was reviewed, and most suitable cores were selected for more detailed lithological examination and sampling for petrophysical and geomechanical properties. There were no coreholes available in close proximity to zones 4, 5, 6, 8 (Fig. 56). Lithological sections and position of the intervals sampled from cores in close proximity to zones 1, 2, 3, 7 (borehole SDH-302 is located within zone 7) and 9 are presented in Fig. 56 and Appendix 2. The interpretation of the lithological types in the overburden in these five coreholes indicates that the Seelyville Coal is a better prospect for UCG than the Springfield Coal with regard to hydrological conditions. The interval directly overlying the coal in these five localities is composed of dominantly fine-grained sediments (shales and siltstones). These low permeability sediments would constitute a good cap rock, preventing any connectivity with potential aquifers, if present at shallower depths. Location SDH-366 (close to zone 9, Fig. 56) with thick sandstone above the Seelyville is an exception. However, this sandstone body is of local nature and was not present within zone 9, as indicated by geophysical logs examined in this zone (Table 7).

4.0 Characterization of the overburden with respect to the possibility of subsidence

4.1 Subsidence and UCG

How the gasification process physically affects the rock column overlying the coal or the "overburden" is one of the most important issues associated with UCG operations. It relates not only to the possibility of subsidence of the land surface above a gasified coal seam but also to the disturbance to the rocks that comprise overlying aquifers and seals. Significant disruption of these strata could cause gas leakage into aquifers and the possibly facilitate leakage of the products of the gasification reaction to the surface. Additionally, by establishing communication with overlying aquifers, subsidence can contribute to flooding of the combustion zone (Gunn, 1977). The effect of subsidence can be minimized or avoided by siting of the UCG operation in a package of physically strong and competent overburden, using burn patterns or modules that leave enough uncombusted coal between the modules to serve as a support system, and adjusting oxygen/air injection rate (SME Mining Engineering Handbook, 1992). For example, at Hanna UCG site (Wyoming), two- and four-well patterns with 60-ft-spaced modules located at a depth of 269 to 400 feet (82 – 122 m) did not result in any subsidence at the surface, but caving of the roof occurred directly over areas of gasified coal (Gunn, 1977).

4.2 Subsidence risk assessment for the selected sites

In Indiana, about 205,000 acres are underlain by underground coal mines (Harper, 1982; Meyer and Montgrain, 2009) and there are multiple indications of disturbances at the ground surface that are related to subsidence from underground coal mining. For Indiana geomechanical conditions, it has been suggested that the effects of subsidence above shallow underground mines (20 to 100 ft deep) are almost certain to reach the surface (Wiram et al., 1973), but surface subsidence rarely develops when the overburden thickness is greater than 300 ft (Eaton and Metzger, 2000). Although subsidence has occasionally been reported from US (but not from Indiana) mines as deep as 600 ft, the U.S. Bureau of Mines has estimated that only 10% of subsidence occurs above mines more than 400 ft deep (Harper, 1982).

In the areas evaluated for potential UCG in this study, there are no underground mines present and subsidence has not been investigated in any detail. Also, from other parts of Indiana, no data are available to better evaluate what would be the depth below which there would be essentially no risk of subsidence. The curve presented in Figure 57 gives a rough estimate of a subsidence risk based on the limited information available from Indiana and elsewhere. Detailed evaluation of the geomechanical attributes of the overlying strata in conjunction with site-specific configurations of the lithologies present in the overburden must be incorporated with module design parameters to effectively simulate the subsidence response of a gasification operation.

Because we have not found any data on geomechanical properties, we identified locations close to the areas studied that had core material available at the IGS library, and selected the most representative locations to test selected geomechanical attributes. In total 11 samples were collected and Table 8 gives their lithological characteristics, whereas Tables 9, 10, 11, and 12 list in-situ stress conditions and porosity, permeability, and geomechanical properties.

The obtained results demonstrate that the mudstone, shales, and carbonates have significantly higher tensile strength (more than 1000 psi) than sandstones for which the highest tensile strength is 537 psi (sample S6, Table 10) . Compressive strength ranges from 5505 psi for sandstone above the Springfield in well SDH-327 (Table 11) to 32,750 psi in carbonate from well SDH-247. Quasi-static Poisson's ratio ranges from 0.13 to 0.30. Porosity and permeability analyses were obtained on sandstone samples and carbonate (Table 12). Porosity of the sandstone samples ranges from 6.8 to 23.5%, whereas the permeability from less than 0.1 md to 345 md. Analyses on shale and mudstones have not been obtained because of the unavailability of the suitable sample material. The complete report of the samples analyses is included in Appendix 3. Fig. 56 and appendix 2 show the locations of the samples and their lithological stratigraphic context.

Table 8. Lithological characteristics of samples selected for geomechanical tests.
Their locations are shown in Fig. 56.

Well	Sample ID	Pressure (psi)	Depth [ft]	Description	Above	UCG zone
SDH-248	S1	235	546	Mudstone, occasionally with sandstone lenses possibly bioturbated	Seelyville	2
	S2	237	552	Sandstone, horizontal to cross laminated	Seelyville	2
	S3	242	562	Black shale with siderite	Seelyville	2
SDH-247	S6	161	375	Sandstone, medium-grained, massive to cross-bedded	Springfield	1
	S7	162	377.5	Shale/siltstone with siderite	Springfield	1
	S8	166	385	Carbonate	Springfield	1
SDH-327	S9	142	331	Sandstone, massive with organic debris	Springfield	3
	S10	141	329	Mudstone/shale	Springfield	3
	S11	125	290	Sandstone, massive to wavy bedded	Springfield	3
SDH-366	S12	255	593	Mudstone/shale	Seelyville	8 and 9
	S13	251	584	Sandstone, coarse-grained, massive to horizontal bedding	Seelyville	8 and 9

Table 9. In-situ stress conditions for the analyzed samples

Well	Sample ID	Depth (ft)	Reservoir Pressure (psi)	Overburden Stress (psi)	Average Horizontal Stress (psi)	Effective Stress[1] (psi)		
						Overburden (psi)	Horizontal (psi)	Mean (psi)
SDH-248	S1	546	235	590	382	355	147	217
	S2	552	237	596	386	323	113	219
	S3	562	242	607	393	365	151	223
SDH-247	S6	375	161	405	263	244	102	149
	S7	377.5	162	408	264	246	102	150
	S8	385	166	416	270	250	104	153
SDH-327	S9	331	142	357	232	215	90	131
	S10	329	141	355	230	214	89	131
	S11	290	125	313	203	188	78	115
SDH-366	S12	593	255	640	415	385	160	235
	S13	584	251	631	409	380	158	232

[1] Stress information provided by Indiana Geological Survey. The effective vertical stress was determined by subtracting the reservoir pressure from the total overburden stress (assuming $\alpha = 1$). The effective horizontal stress was determined by subtracting the reservoir pressure from the average horizontal stress. The effective mean stress was determined by averaging the three principal stresses less the reservoir pressure (i.e., $(\sigma_V + 2 \times \sigma_H)/3 - \alpha$*reservoir pressure).

Table 10. Summary of indirect tensile strength tests (Brazilian method)

Well	**Sample ID**	**Lab Sample ID**	**Depth (ft)**	**Lithology**	**Average Length (in)**	**Average Diameter (in.)**	**As-Received Mass (g)**	**As Received Bulk Density (g/cm^3)**	**Maximum Load (lbf)**	**Tensile Strength (psi)**
SDH-248	S1	IG1-2	546	Mudstone	0.371	0.740	6.590	2.520	454	1053
	S2	IG2-2	552	Sandstone	0.527	0.988	14.947	2.258	375	459
	S3	IG3-2	562	Shale	0.533	0.992	15.250	2.259	760	915
SDH-247	S6	IG6-2	375	Sandstone	0.496	0.991	14.697	2.344	415	537
	S7	IG7-2	377.5	Shale/ Siltstone	0.503	0.991	15.740	2.476	800	1022
	S8	IG8-3	385	Carbonate	0.520	0.996	18.373	2.767	1778	2185
SDH-327	S9	IG9-3	331	Sandstone	0.548	0.992	15.995	2.305	332	389
	S10	IG10-1	329	Mudstone/ Shale	0.268	0.491	2.098	2.523	272	1316
	S11	IG11-2	290	Sandstone	0.377	0.741	5.870	2.203	275	627
SDH-366	S12	IG12-3	593	Mudstone/ Shale	0.374	0.744	6.796	2.551	532	1217
	S13	IG13-3	584	Sandstone	0.349	0.736	5.001	2.055	104	258

[1] Brazil indirect tensile tests on horizontal samples were performed with one orientation with regards to bedding. The load was applied perpendicular to the bedding of the sample (vertical orientation to the load).

Table 11. Summary of single stage triaxial compression tests

Well	Sample ID	Lab Sample ID	Depth (ft)	Bulk Density (g/cm³)	Average Length (in)	Effective Confining Pressure (psi)[1]	Effective Compressive Strength (psi)	Residual Effective Compressive Strength (psi)	Quasi-Static Young's Modulus (psi)	Quasi-Static Poisson's Ratio
SDH-248	S1	IG1-2	546	2.552	0.371	217	7815	4140	906,200	0.15
	S2	IG2-2	552	2.268	0.527	219	6490	3020	1,029,000	0.25
	S3	IG3-2	562	2.243	0.533	223	6465	2290	579,700	0.16
SDH-247	S6	IG6-2	375	2.578	0.496	149	13,515	-	3,519,000	0.18
	S7	IG7-2	377.5	2.502	0.503	150	10,020	2180	1,219,000	0.21
	S8	IG8-3	385	2.826	0.520	153	32,750	7375	7,528,000	0.25
SDH-327	S9	IG9-3	331	2.284	0.548	131	8045	1910	1,644,000	0.28
	S10	IG10-1	329	2.522	0.268	131	-	-	1,031,000	0.13
	S11	IG11-2	290	2.240	0.377	115	5505	1740	1,044,000	0.24
SDH-366	S12	IG12-3	593	2.573	0.374	235	9935	2385	1,085,000	0.22
	S13	IG13-3	584	2.240	0.349	232	6615	3030	1,683,000	0.30

[1] Pore pressure = 0 psi for all tests.
[2] The test aborted prematurely due to a power outage. Effective compressive strength and residual effective compressive strength were not attained. Young's Modulus and Poisson's Ratio were both derived from available data. (Vertical orientation to the load).

Table 12. Summary of physical properties and Klinkenburg corrected permeability tests

Well	Sample ID	Lab Sample ID	Depth (ft)	Sample Length (in)	Sample Diameter (in)	Ambient Porosity (%)	Over-burden Porosity (%)	Dry Bulk Density (g/cc)	Grain Density (g/cc)	Gas Permeability (md)	Klinkenburg Corrected Permeability (md)	NOB Stress (psi)
SDH -248	S2	IG2-3	552	0.958	0.988	15.48	15.81	2.277	2.694	3.845	2.885	219
							15.64			3.688	2.867	400
SDH -247	S6	IG6-3	375	0.95	0.993	6.83	6.61	2.488	2.671	0.144	0.077	149
							6.61			0.125	0.067	400
	S8	IG8-2	385	0.971	0.993	3.02	2.99	2.759	2.845	<0.01	n/a	153
							2.9			<0.01	n/a	400
SDH -327	S9	IG9-2	331	0.741	0.735	19.04	18.43	2.237	2.763	52.275	38.565	131
							18.43			40.510	30.328	400
	S11	IG11-3	290	0.671	0.99	18	18.05	2.219	2.706	14.334	10.843	115
							17.76			13.679	12.203	400
SDH -366	S13	IG13-2	584	1.137	1.041	23.5	21.62	2.036	2.661	391.489	345.718	232
							21.31			368.450	356.530	400

5.0 Other considerations

5.1 Amount of coal and well spacing

Gas produced by the underground gasification process can potentially be used in a series of applications. These applications range from supplying mobile units to provide gas for an agricultural or industrial application to large power and chemical plants producing hundreds and thousands of megawatts (MW) of electrical energy and vast amounts of hydrocarbon-based products. For this reason, the evaluation of potentially productive sites must include the determination of the amount of coal available in a gasification project in conjunction with a consideration of the potential applications of the produced gas. Additionally, for each potential site, the productive lifetime of the site must be determined as a function of required gas yield. For example, for the 20-year continuous operation of a 300 MW UCG-based combined cycle power plant at 50% efficiency, 75.6×10^9 Nm^3 of syngas had to be produced with a heating value of 5 MJ/m^3. Based on experimental data of the Chinchilla plant, Australia, this required 33 $\times 10^6$ metric tons of gasified coal needed (Shafirovich and Varma, 2009).

In addition to the amount of coal available, selection of well spacing or geometry of the gasification modules is a very important issue. One reason is that drilling and completion of wells is a major cost item in a UCG operation. Secondly, as mentioned earlier, the well spacing should be selected so that no subsidence and subsidence-related effects occur. No comprehensive studies exist that investigate this maximum well spacing/subsidence issue, and therefore this issue must be carefully considered for each prospective site. As an example, the distance between the injection and production wells in Spain was 100 m, and in Russia about 20 m (Shafirovich et al., 2009). A common sense recommendation would be to begin a gasification operation with a well spacing that leaves a substantial amount of uncombusted coal in place for structural support between gasification modules and then reduce the spacing as more detailed data are acquired that would justify reconfiguring the well spacing. The Hanna, Wyoming, operation used 16 and 18 m spacing between the wells, used a block with 4,600 tons of coal (~130 m deep), achieved complete combustion ("practically all coal contacted by the combustion front was completely gasified"), was completed with no subsidence or detriment to the overlying potable aquifer systems, and turned out to be competitive economically with natural gas prices (Gunn, 1977; Moll, 1976).

5.2 Land-use restrictions

There is no indication in the literature that UCG must be located away from towns, roads, and other surface features any more so than underground coal mines, assuming that the process design, operational constraints, and environmental monitoring reduce the risk to tolerable limits the possibility of groundwater contamination, surface subsidence, and air pollution. Therefore, the land-use restrictions used for underground mining could also be potentially applicable to the operation of UCG sites. The selection between traditional mining versus UCG will likely ultimately be decided based on economic considerations rather than surface land usage.

6.0 Conclusions

1. This study provides a compilation of the available data on coal properties, hydrology, and lithologic characteristics in the areas selected as the most promising for UCG in Indiana. The compilation includes tables of coal properties important to UCG use and summaries of individual parameters for the Springfield Coal and the Seelyville Coal and maps of distributions of selected coal properties. These data can be used in further modeling studies leading to the final selection of individual sites prior to initiating an engineering and design study for the construction of a UCG plant.
2. This study has identified several deficiencies related to the available coal-related data. For all sites and both coal beds, there are no direct data indicating swelling properties of the coal, such as free swelling index (FSI), maximum fluidity, temperature of maximum fluidity, plastic range, etc. Coal swelling may cause serious problems while connecting an injection well to the production well. Several zones have very limited data on the clastic partings, and new boreholes would be needed to supply more data.
3. The presence of permeable, coarser-grained clastic strata, generally sandstone, that may serve as a possible aquifer is limited to isolated occurrences, primarily in zone 8 (Seelyville) and zone 4 (Seelyville). These sand bodies range from 10 to 20 ft in thickness and are highly discontinuous features. Although in most cases these porous zones do not directly overlie the coal seams, a careful assessment of the overburden at specific sites should be undertaken to carefully identify the extent and the relationship of porous and permeable units that might be present to any overlying underground sources of drinking water.
4. Geomechanical properties of the overburden in the areas of southwestern Indiana are not well known and, therefore, the strengths of the rocks that overlie the coals are poorly constrained. How well they will respond in terms of structurally supporting their own mass and isolating the products of gasification from the overlying potable aquifer systems has not been determined. The newly obtained data give some indication of the ranges of geomechanical properties but there must be some detailed observations and interpretations of the mechanical behavior of rock column undertaken to better serve numerical simulations of the gasification process.
5. While some conclusions and general information can be derived from studies and UCG tests that have taken place in numerous parts of the world, site-specific information on the performance of the coals and overburden rocks located in southwestern Indiana must be collected before realistic and representative conclusions can be drawn about the viability of deploying this technology within the state. This information is vital for projects to successfully extract energy for the state’s coal resources while operating in an environmentally effective manner.

Acknowledgements

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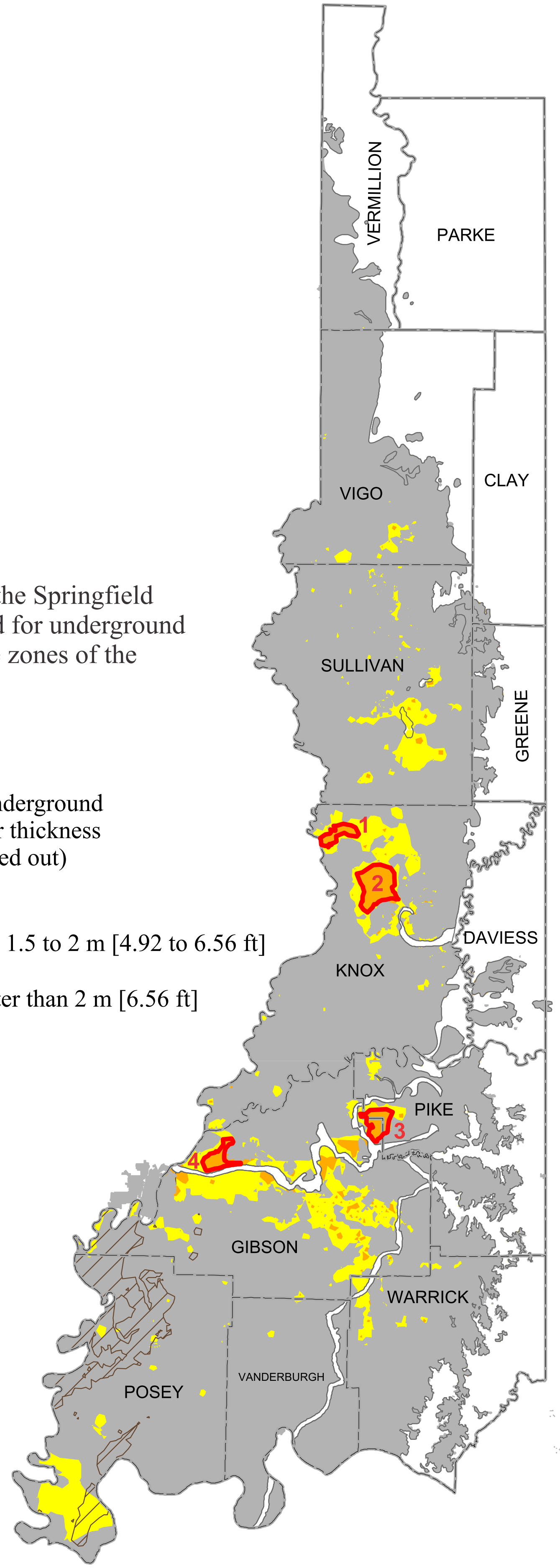
Figure 1. Map of southwestern Indiana showing the Springfield Coal Member thicker than 1.5 m to be considered for underground coal gasification (UCG). Numbers 1 to 4 indicate zones of the best UCG potential identified in our earlier study (Shafirovich et al., 2009).



Springfield Coal Member unavailable for underground gasification (depth less than 200 ft [60 m] or thickness less than 1.5 m or active mining or coal mined out)

Adequate depth [>60 m] and thickness from 1.5 to 2 m [4.92 to 6.56 ft]

Adequate depth [>60 m] and thickness greater than 2 m [6.56 ft]

Depth greater than 200.0 m [656.17 feet]

Selected zone

County boundary

No coal

10 miles

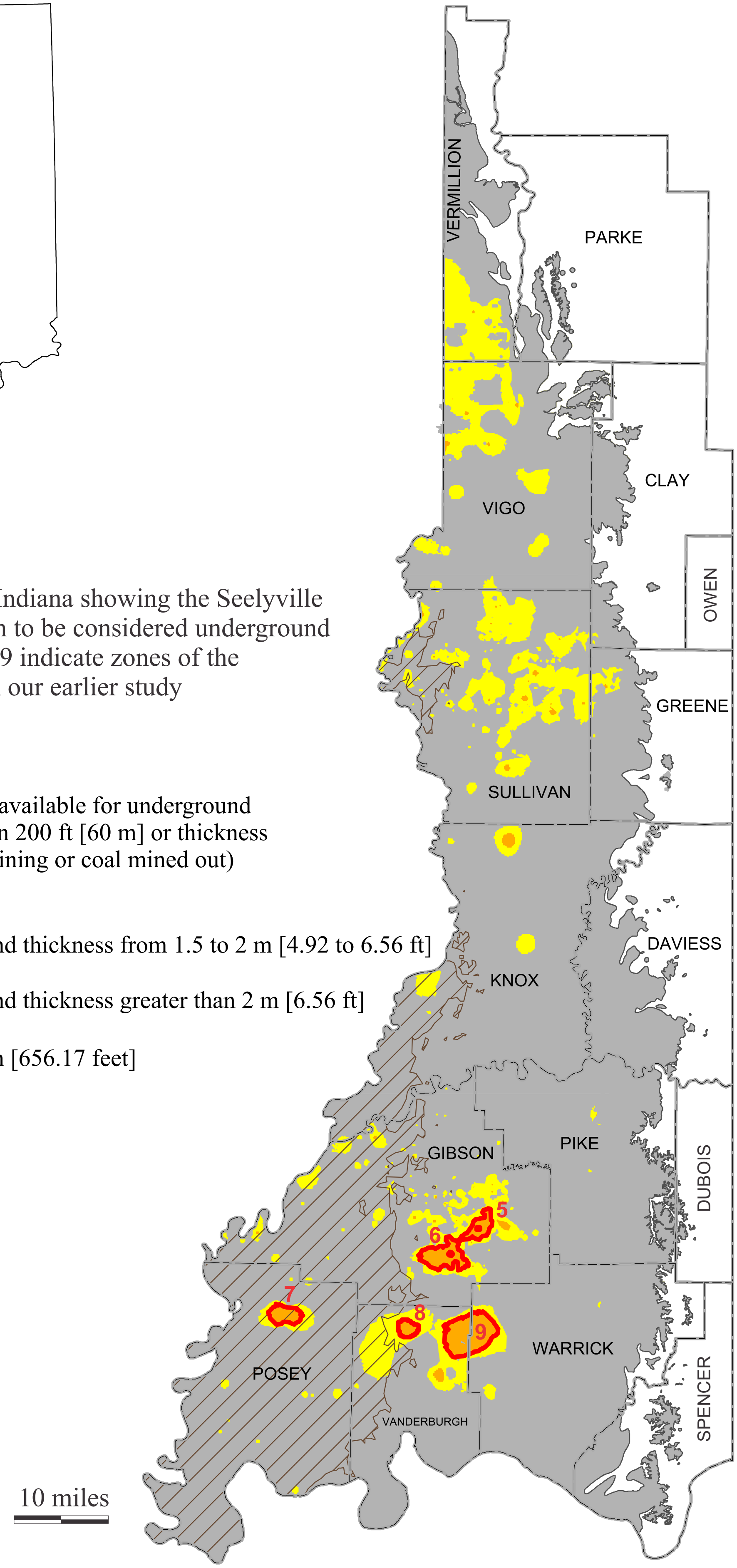


Figure 2. Map of southwestern Indiana showing the Seelyville Coal Member thicker than 1.5 m to be considered underground coal gasification. Numbers 5 to 9 indicate zones of the best UCG potential identified in our earlier study (Shafirovich et al., 2009).

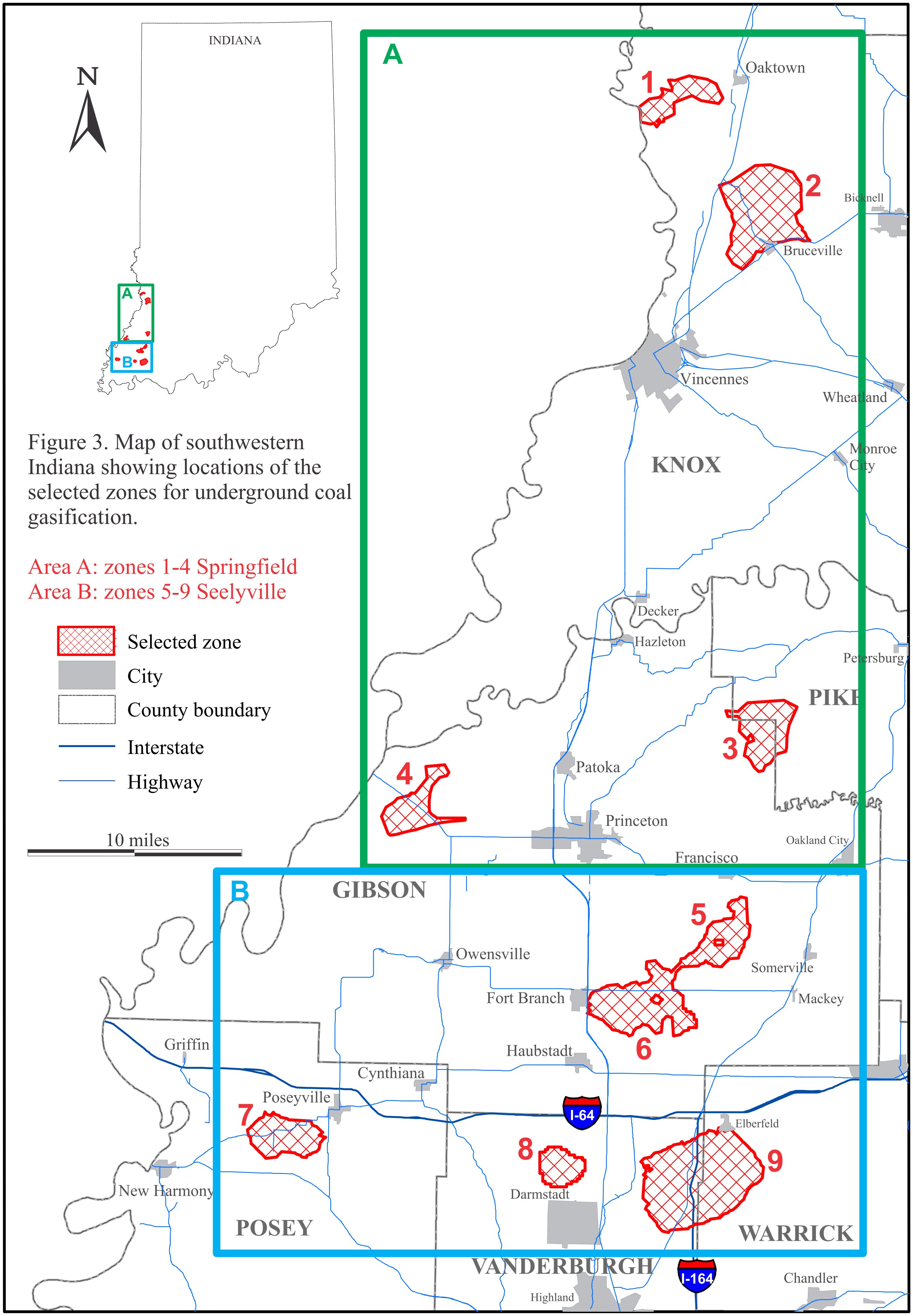


Figure 3. Map of southwestern Indiana showing locations of the selected zones for underground coal gasification.

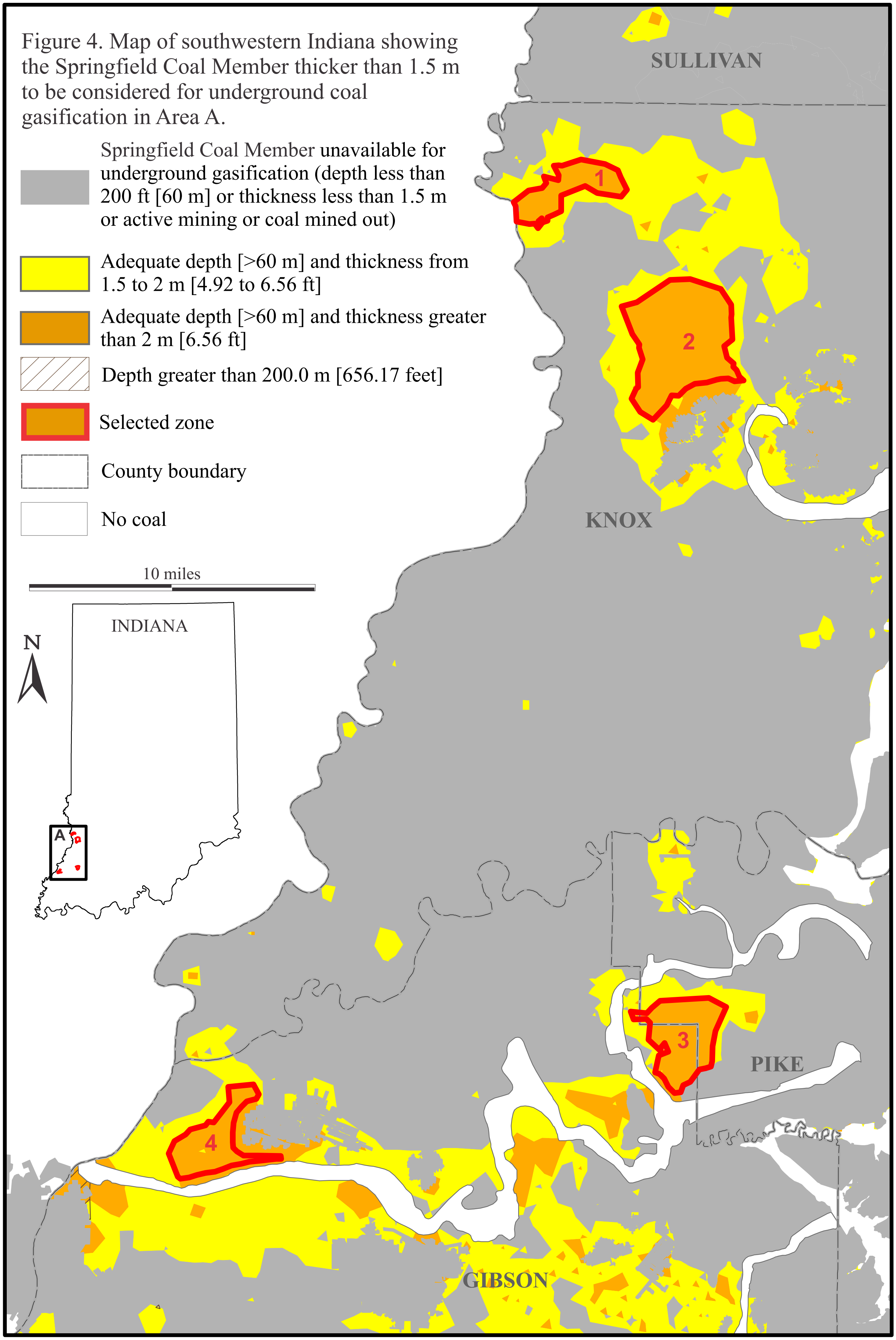


Figure 4. Map of southwestern Indiana showing the Springfield Coal Member thicker than 1.5 m to be considered for underground coal gasification in Area A.

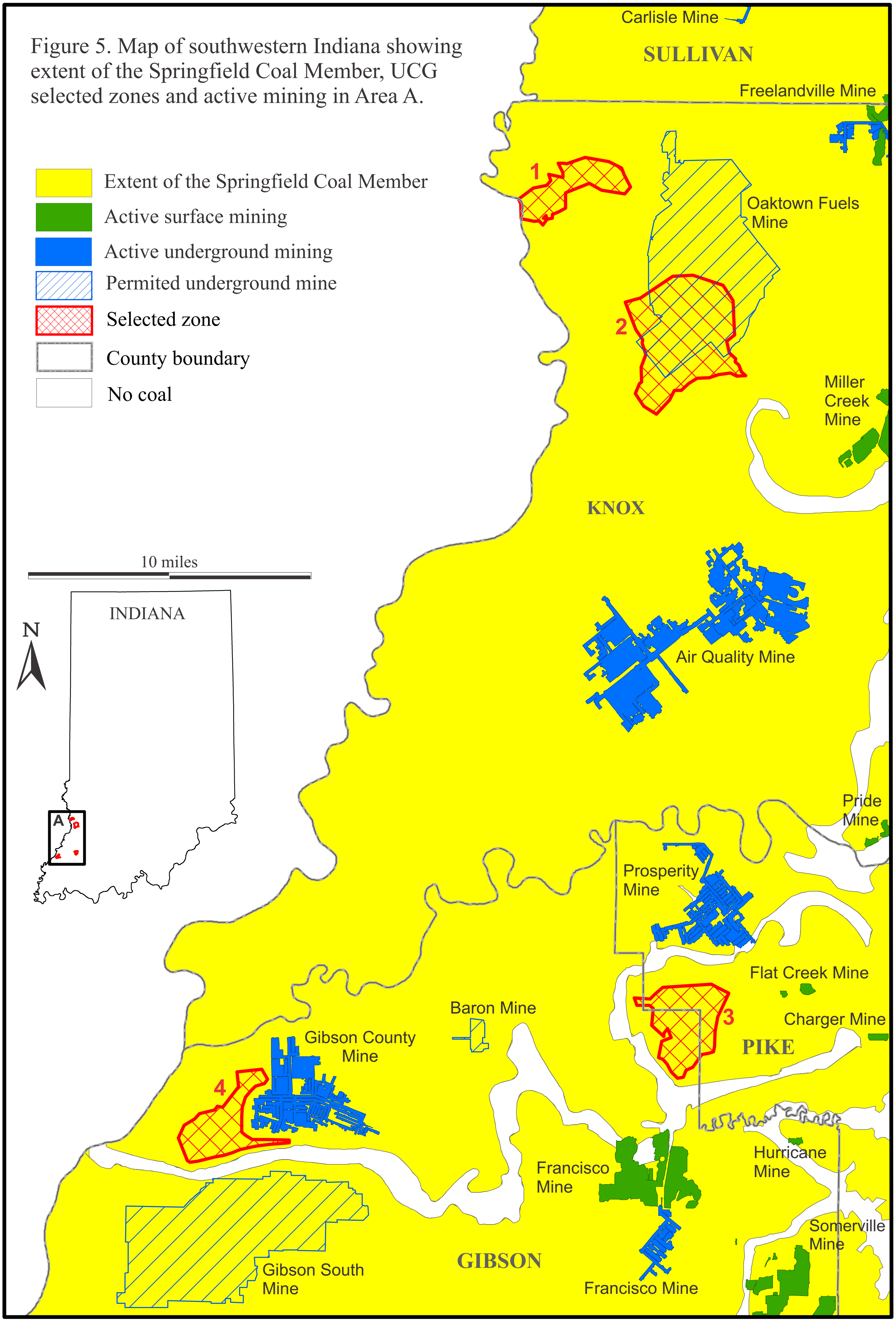


Figure 5. Map of southwestern Indiana showing extent of the Springfield Coal Member, UCG selected zones and active mining in Area A.

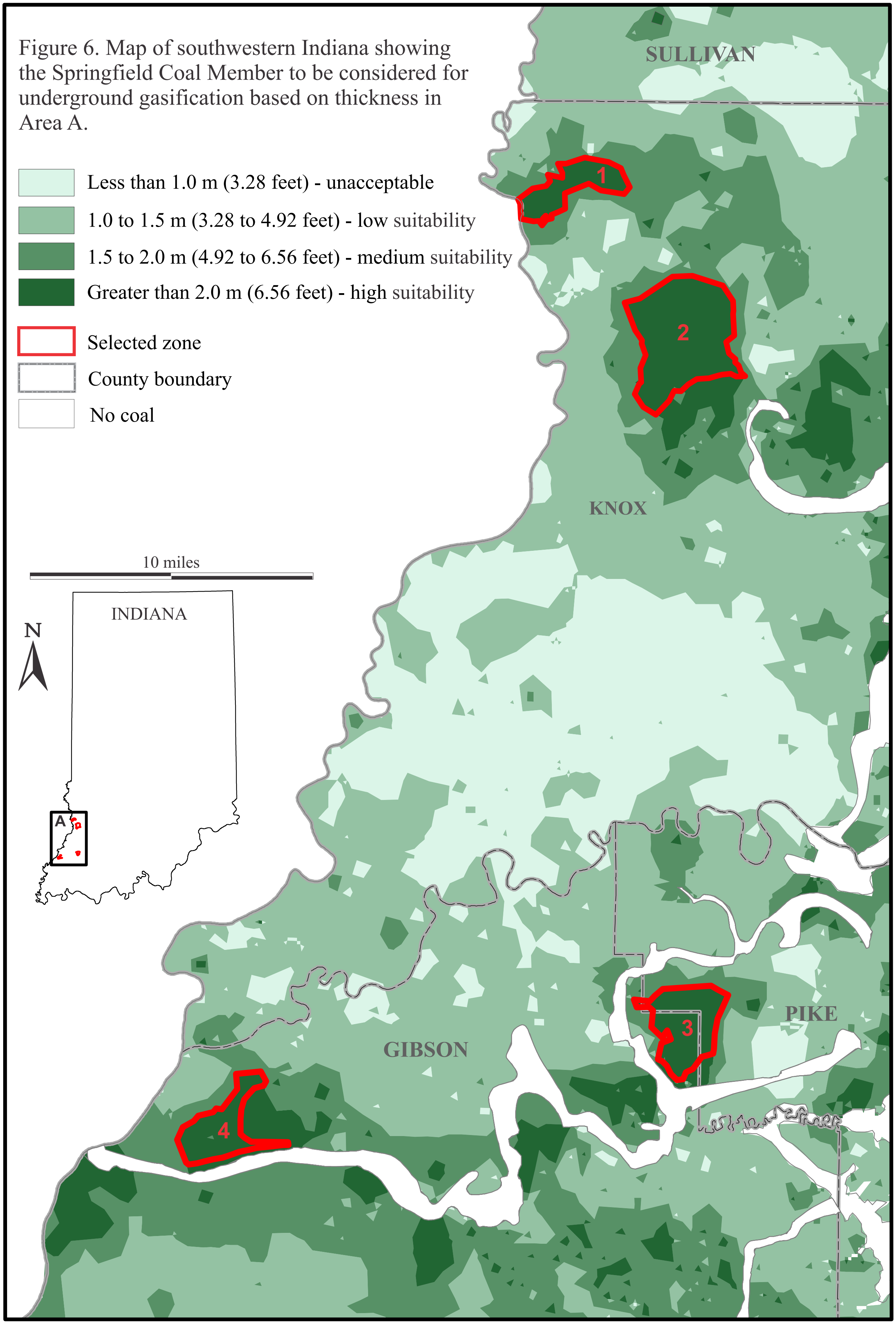


Figure 6. Map of southwestern Indiana showing the Springfield Coal Member to be considered for underground gasification based on thickness in Area A.

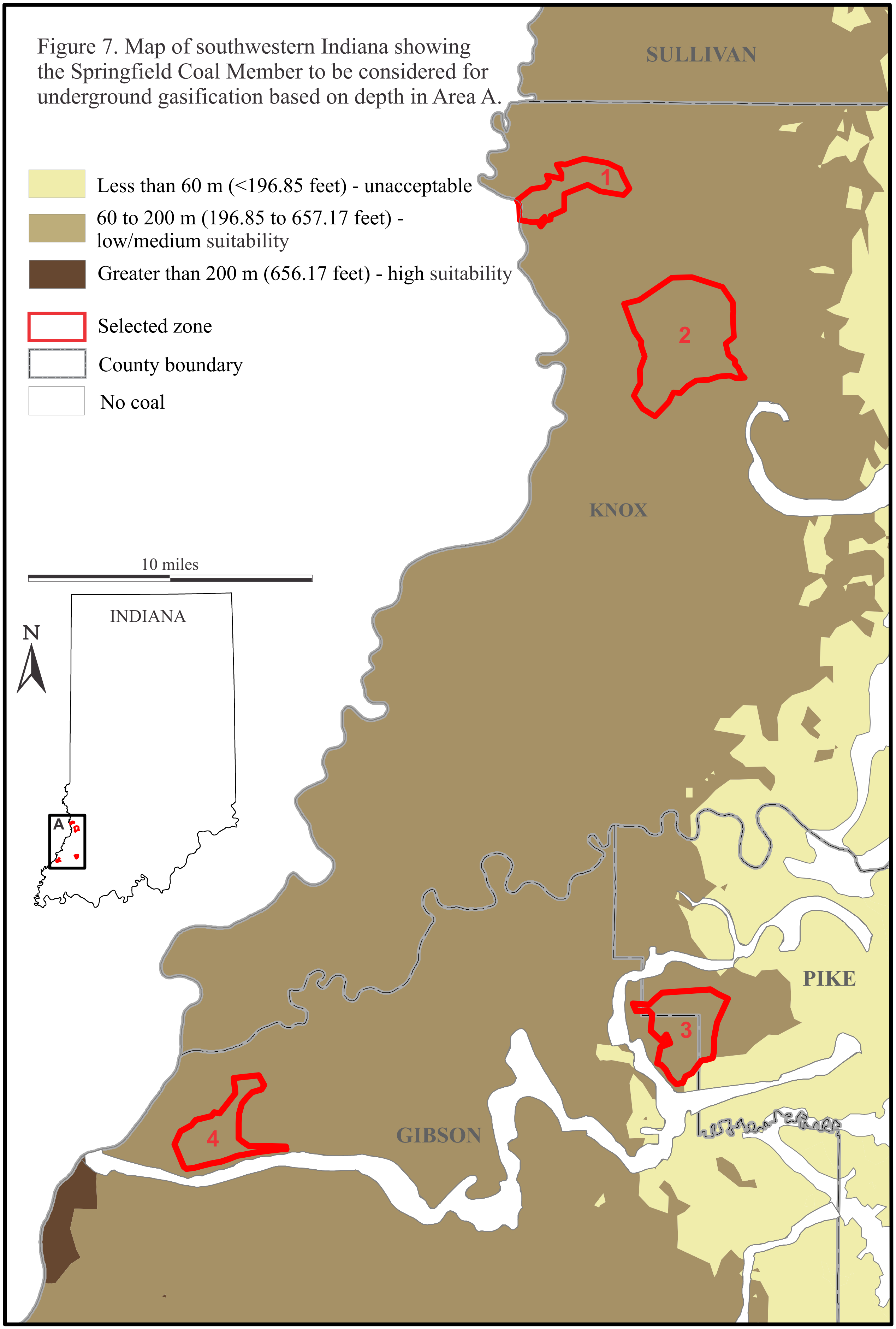


Figure 7. Map of southwestern Indiana showing the Springfield Coal Member to be considered for underground gasification based on depth in Area A.

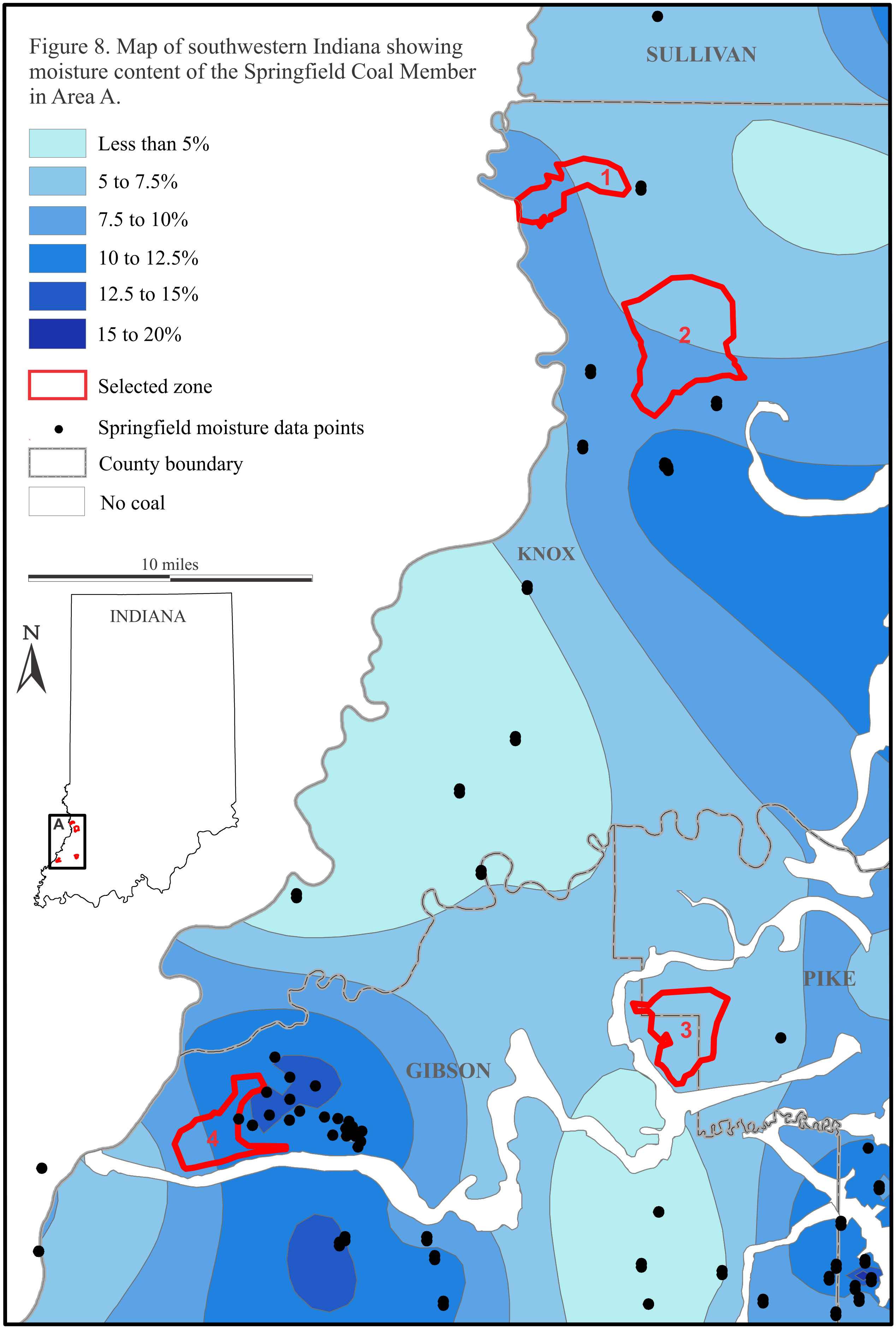


Figure 8. Map of southwestern Indiana showing moisture content of the Springfield Coal Member in Area A.

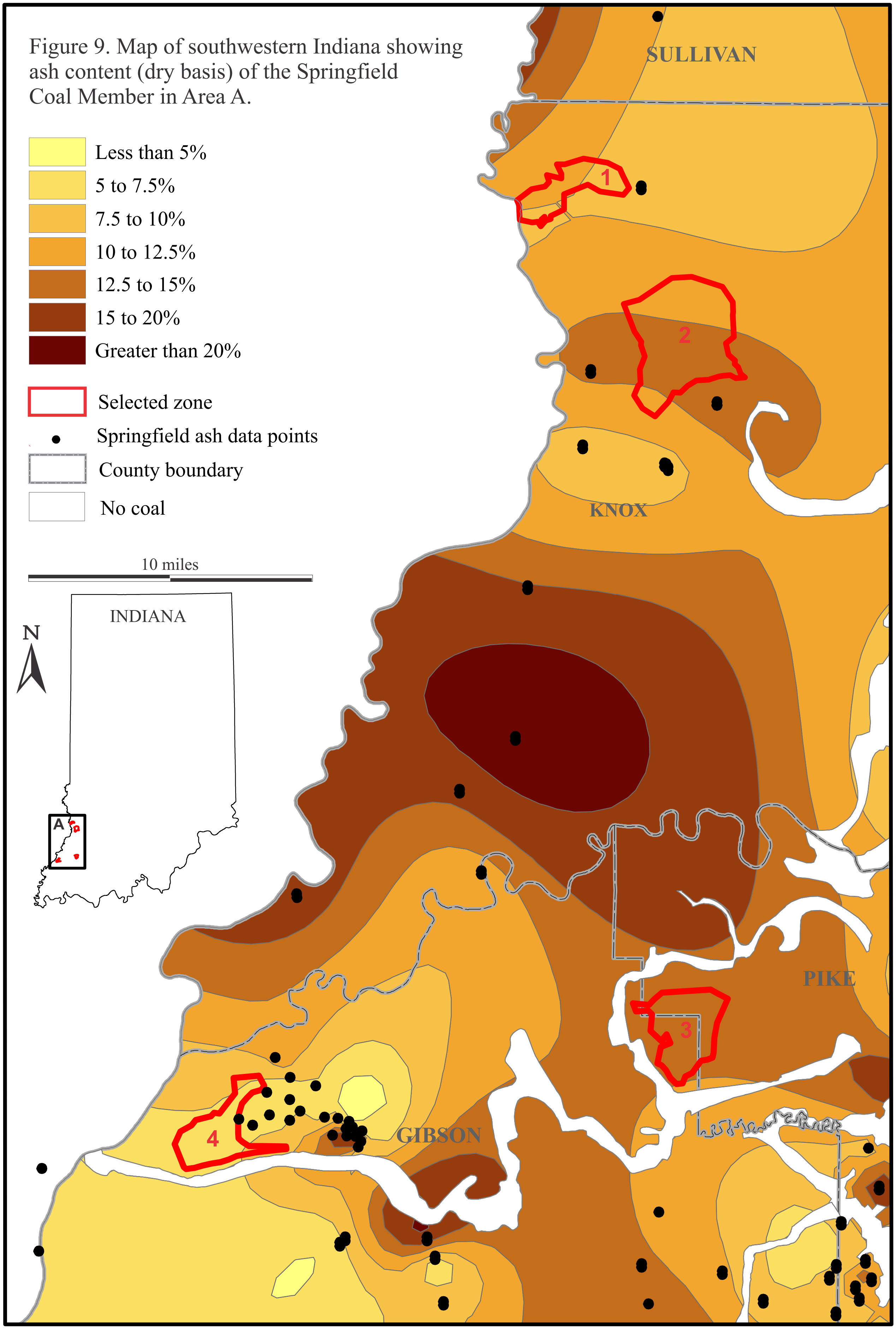


Figure 9. Map of southwestern Indiana showing ash content (dry basis) of the Springfield Coal Member in Area A.

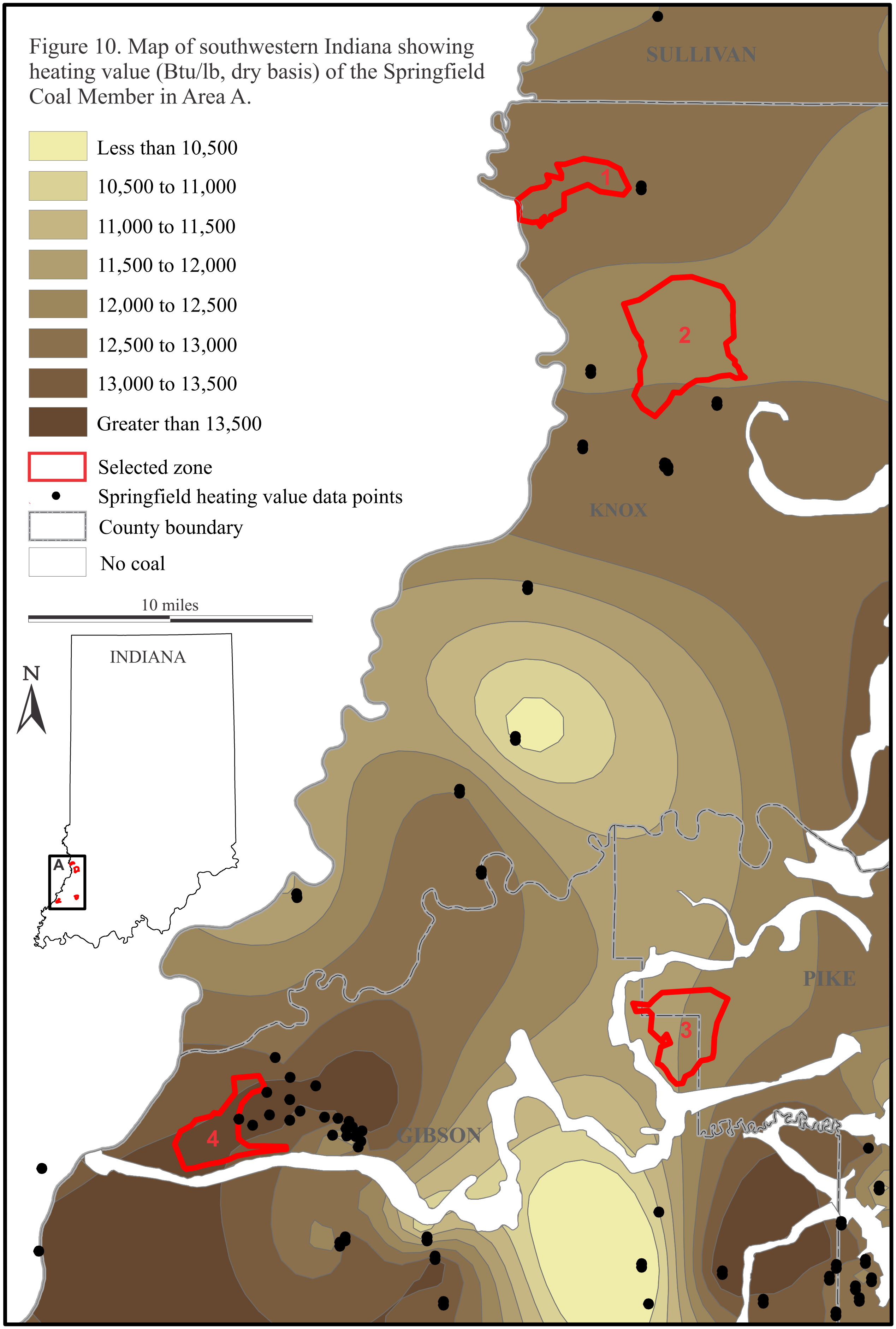
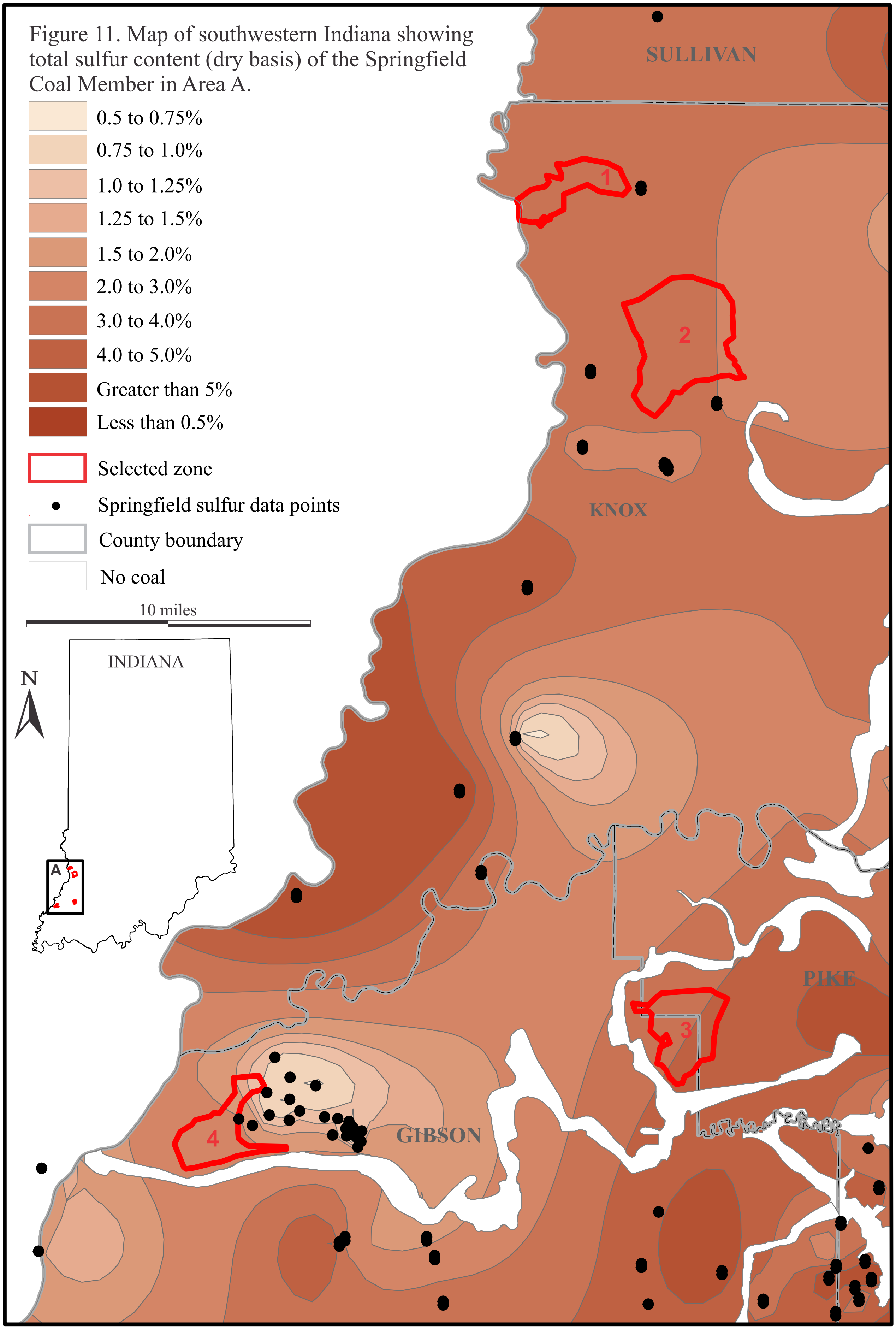


Figure 10. Map of southwestern Indiana showing heating value (Btu/lb, dry basis) of the Springfield Coal Member in Area A.

Figure 11. Map of southwestern Indiana showing total sulfur content (dry basis) of the Springfield Coal Member in Area A.



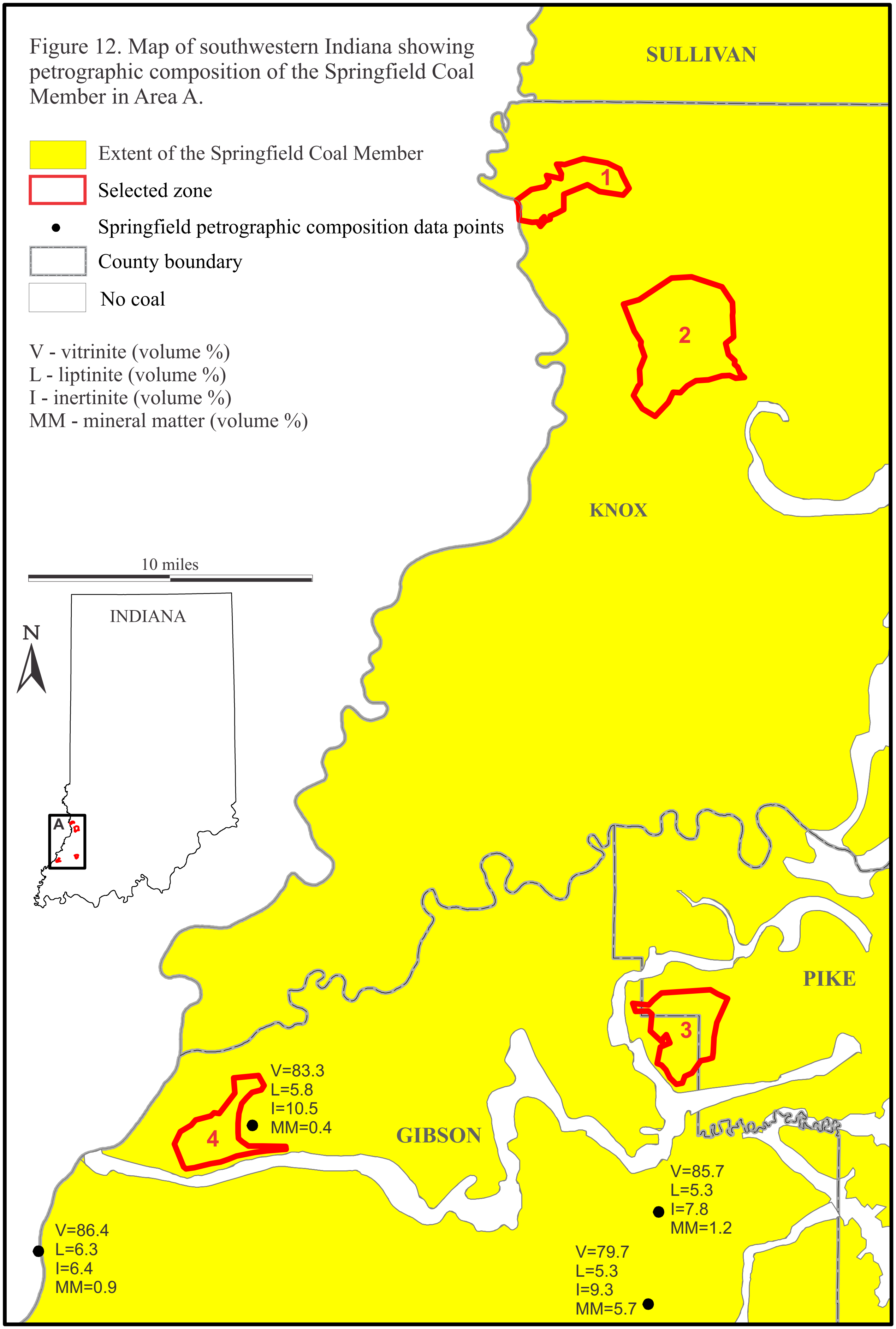


Figure 12. Map of southwestern Indiana showing petrographic composition of the Springfield Coal Member in Area A.

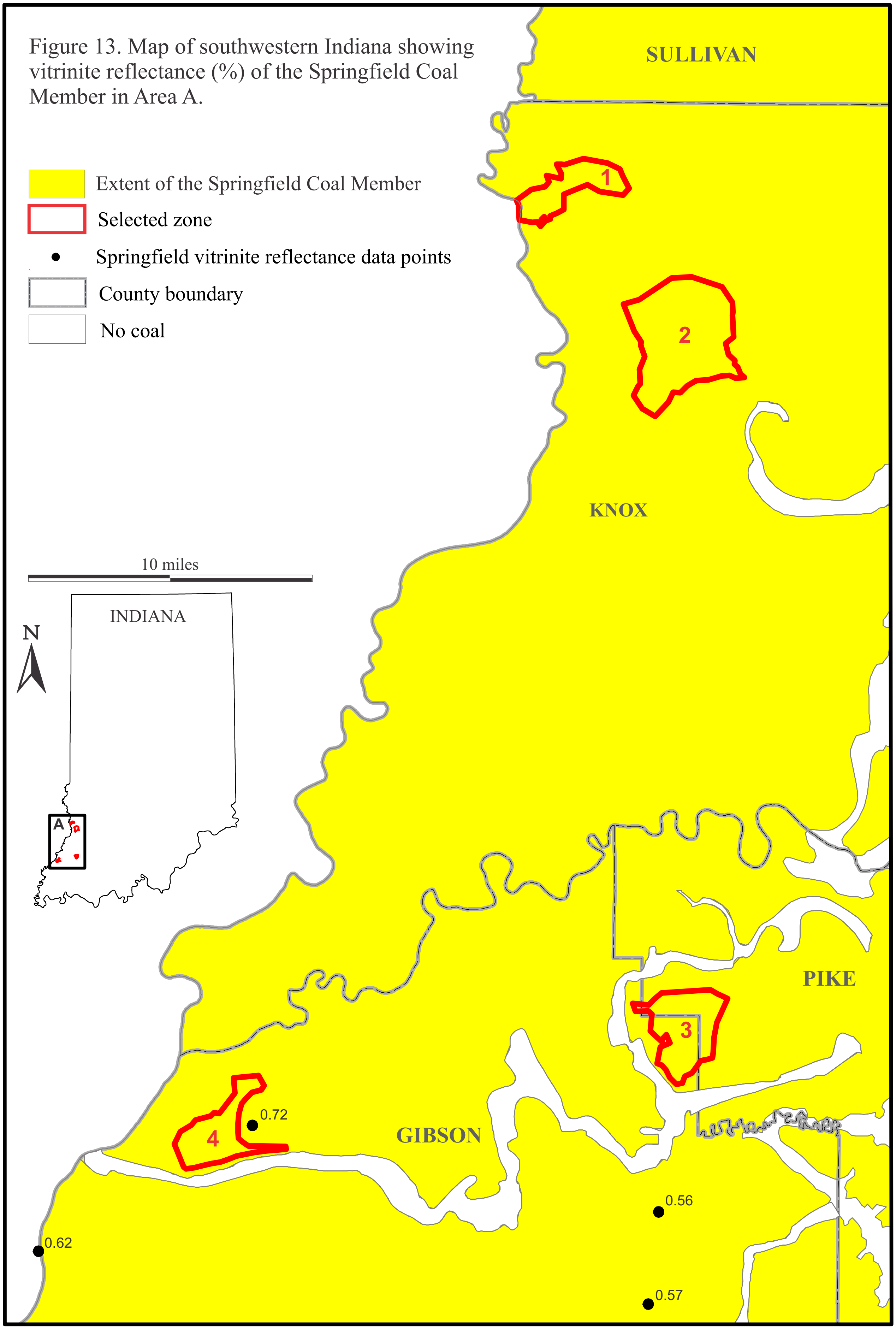


Figure 13. Map of southwestern Indiana showing vitrinite reflectance (%) of the Springfield Coal Member in Area A.

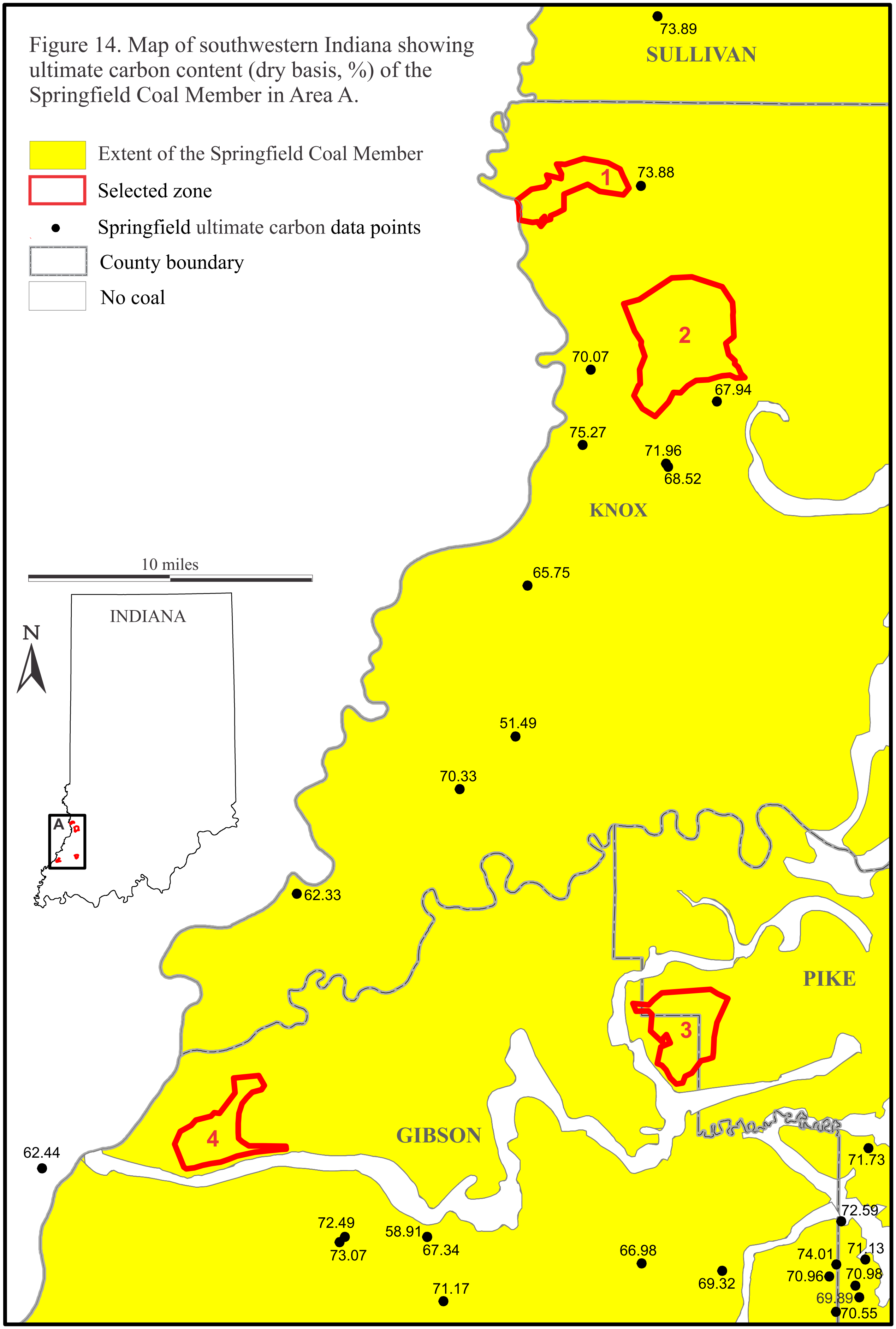


Figure 14. Map of southwestern Indiana showing ultimate carbon content (dry basis, %) of the Springfield Coal Member in Area A.

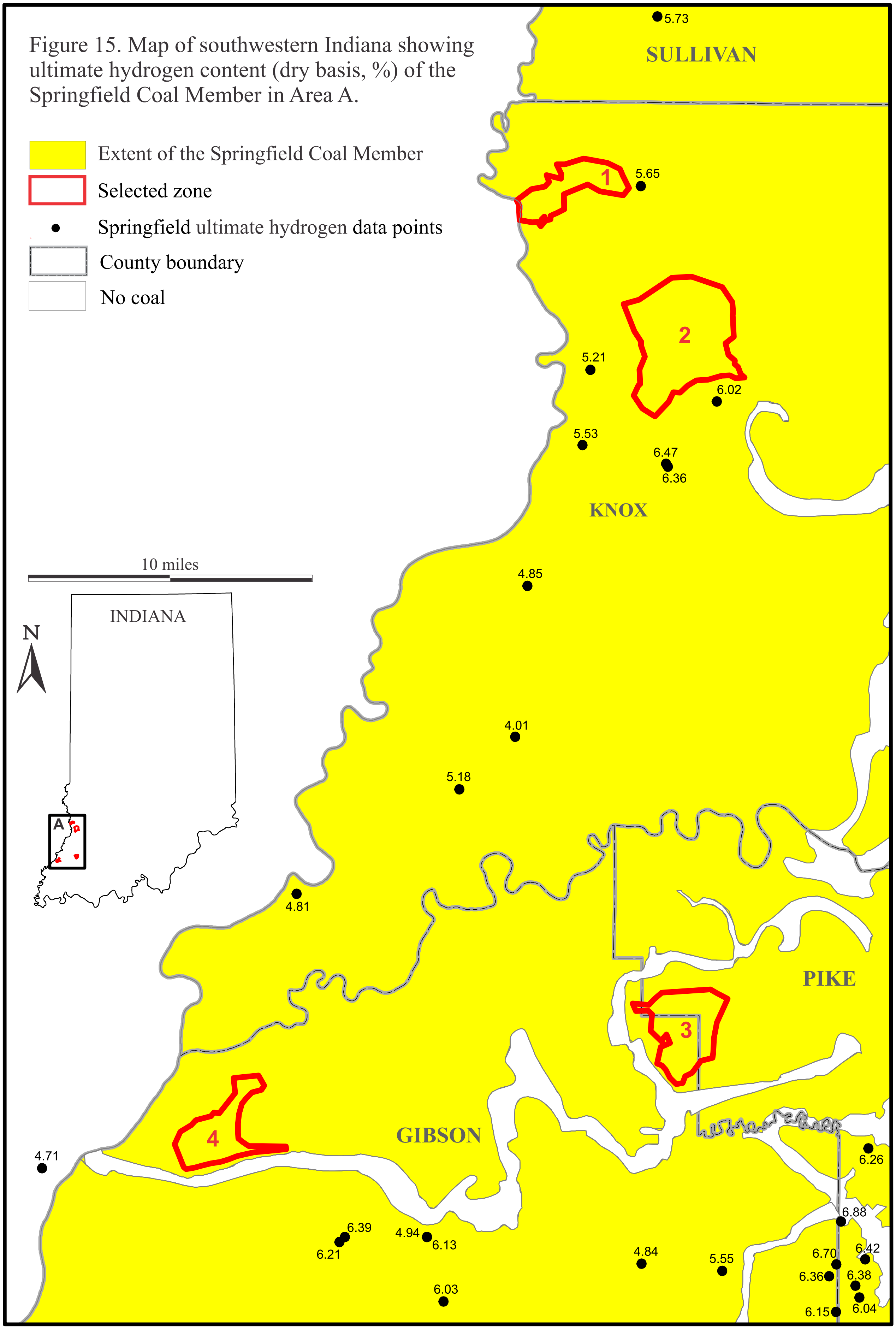


Figure 15. Map of southwestern Indiana showing ultimate hydrogen content (dry basis, %) of the Springfield Coal Member in Area A.

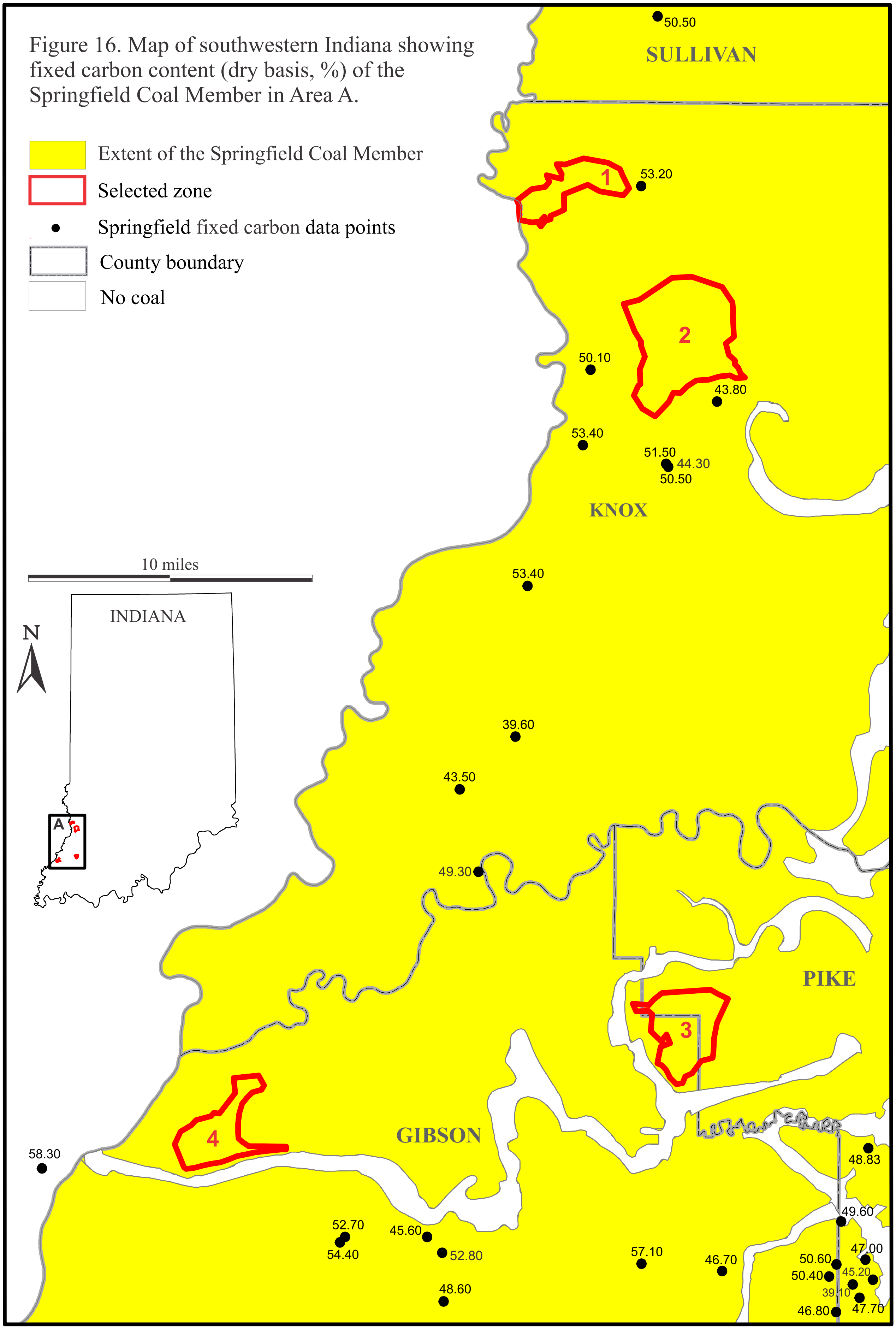


Figure 16. Map of southwestern Indiana showing fixed carbon content (dry basis, %) of the Springfield Coal Member in Area A.

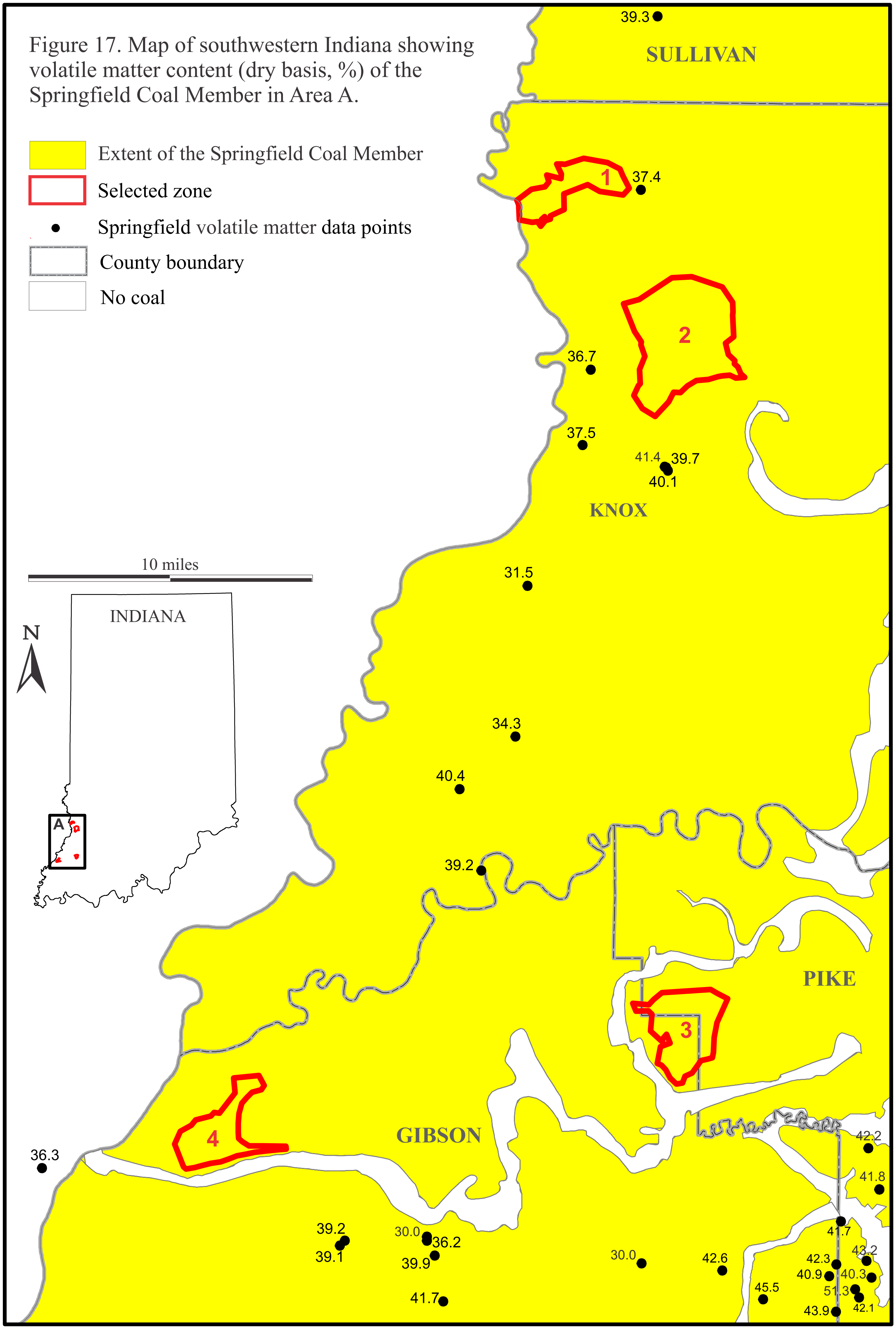


Figure 17. Map of southwestern Indiana showing volatile matter content (dry basis, %) of the Springfield Coal Member in Area A.

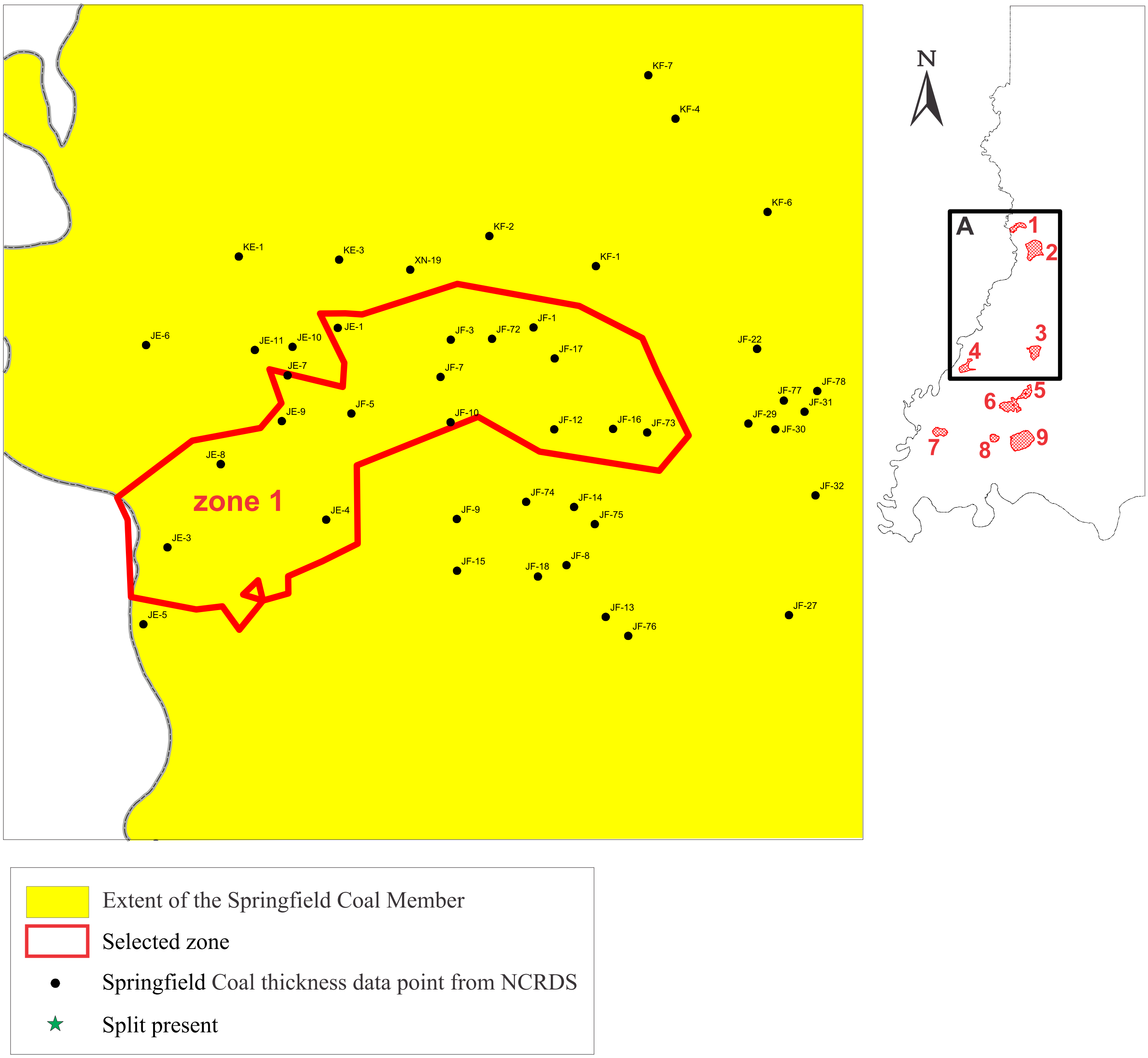


Figure 18. Map of southwestern Indiana showing distribution of thickness data points of the Springfield Coal Member and presence of splits in zone 1 (Area A). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE.

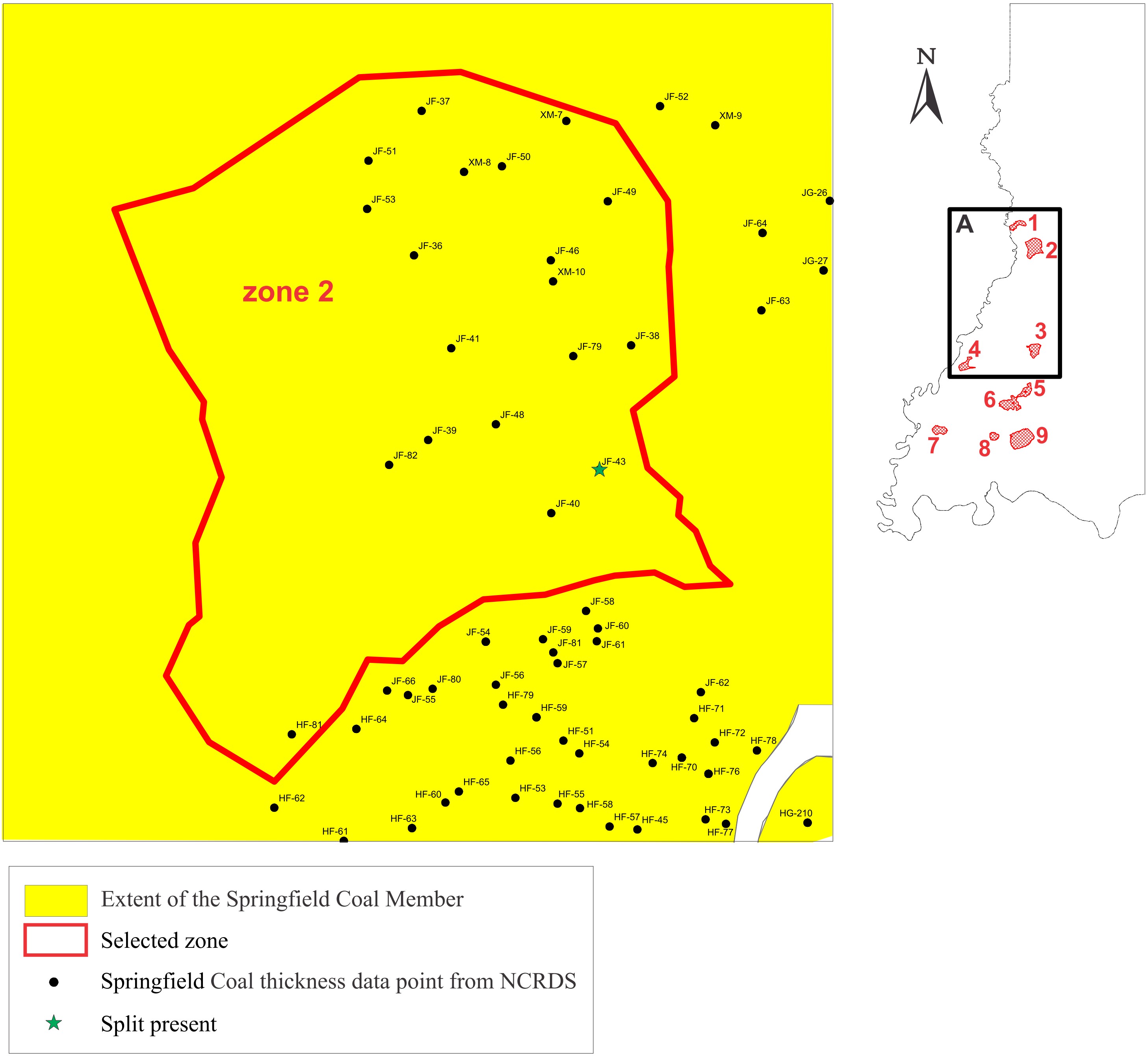


Figure 19. Map of southwestern Indiana showing distribution of thickness data points of the Springfield Coal Member and presence of splits in zone 2 (Area A). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE. Thc. - thickness.

Well ID	Top [ft]	Bottom [ft]	Thc. [ft]	Lithology	Notes	Parting thicker than 3.28 ft (1m)	Total coal thc.	Total splits thc.	**% of coal**
JF-43	312.7	314.5	0.8	COAL					
JF-43	314.5	314.7	0.2	Clay	Parting	NO	1.6	0.2	**88.9**
JF-43	314.7	315.5	0.8	COAL					

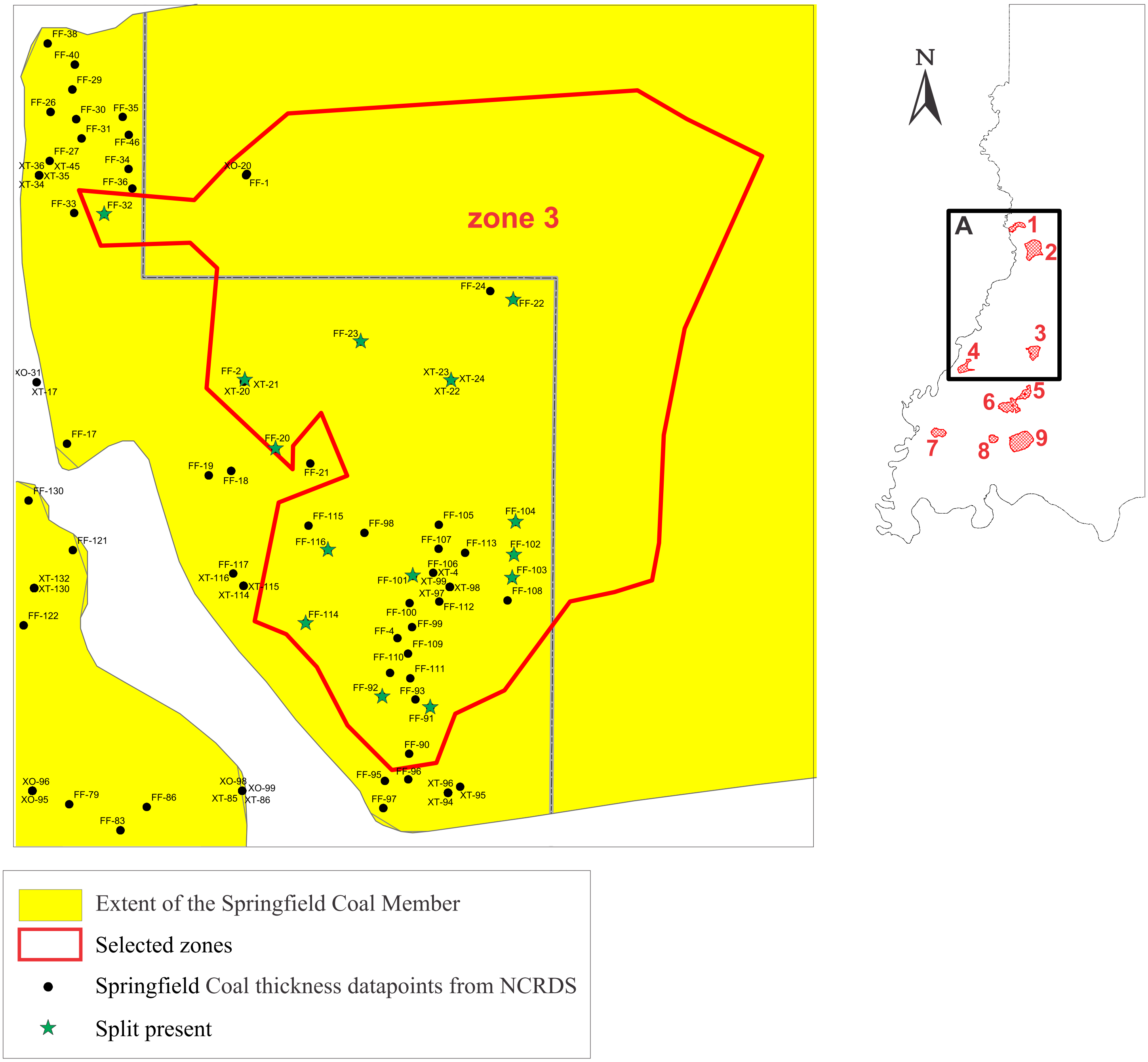


Figure 20. Map of southwestern Indiana showing distribution of thickness datapoints of the Springfield Coal Member and presence of splits in zone 3 (Area A). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE! Thc. - thickness.

Table is on the next page

Figure 20. Continued.

Well ID	Top [ft]	Bottom [ft]	Thc. [ft]	Lithology	Notes	Parting thicker than 3.28 ft (1m)	Total coal thc.	Total splits thc.	**% of coal**
FF-32	321.5	327.5	6.0	COAL					
FF-32	327.5	328.9	1.4	No record	Parting	NO	7.42	1.42	**83.9**
FF-32	328.9	330.4	1.4	COAL					
FF-22	367.8	369.3	1.4	COAL					
FF-22	369.3	370.7	1.4	No record	Parting	NO	7.42	1.42	**83.9**
FF-22	370.7	376.7	6.0	COAL					
FF-23	317.5	318.9	1.4	COAL					
FF-23	318.9	320.9	2.0	No record	Parting	NO	9.84	2.00	**83.1**
FF-23	320.9	329.4	8.4	COAL					
FF-20	257.4	258.8	1.4	COAL					
FF-20	258.8	260.2	1.4	No record	Parting	NO	7.42	1.42	**83.9**
FF-20	260.2	266.2	6.0	COAL					
FF-116	230.0	231.5	1.5	COAL					
FF-116	231.5	233.0	1.5	No record	Parting	NO	7.50	1.50	**83.3**
FF-116	233.0	239.0	6.0	COAL					
FF-114	270.0	271.5	1.5	COAL					
FF-114	271.5	273.0	1.5	No record	Parting	NO	5.5	1.5	**78.6**
FF-114	273.0	277.0	4.0	COAL					
FF-92	218.0	219.4	1.4	COAL					
FF-92	219.4	220.8	1.4	No record	Parting	NO	8.4	1.4	**85.6**
FF-92	220.8	227.8	7.0	COAL					
FF-91	214.8	216.3	1.4	COAL					
FF-91	216.3	217.7	1.4	No record	Parting	NO			
FF-91	217.7	224.7	7.0	COAL			9.8	2.8	**77.6**
FF-91	224.7	226.1	1.4	No record	Parting	NO			
FF-91	226.1	227.5	1.4	COAL					
FF-102	273.0	274.5	1.5	COAL					
FF-102	274.5	278.5	4.0	No record	Parting	**YES**	7.0	4.0	**63.6**
FF-102	278.5	284.0	5.5	COAL					
FF-103	227.0	229.5	2.5	COAL					
FF-103	229.5	232.5	3.0	No record	Parting	NO	8.5	3.0	**73.9**
FF-103	232.5	238.5	6.0	COAL					
FF-104	260.0	262.0	2.0	COAL					
FF-104	262.0	267.0	5.0	No record	Parting	**YES**			
FF-104	267.0	270.0	3.0	COAL			6.5	6.5	**50.0**
FF-104	270.0	271.5	1.5	No record	Parting	NO			
FF-104	271.5	273.0	1.5	COAL					
XT-20	258.0	259.5	1.5	COAL					
XT-20	259.5	261.0	1.5	No record	Parting	NO	7.5	1.5	**83.3**
XT-20	261.0	267.0	6.0	COAL					
XT-23	318.0	319.5	1.5	COAL					
XT-23	319.5	321.5	2.0	No record	Parting	NO	10.0	2.0	**83.3**
XT-23	321.5	330.0	8.5	COAL					
FF-101	267.0	270.0	3.0	COAL					
FF-101	270.0	274.0	4.0	No record	Parting	**YES**	9.0	4.0	**69.2**
FF-101	274.0	280.0	6.0	COAL					

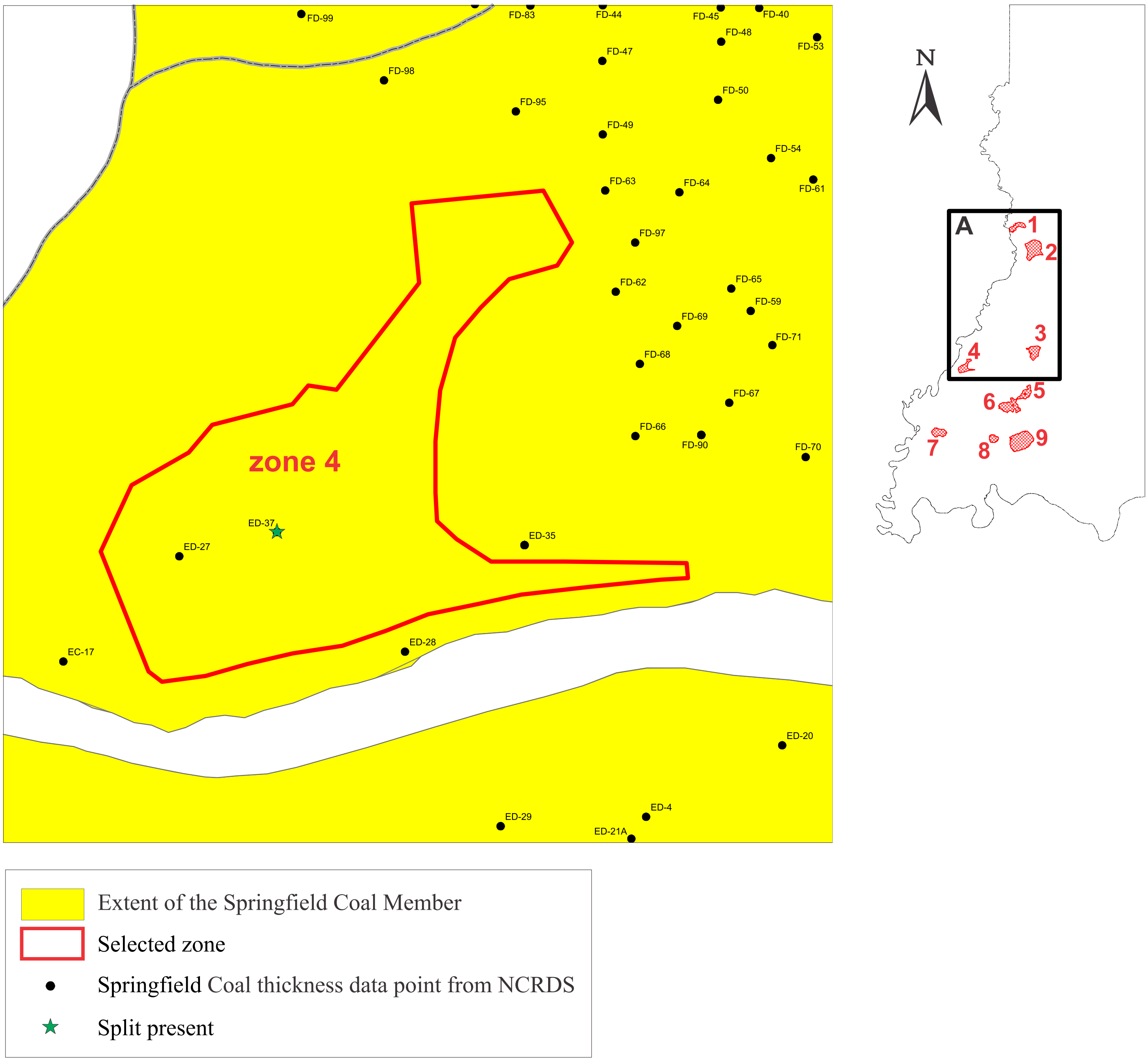


Figure 21. Map of southwestern Indiana showing distribution of thickness data points of the Springfield Coal Member and presence of splits in zone 4 (Area A). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE. Thc. - thickness.

Well ID	Top [ft]	Bottom [ft]	Thc. [ft]	Lithology	Notes	Parting thicker than 3.28 ft (1m)	Total coal thc.	Total splits thc.	**% of coal**
ED-37	510.0	510.5	0.54	COAL					
ED-37	510.5	510.6	0.06	Pyrite	Parting	NO	6.48	0.06	**99.1**
ED-37	510.6	516.5	5.94	COAL					

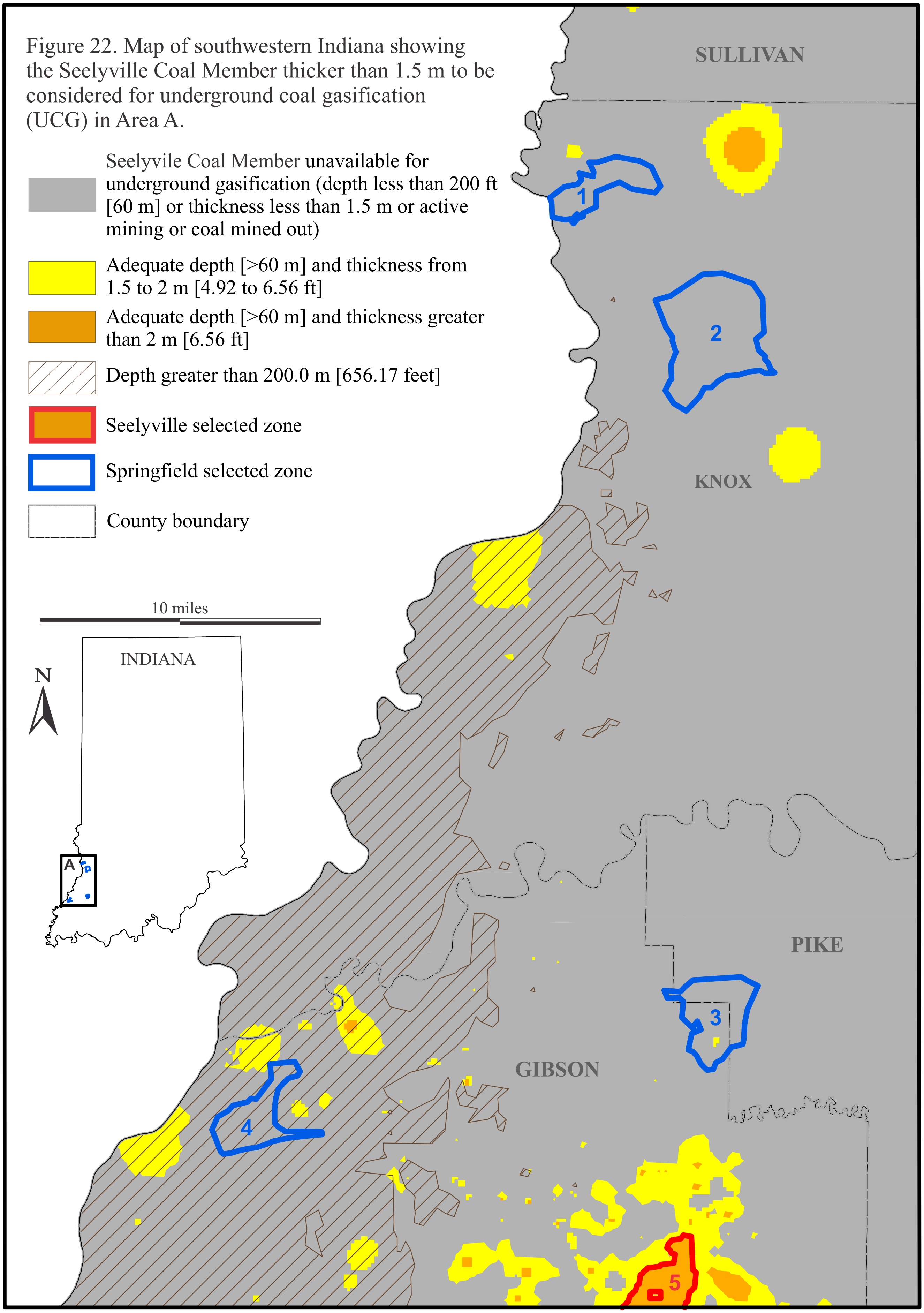


Figure 22. Map of southwestern Indiana showing the Seelyville Coal Member thicker than 1.5 m to be considered for underground coal gasification (UCG) in Area A.

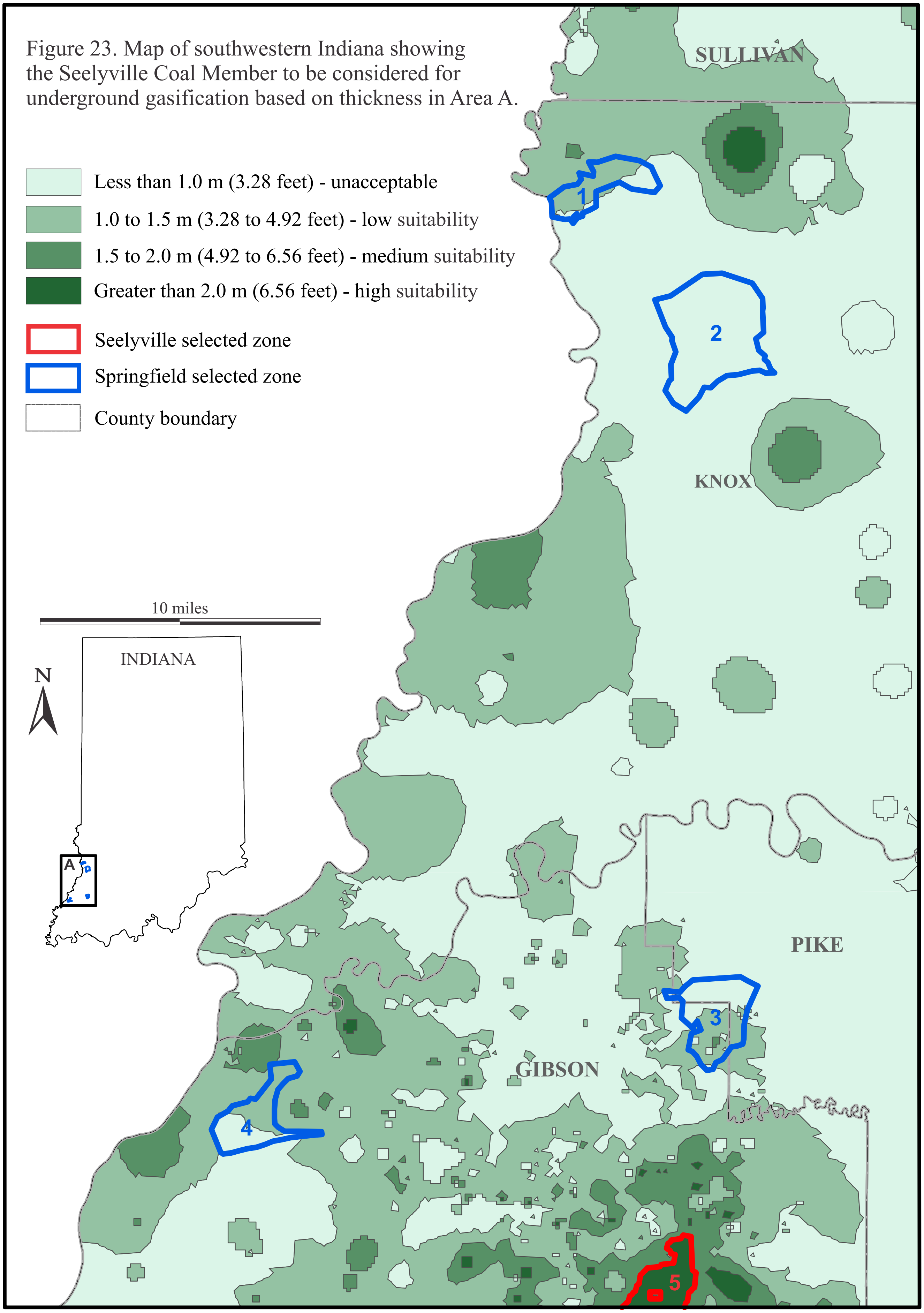


Figure 23. Map of southwestern Indiana showing the Seelyville Coal Member to be considered for underground gasification based on thickness in Area A.

Figure 24. Map of southwestern Indiana showing the Seelyville Coal Member to be considered for underground gasification based on depth in Area A.

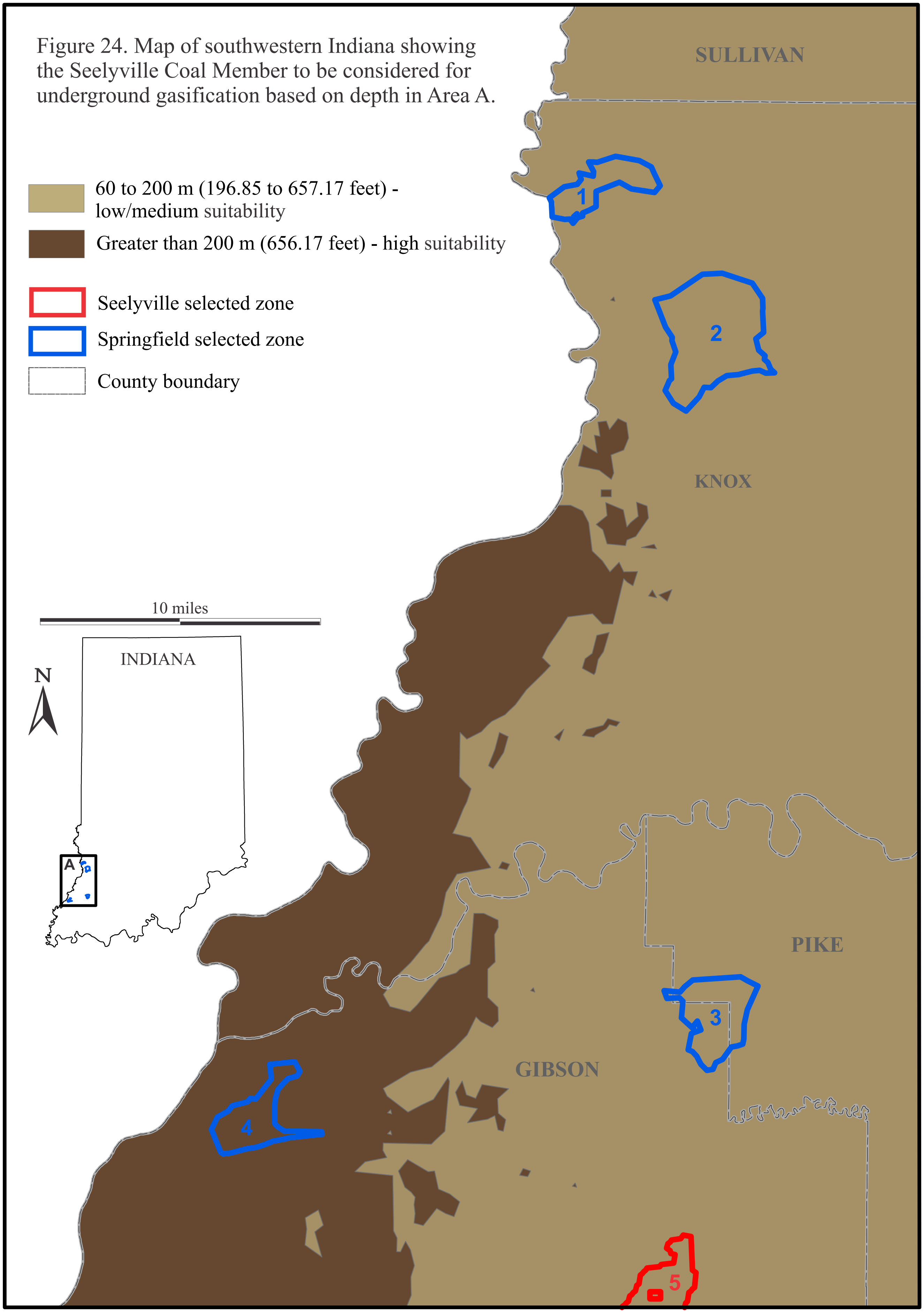
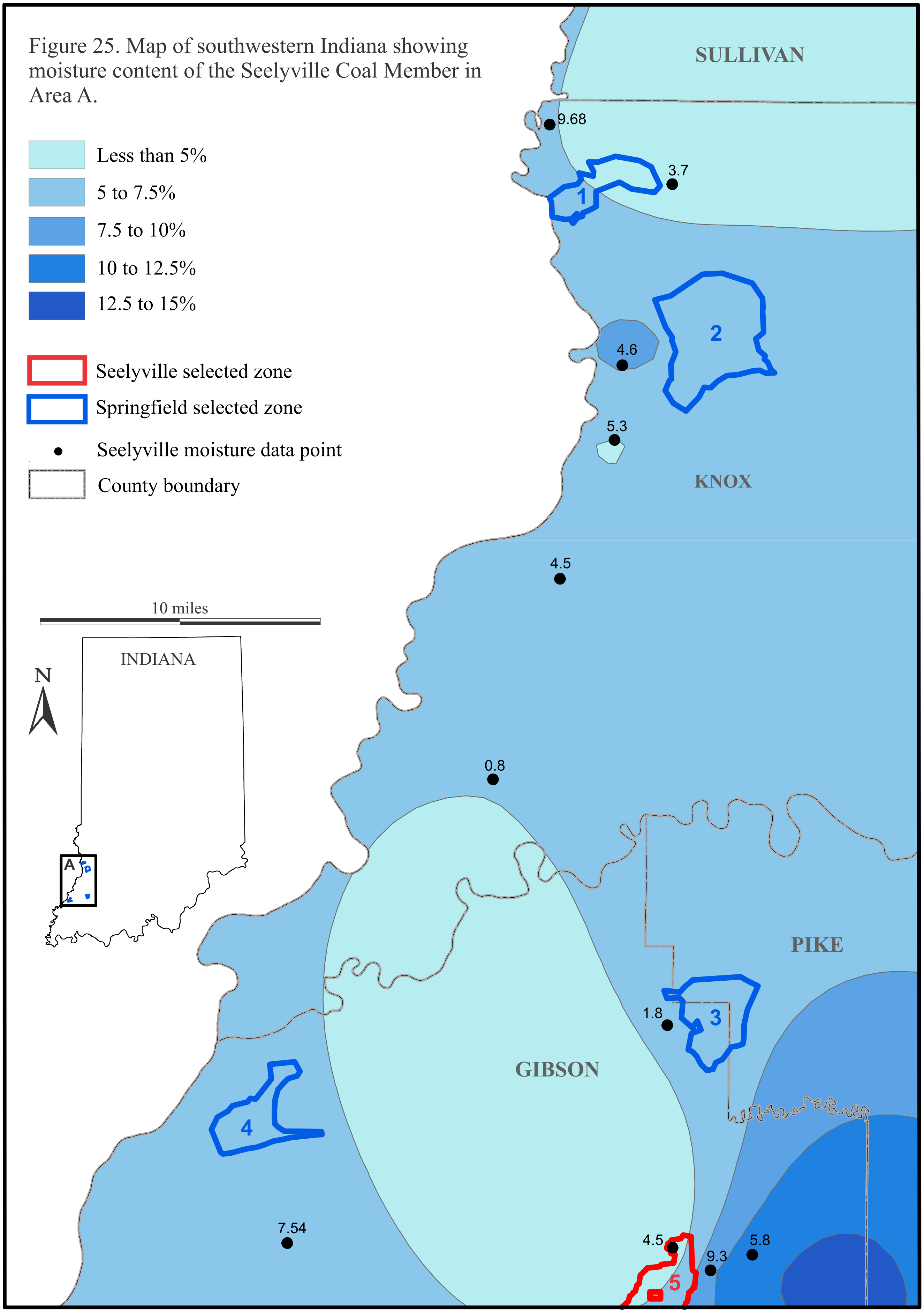


Figure 25. Map of southwestern Indiana showing moisture content of the Seelyville Coal Member in Area A.



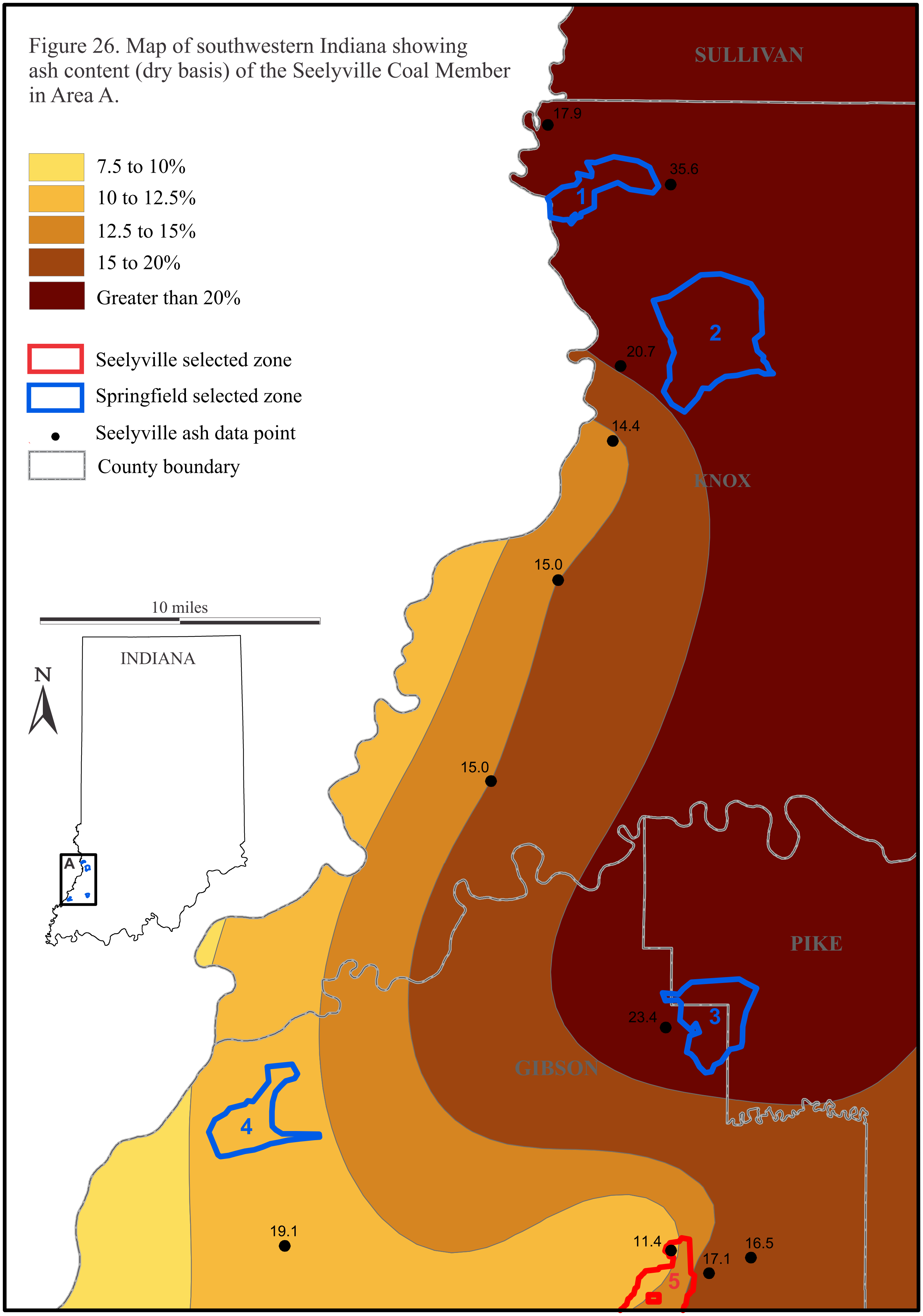


Figure 26. Map of southwestern Indiana showing ash content (dry basis) of the Seelyville Coal Member in Area A.

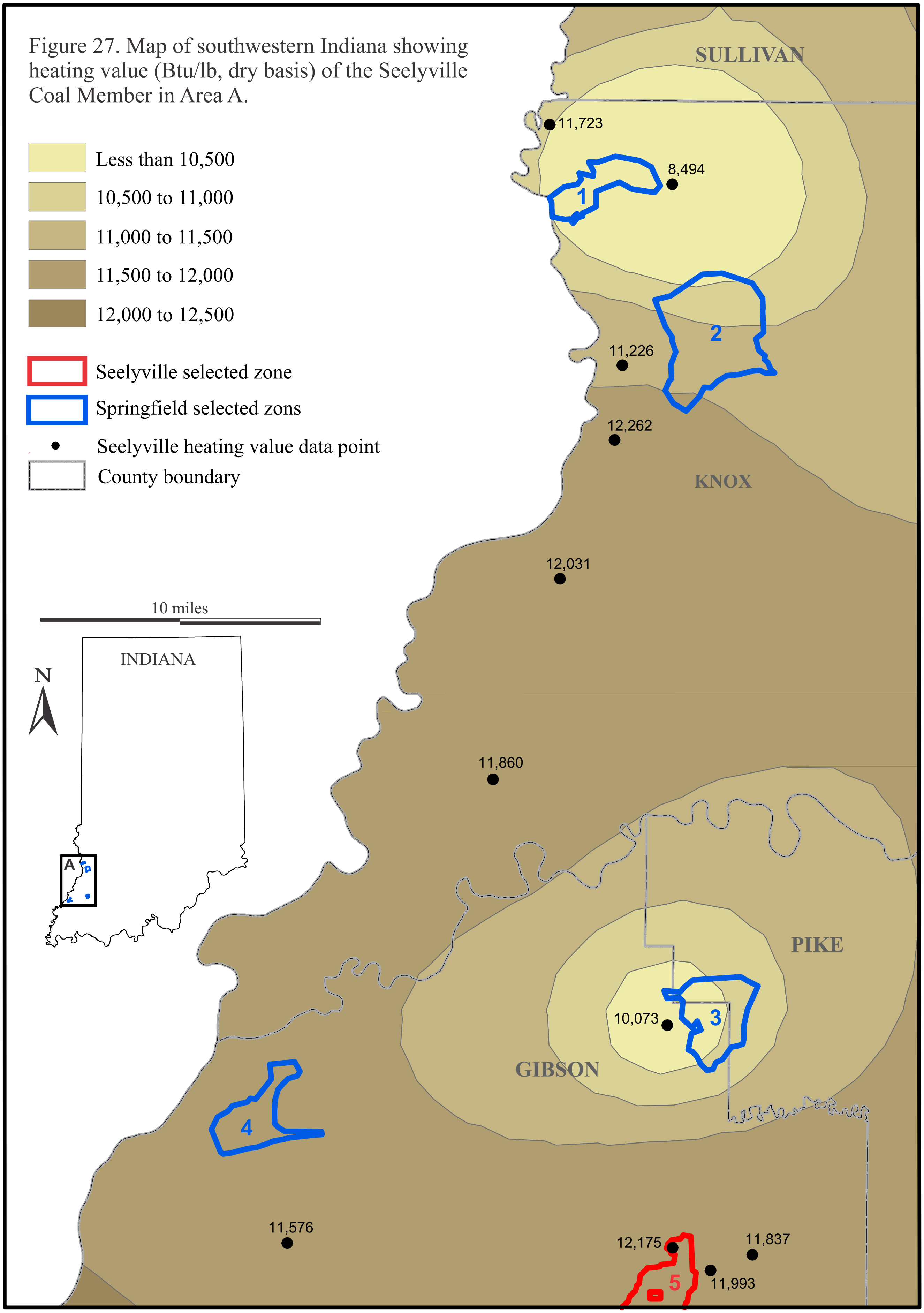


Figure 27. Map of southwestern Indiana showing heating value (Btu/lb, dry basis) of the Seelyville Coal Member in Area A.

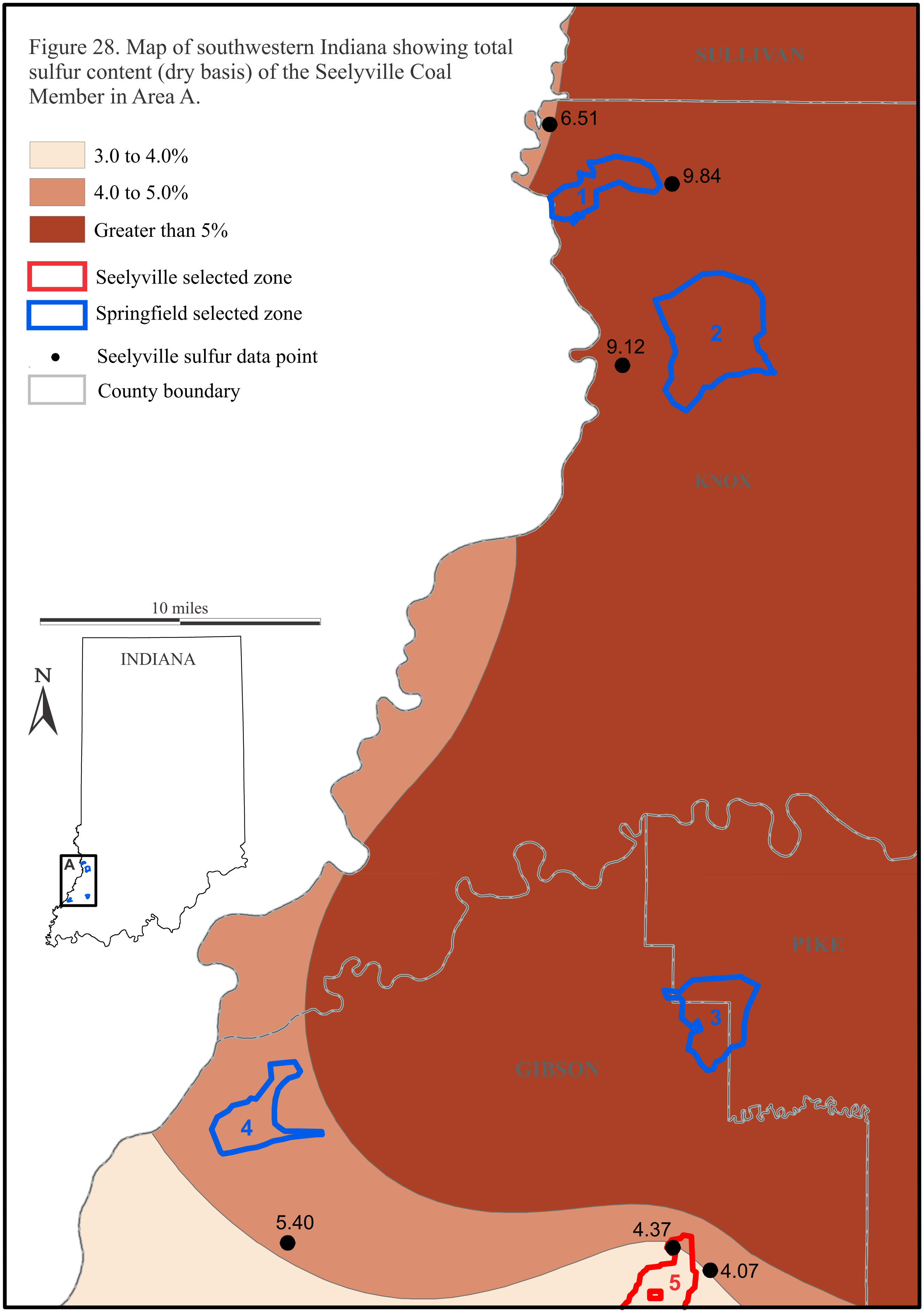


Figure 28. Map of southwestern Indiana showing total sulfur content (dry basis) of the Seelyville Coal Member in Area A.

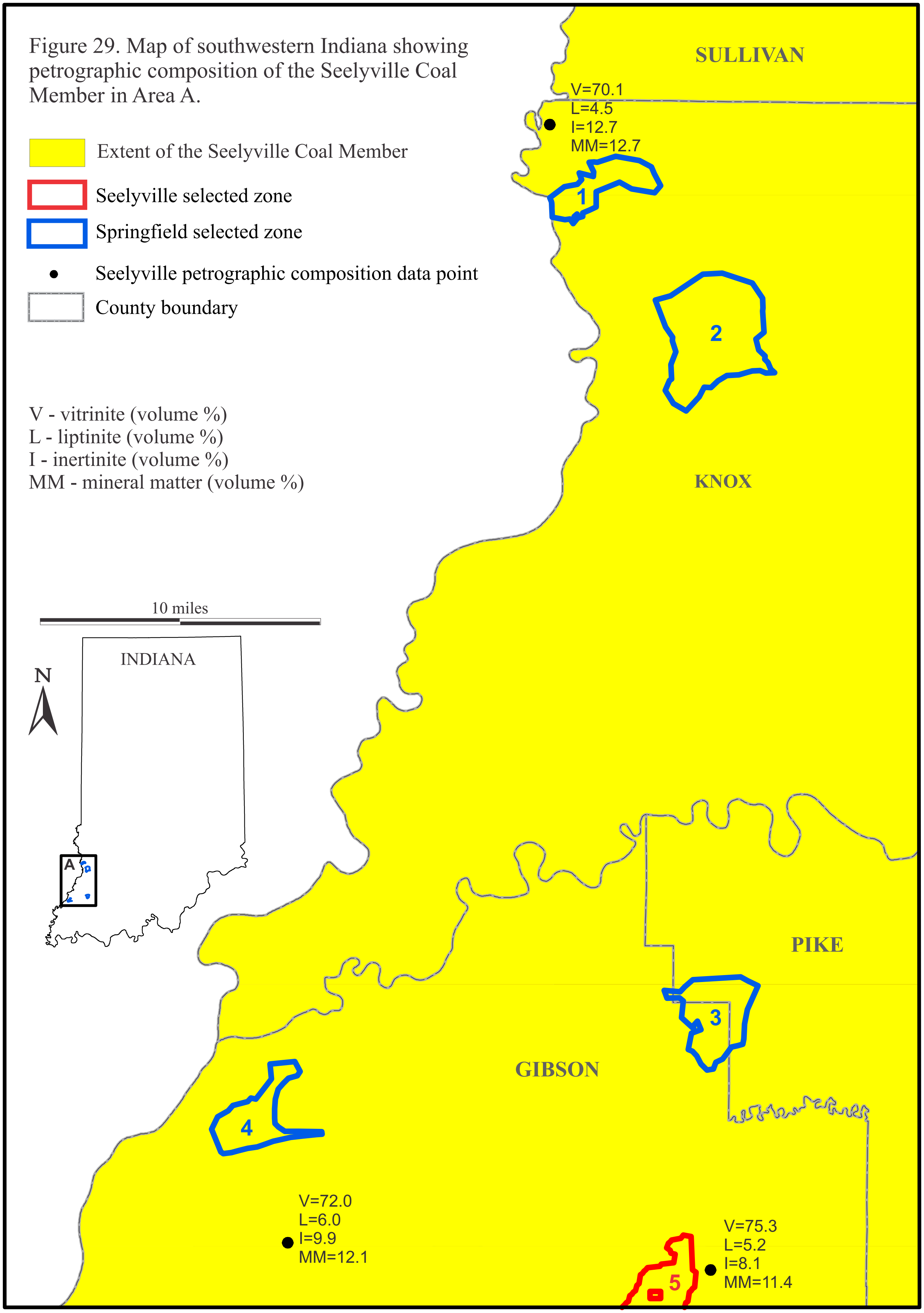


Figure 29. Map of southwestern Indiana showing petrographic composition of the Seelyville Coal Member in Area A.

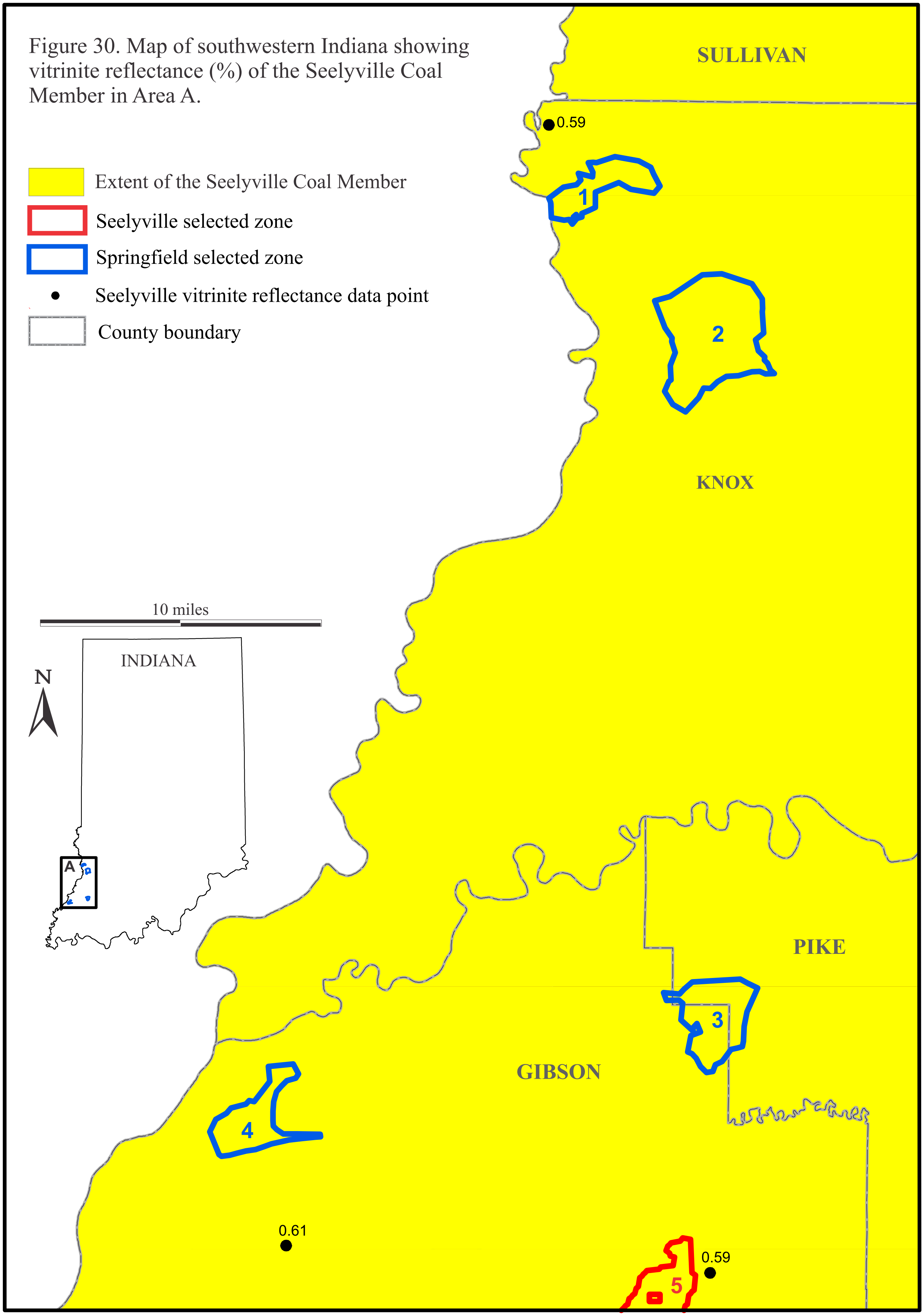


Figure 30. Map of southwestern Indiana showing vitrinite reflectance (%) of the Seelyville Coal Member in Area A.

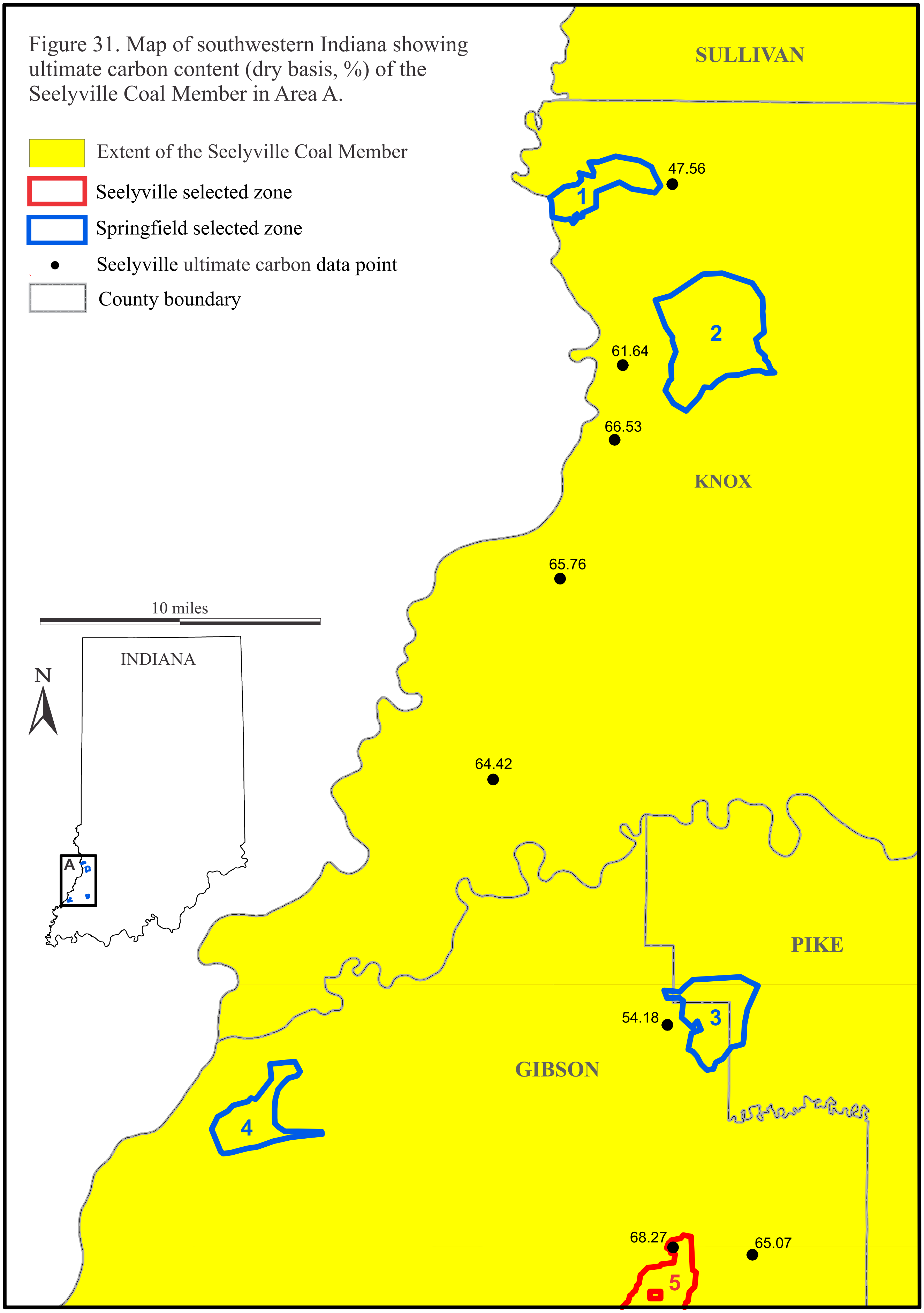
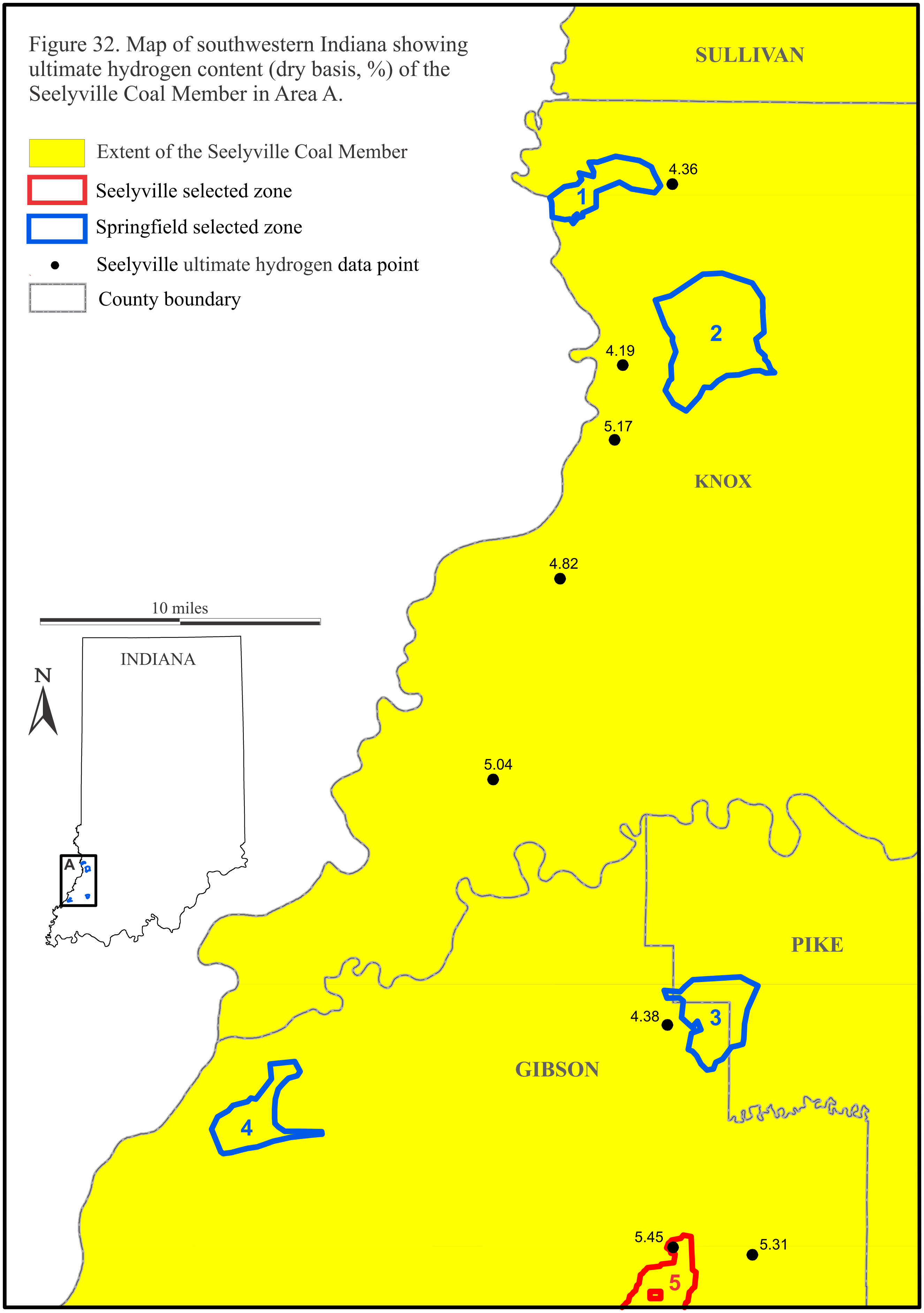


Figure 31. Map of southwestern Indiana showing ultimate carbon content (dry basis, %) of the Seelyville Coal Member in Area A.

Figure 32. Map of southwestern Indiana showing ultimate hydrogen content (dry basis, %) of the Seelyville Coal Member in Area A.



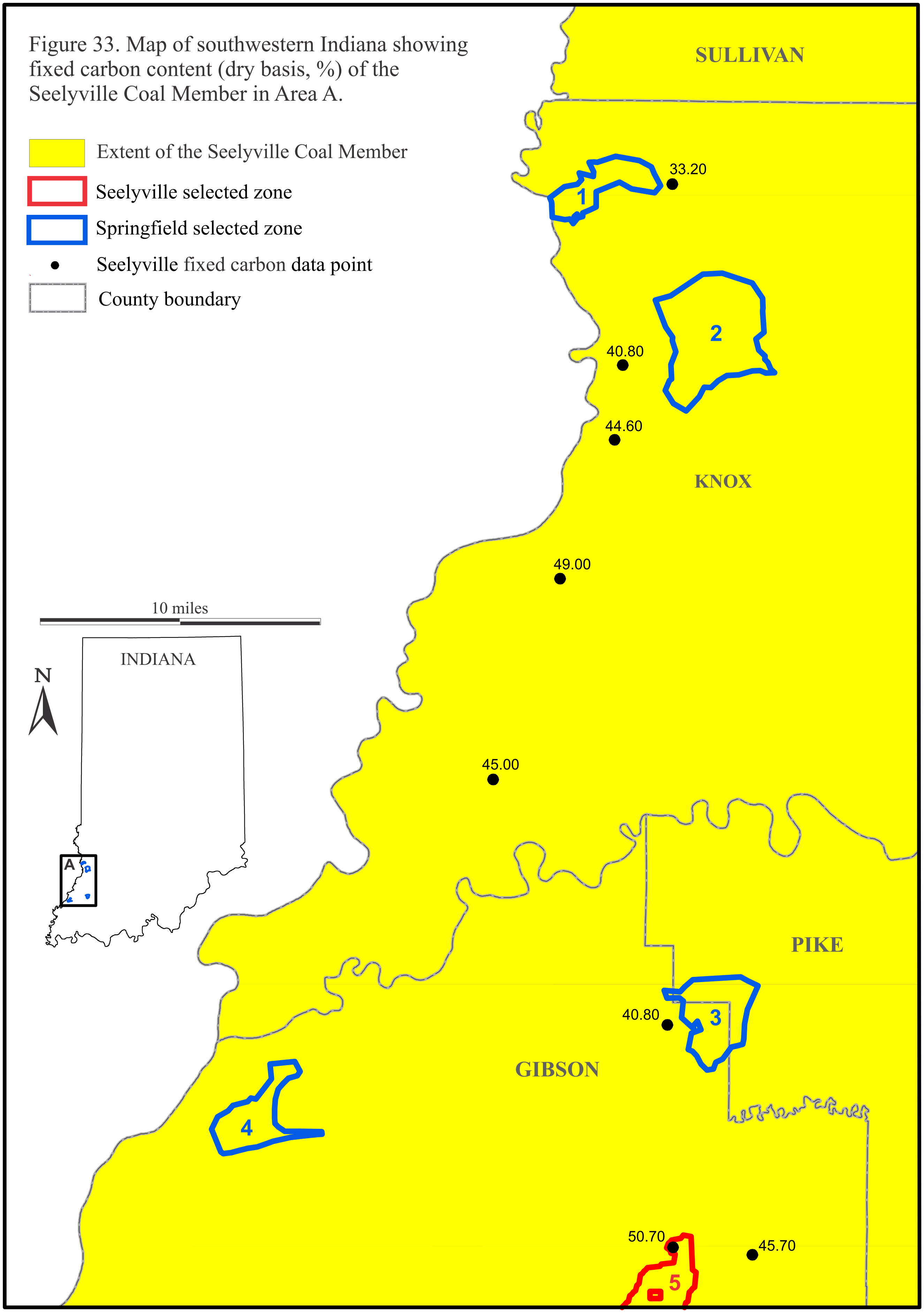


Figure 33. Map of southwestern Indiana showing fixed carbon content (dry basis, %) of the Seelyville Coal Member in Area A.

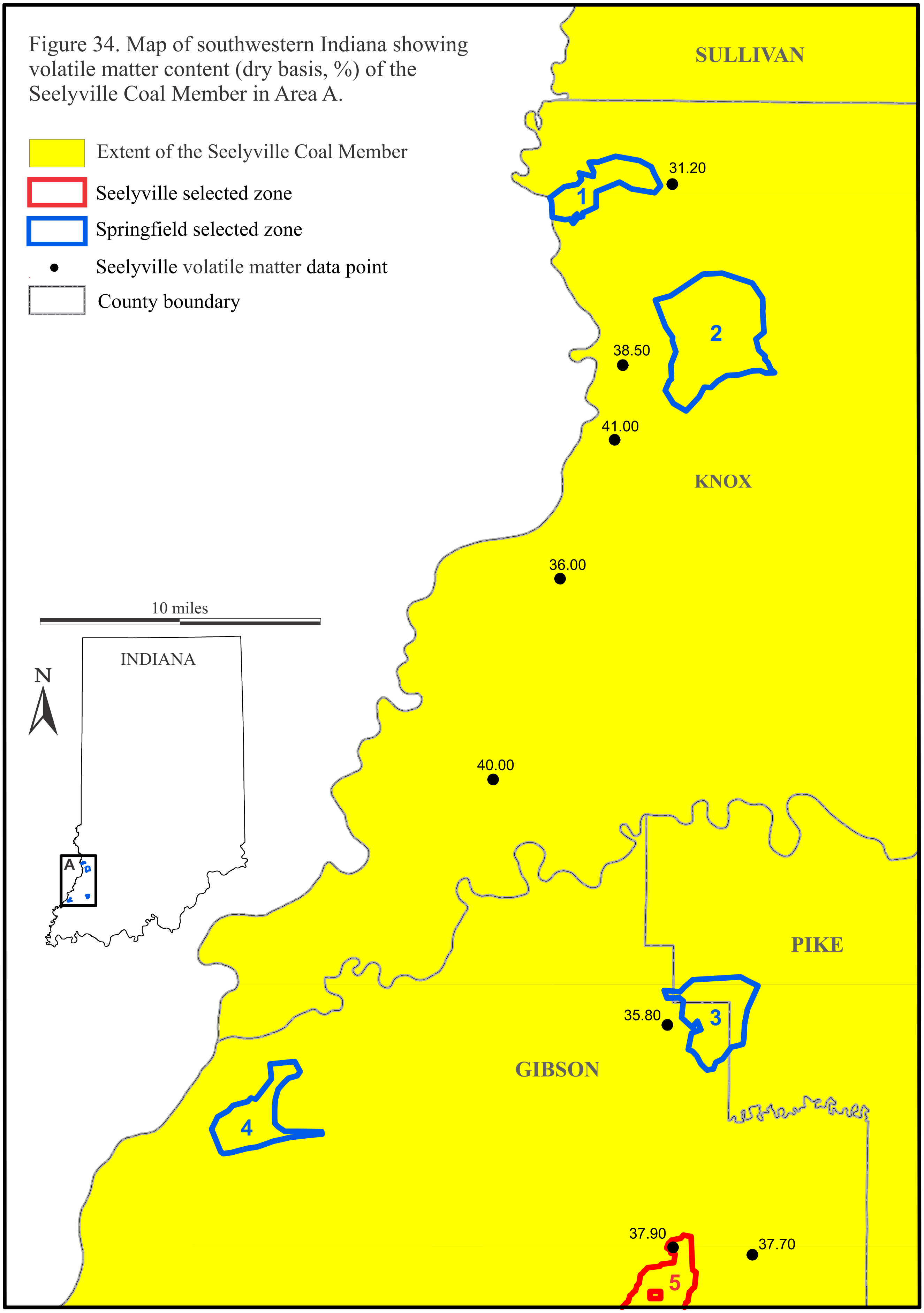


Figure 34. Map of southwestern Indiana showing volatile matter content (dry basis, %) of the Seelyville Coal Member in Area A.

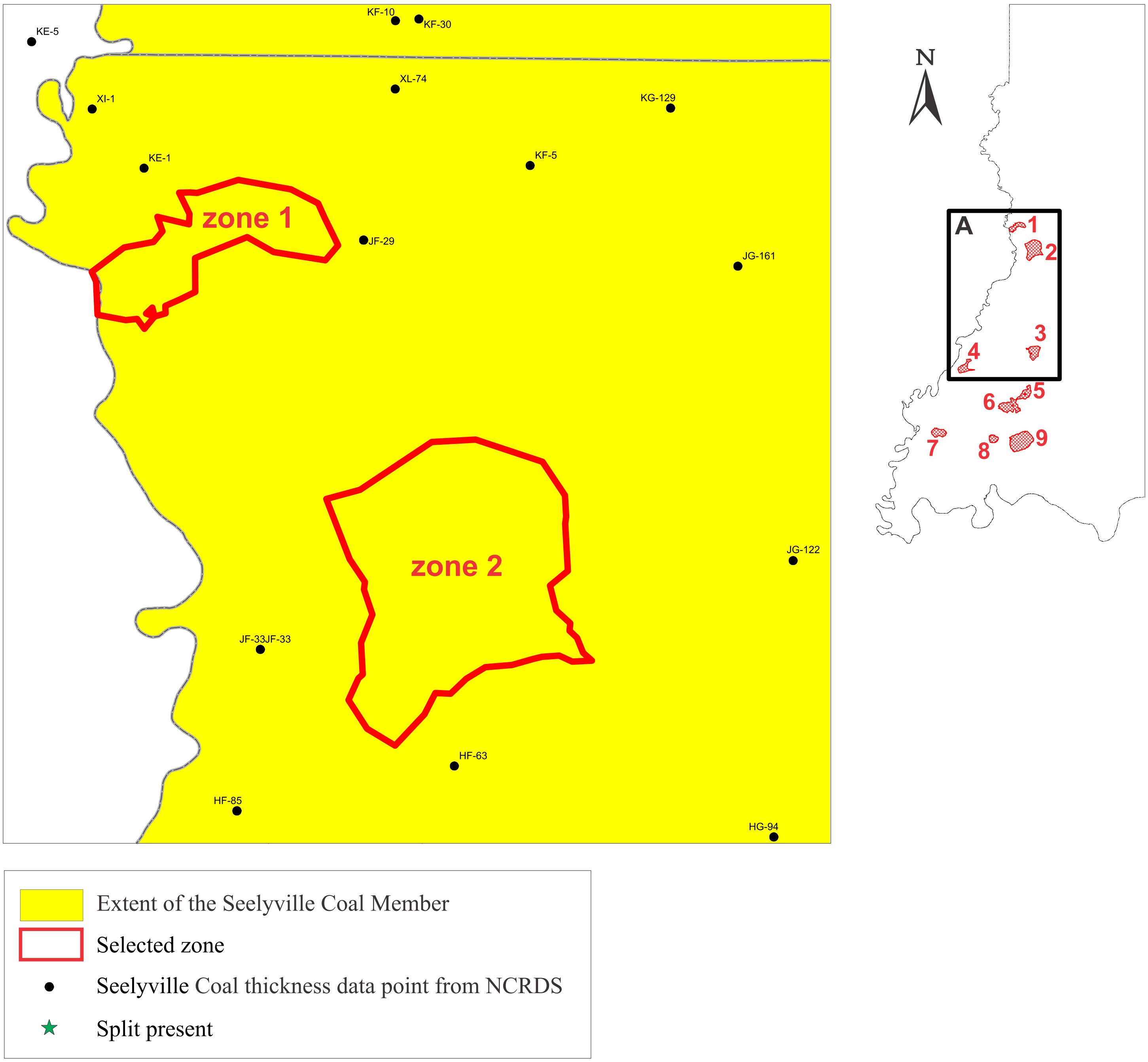


Figure 35. Map of southwestern Indiana showing distribution of thickness data points of the Seelyville Coal Member and presence of splits in zones 1 and 2 (Area A). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE.

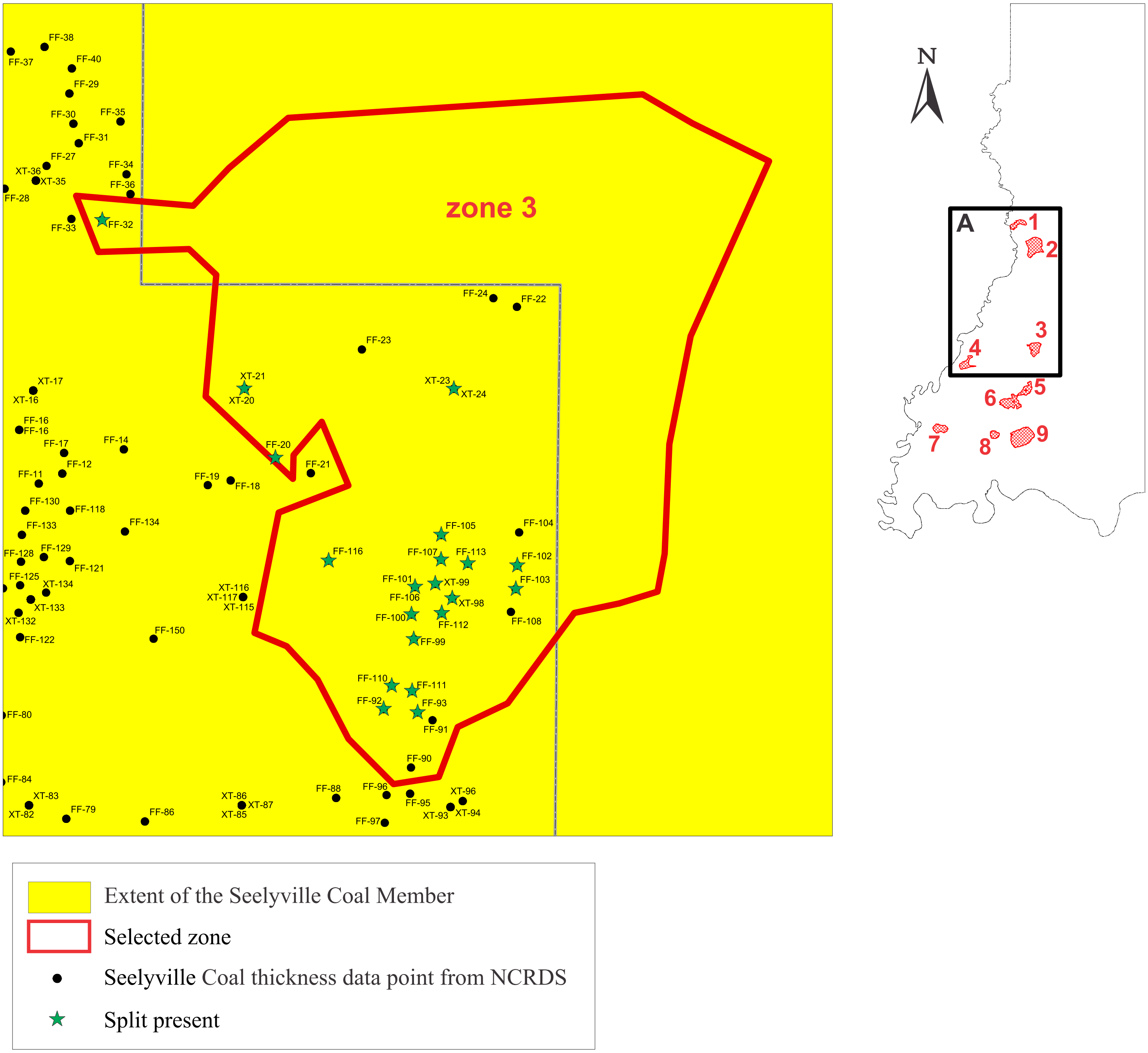
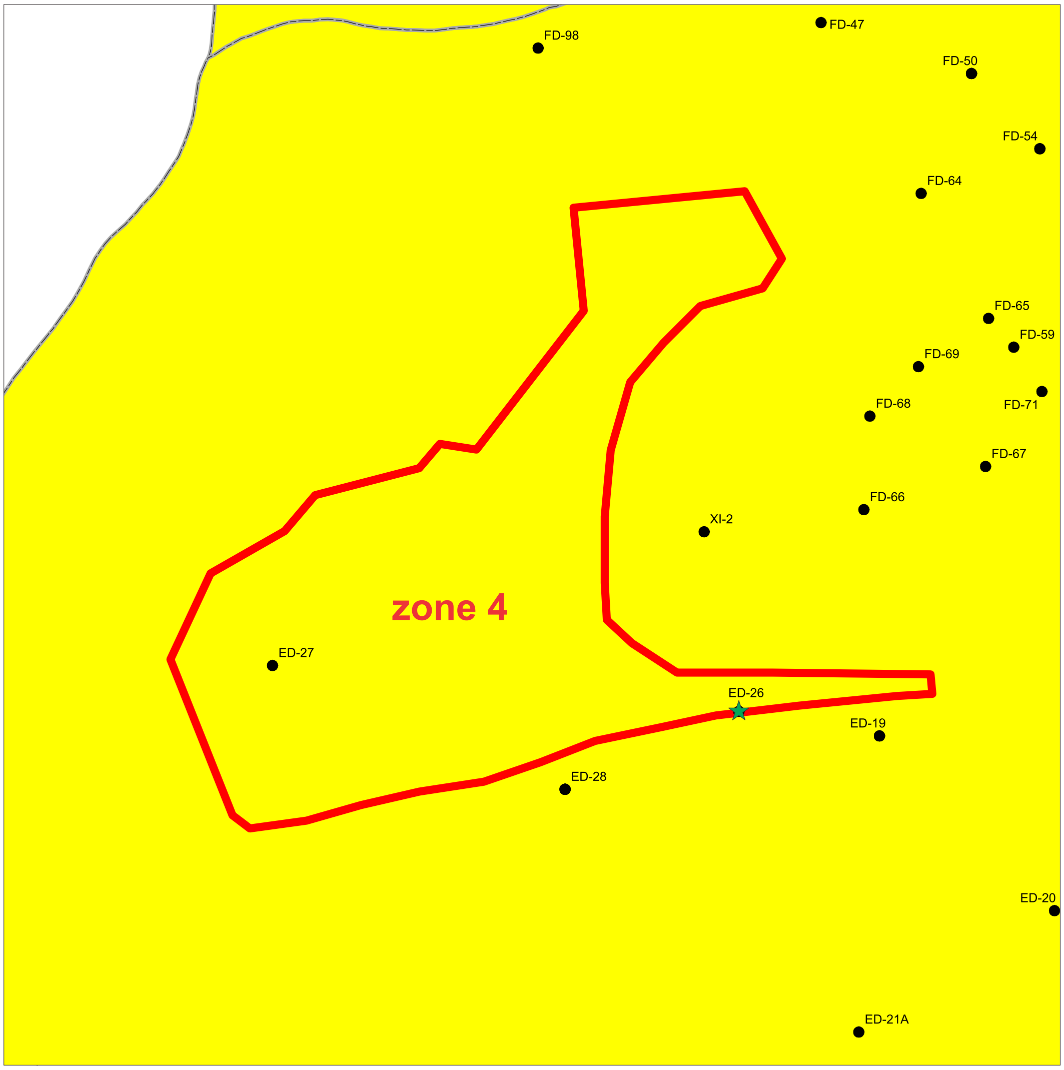


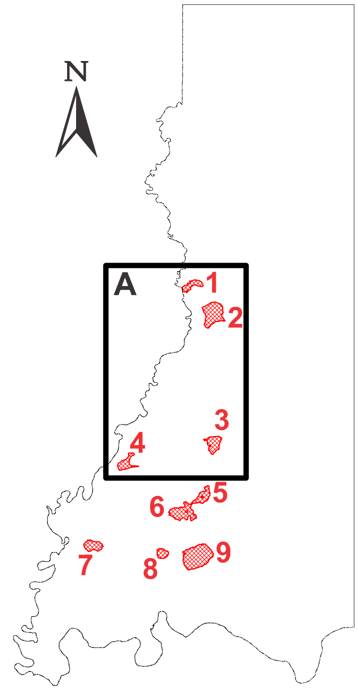
Figure 36. Map of southwestern Indiana showing distribution of thickness data points of the Seelyville Coal Member and presence of splits in zone 3 (Area A). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE. Thc. - thickness.

Table is on the next page

Figure 36. Continued.

Well ID	Top [ft]	Bottom [ft]	Thc. [ft]	Lithology	Notes	Parting thicker than 3.28 ft (1m)	Total coal thc.	Total splits thc.	% of coal
FF-32	505.4	508.4	3.0	COAL					
FF-32	508.4	515.4	7.0	No record	Parting	YES	6.0	7.0	**46.2**
FF-32	515.4	518.4	3.0	COAL					
FF-20	431.2	434.2	3.0	COAL					
FF-20	434.2	454.2	20.0	No record	Parting	YES	5.4	20.0	**21.3**
FF-20	454.2	456.6	2.4	COAL					
FF-116	405.0	406.5	1.5	COAL					
FF-116	406.5	422.0	15.5	No record	Parting	YES	2.5	15.5	**13.9**
FF-116	422.0	423.0	1.0	COAL					
FF-105	438.0	439.0	1.0	COAL					
FF-105	439.0	455.0	16.0	No record	Parting	YES	4.5	16.0	**22.0**
FF-105	455.0	458.5	3.5	COAL					
FF-113	433.0	436.0	3.0	COAL					
FF-113	436.0	458.0	22.0	No record	Parting	YES	8.0	22.0	**26.7**
FF-113	458.0	463.0	5.0	COAL					
FF-102	372.0	373.0	1.0	COAL					
FF-102	373.0	391.0	18.0	No record	Parting	YES			
FF-102	391.0	392.0	1.0	COAL			5.0	26.0	**16.1**
FF-102	392.0	400.0	8.0	No record	Parting	YES			
FF-102	400.0	403.0	3.0	COAL					
FF-103	409.0	412.0	3.0	COAL					
FF-103	412.0	422.0	10.0	No record	Parting	YES	5.5	10.0	**35.5**
FF-103	422.0	424.5	2.5	COAL					
FF-106	435.0	439.0	4.0	COAL					
FF-106	439.0	463.0	24.0	No record	Parting	YES	7.5	24.0	**23.8**
FF-106	463.0	466.5	3.5	COAL					
XT-20	432.0	435.0	3.0	COAL					
XT-20	435.0	455.0	20.0	No record	Parting	YES	5.5	20.0	**21.6**
XT-20	455.0	457.5	2.5	COAL					
XT-21	438.0	440.0	2.0	COAL					
XT-21	440.0	441.5	1.5	No record	Parting	NO	3.5	1.5	**70.0**
XT-21	441.5	443.0	1.5	COAL					
XT-23	507.0	509.0	2.0	COAL					
XT-23	509.0	536.0	27.0	No record	Parting	YES			
XT-23	536.0	539.5	3.5	COAL			6.5	47.5	**12.0**
XT-23	539.5	560.0	20.5	No record	Parting	YES			
XT-23	560.0	561.0	1.0	COAL					
FF-107	441.0	442.5	1.5	COAL					
FF-107	442.5	459.0	16.5	No record	Parting	YES	5.5	16.5	**25.0**
FF-107	459.0	463.0	4.0	COAL					
FF-101	433.0	434.5	1.5	COAL					
FF-101	434.5	443.0	8.5	No record	Parting	YES			
FF-101	443.0	444.0	1.0	COAL			5.5	18.5	**22.9**
FF-101	444.0	454.0	10.0	No record	Parting	YES			
FF-101	454.0	457.0	3.0	COAL					
FF-100	422.8	426.3	3.4	COAL					
FF-100	426.3	447.7	21.4	No record	Parting	YES	6.4	21.4	**23.1**
FF-100	447.7	450.7	3.0	COAL					
FF-111	420.0	421.5	1.5	COAL					
FF-111	421.5	422.5	1.0	No record	Parting	NO	5.5	1.0	**84.6**
FF-111	422.5	426.5	4.0	COAL					
FF-92	410.8	412.3	1.4	COAL					
FF-92	412.3	420.7	8.4	No record	Parting	YES	4.4	8.4	**34.4**
FF-92	420.7	423.7	3.0	COAL					
FF-93	421.0	424.4	3.4	COAL					
FF-93	424.4	442.8	18.4	No record	Parting	YES	4.4	18.4	**19.4**
FF-93	442.8	443.8	1.0	COAL					





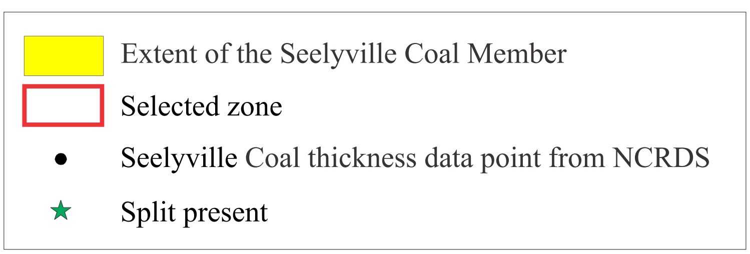
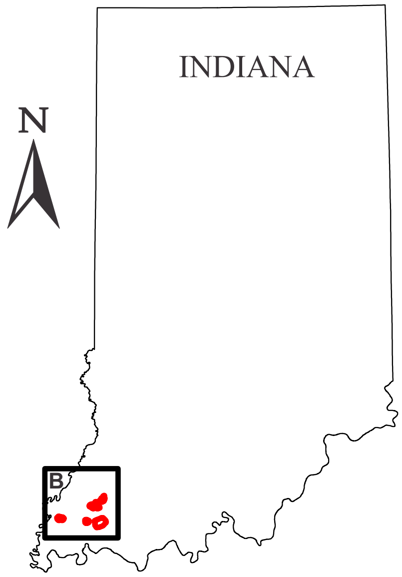


Figure 37. Map of southwestern Indiana showing distribution of thickness data points of the Seelyville Coal Member and presence of splits in zone 4 (Area A). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE. Thc. - thickness.

Well ID	Top [ft]	Bottom [ft]	Thc. [ft]	Lithology	Notes	Parting thicker than 3.28 ft (1m)	Total coal thc.	Total splits thc.	**% of coal**
ED-26	723.0	724.5	1.5	COAL					
ED-26	724.5	726.0	1.5	No record	Parting	NO	3.0	1.5	**66.7**
ED-26	726.0	727.5	1.5	COAL					

Figure 38. Map of southwestern Indiana showing the Seelyville Coal Member thicker than 1.5 m to be considered for underground coal gasification (UCG) in Area B.



Seelyvile Coal Member unavailable for underground gasification (depth less than 200 ft [60 m] or thickness less than 1.5 m or active mining or coal mined out)

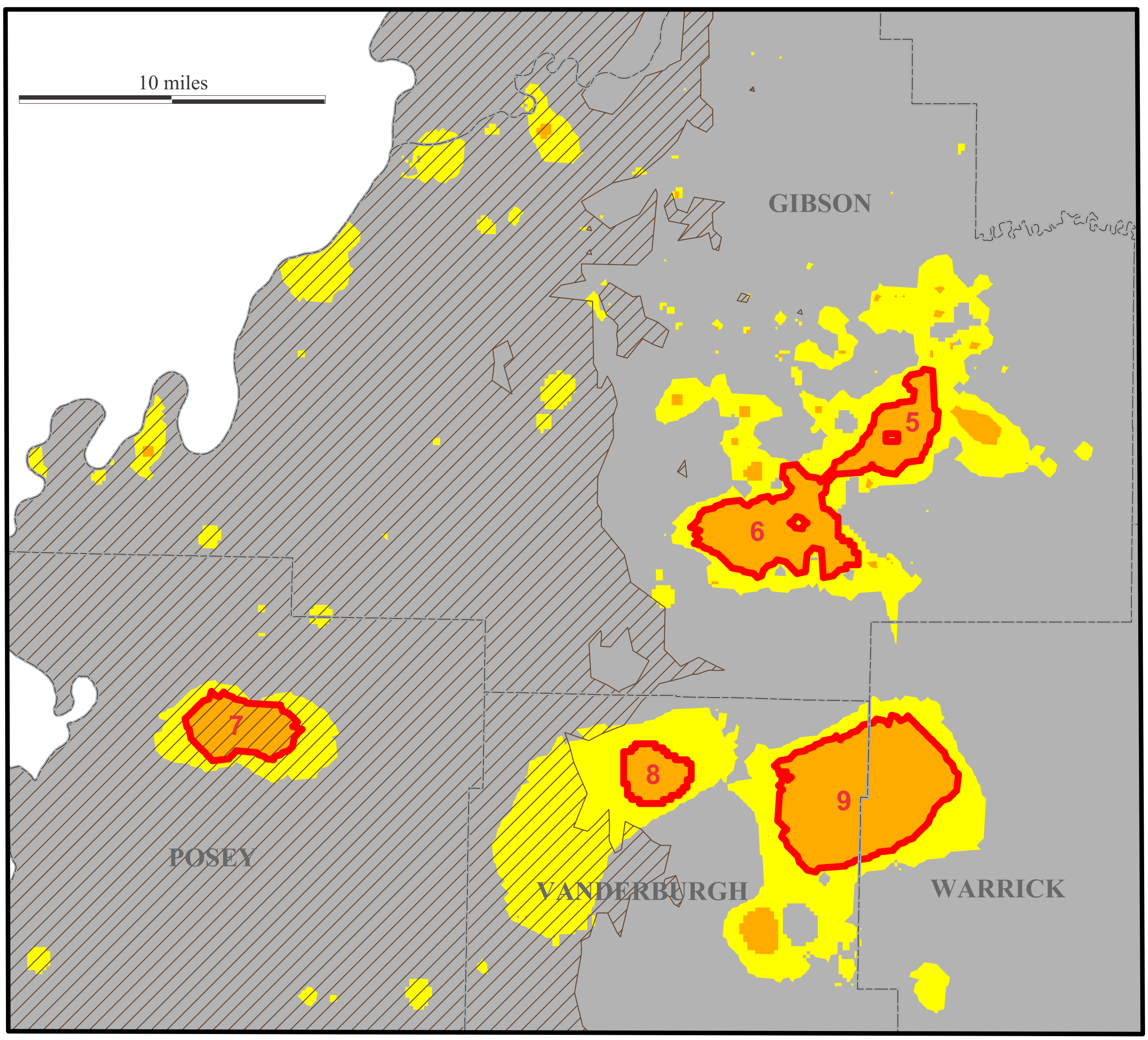
Adequate depth [>60 m] and thickness from 1.5 to 2 m [4.92 to 6.56 ft]

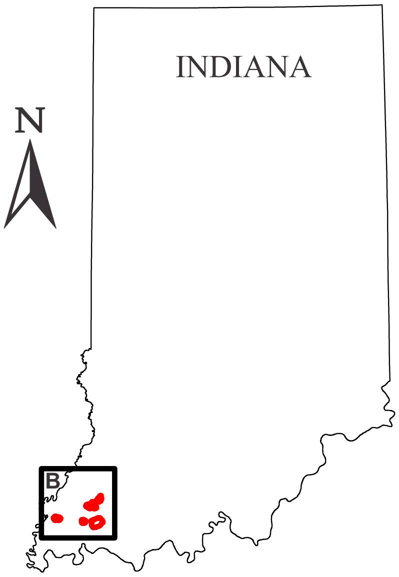
Adequate depth [>60 m] and thickness greater than 2 m [6.56 ft]

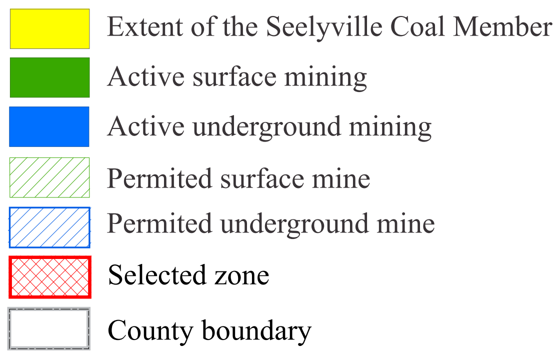
Depth greater than 200.0 m [656.17 feet]

Selected zone

County boundary







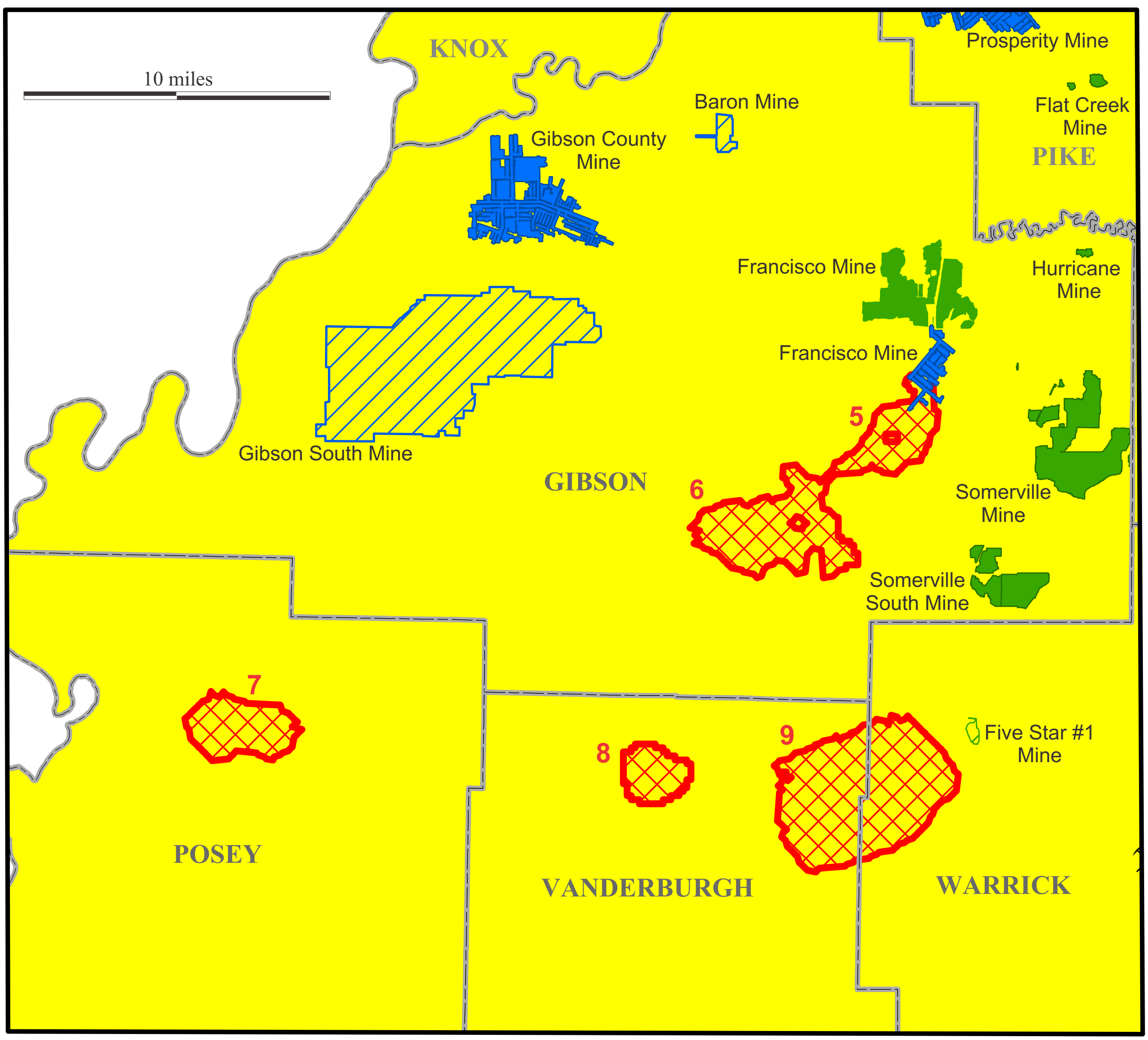


Figure 39. Map of southwestern Indiana showing extent of the Seelyville Coal Member, UCG selected zones and active mining in Area B.

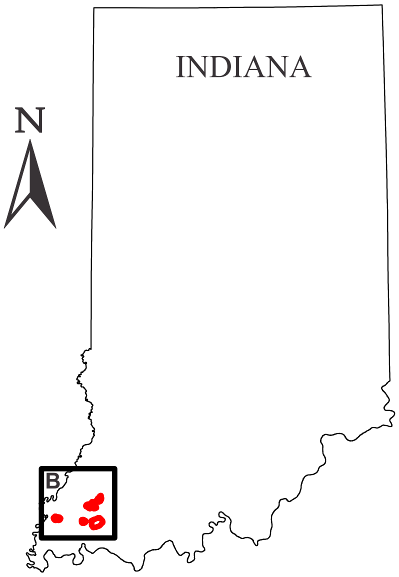
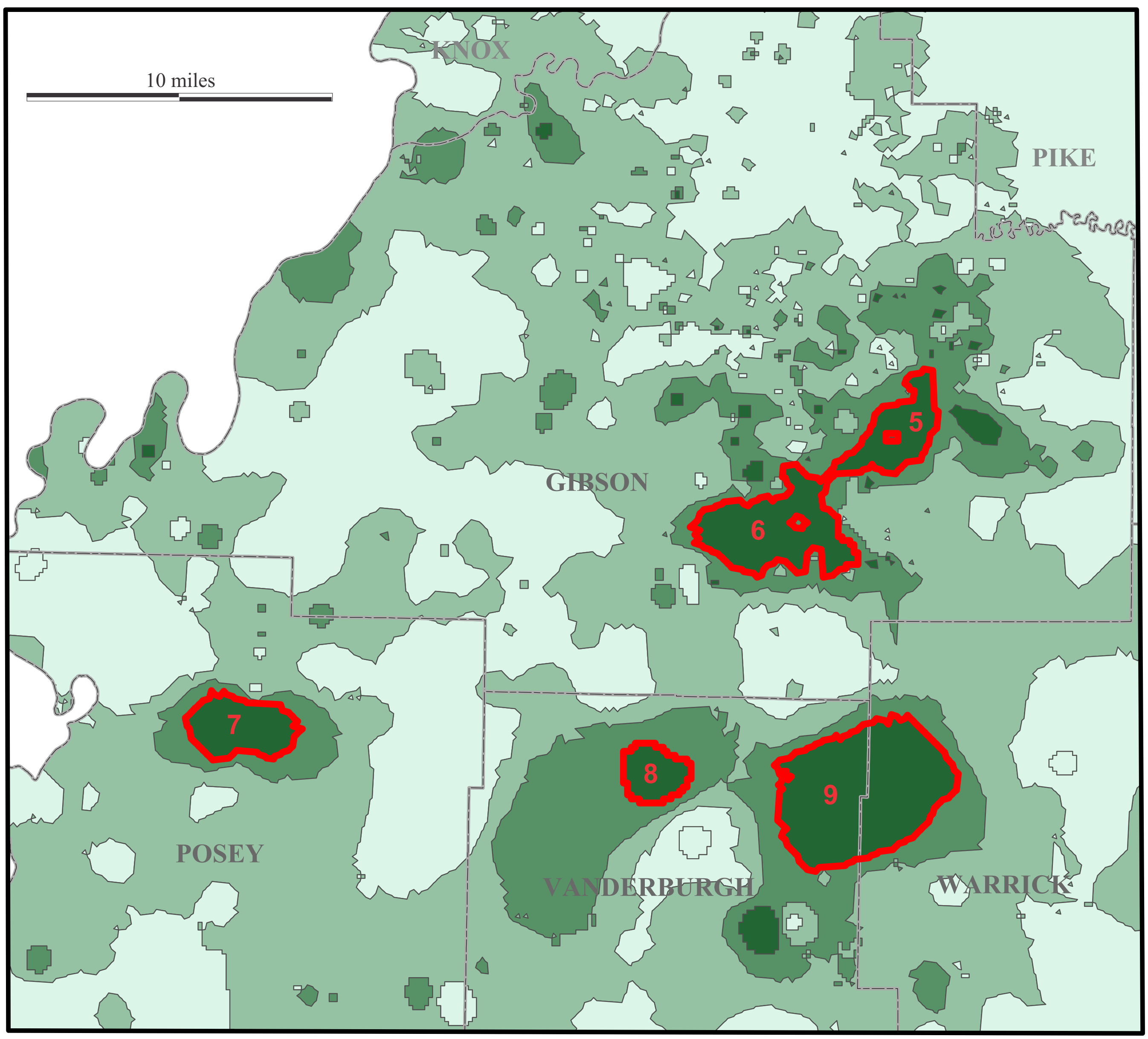


Figure 40. Map of southwestern Indiana showing the Seelyville Coal Member to be considered for underground gasification based on thickness in Area B.

- Less than 1.0 m (3.28 feet) - unacceptable
- 1.0 to 1.5 m (3.28 to 4.92 feet) - low suitability
- 1.5 to 2.0 m (4.92 to 6.56 feet) - medium suitability
- Greater than 2.0 m (6.56 feet) - high suitability
- Selected zones
- County boundary



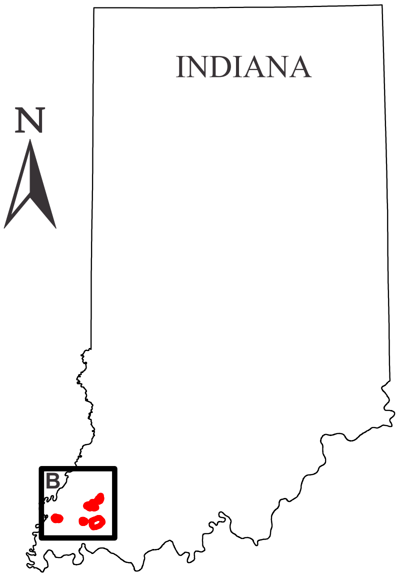


Figure 41. Map of southwestern Indiana showing the Seelyville Coal Member to be considered for underground gasification based on depth in Area B.

60 to 200.0 m (196.85 to 657.17 feet) - low/medium suitability

Greater than 200.0 m (656.17 feet) - high suitability

Selected zones

County boundary

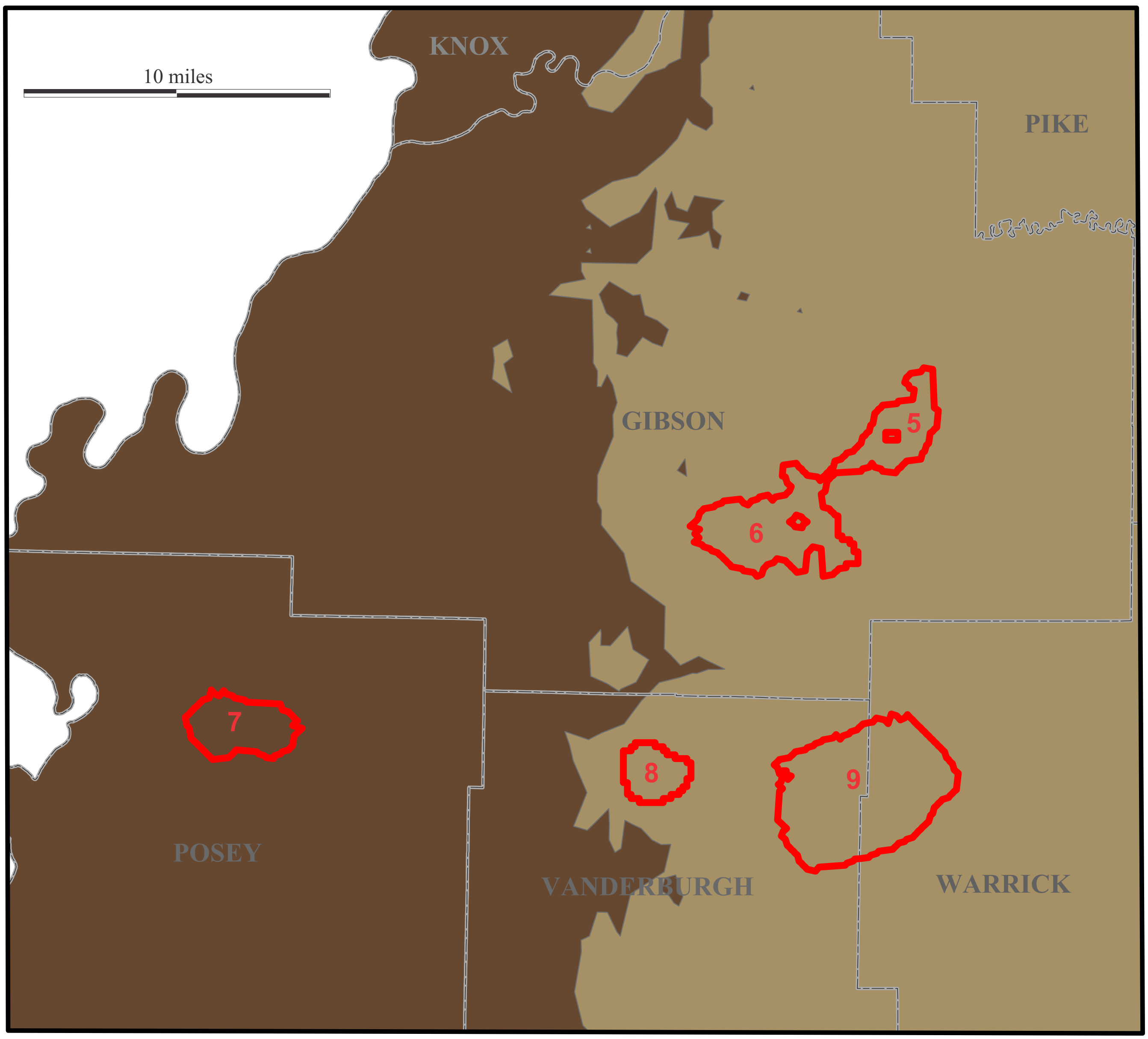
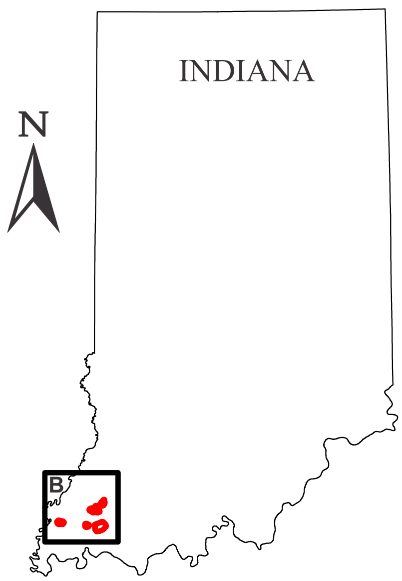
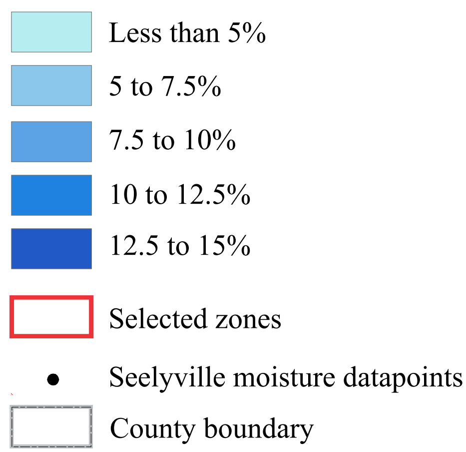
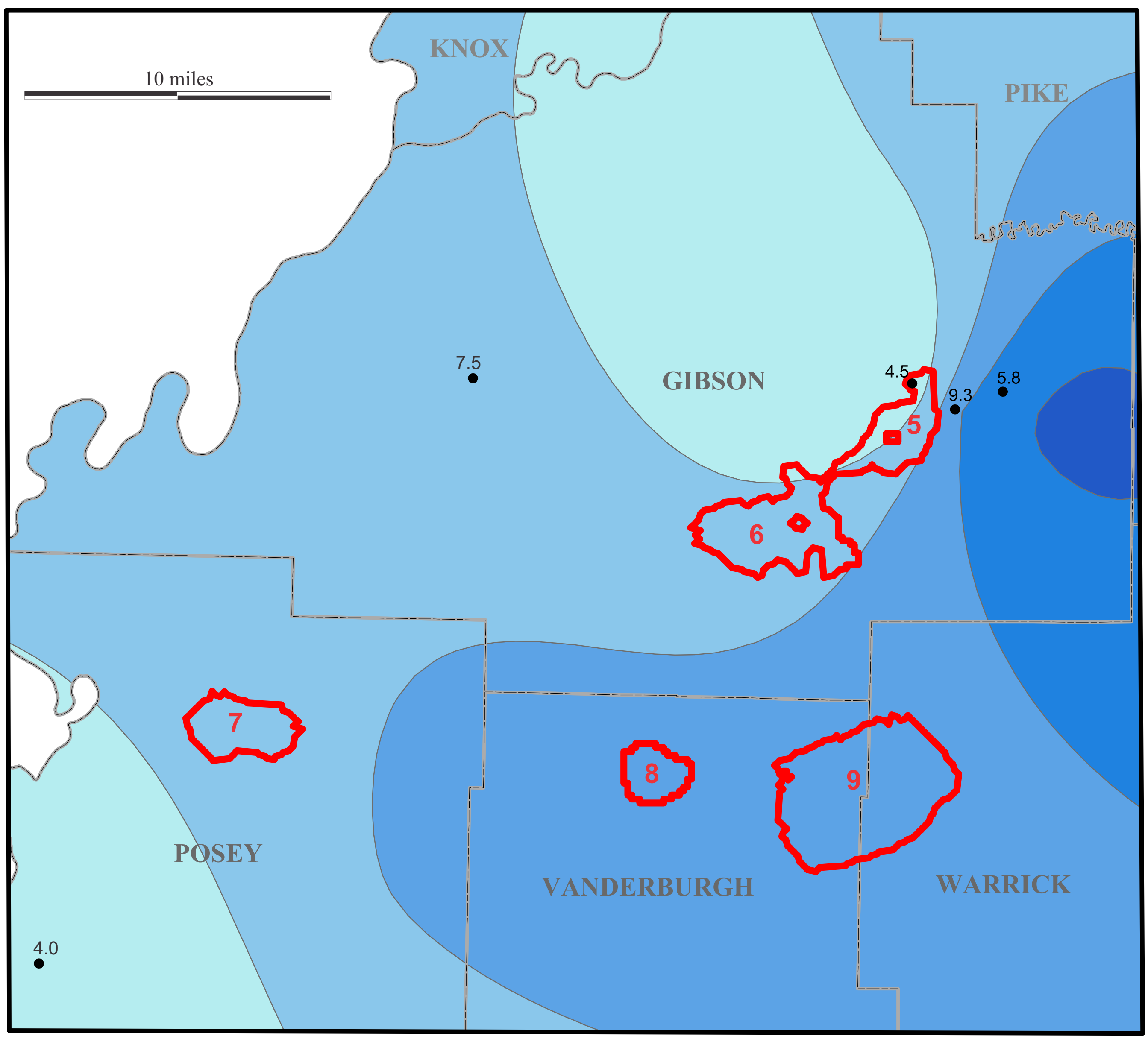


Figure 42. Map of southwestern Indiana showing moisture content of the Seelyville Coal Member in Area B.







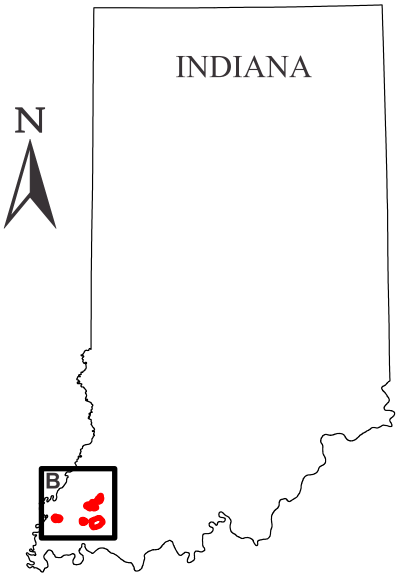
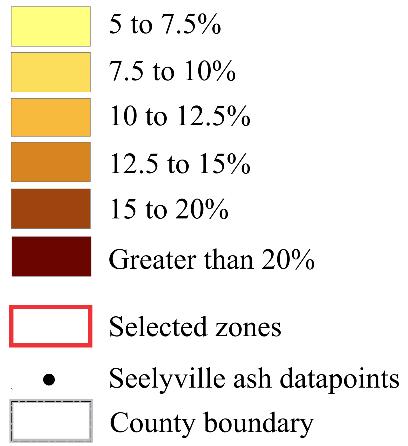
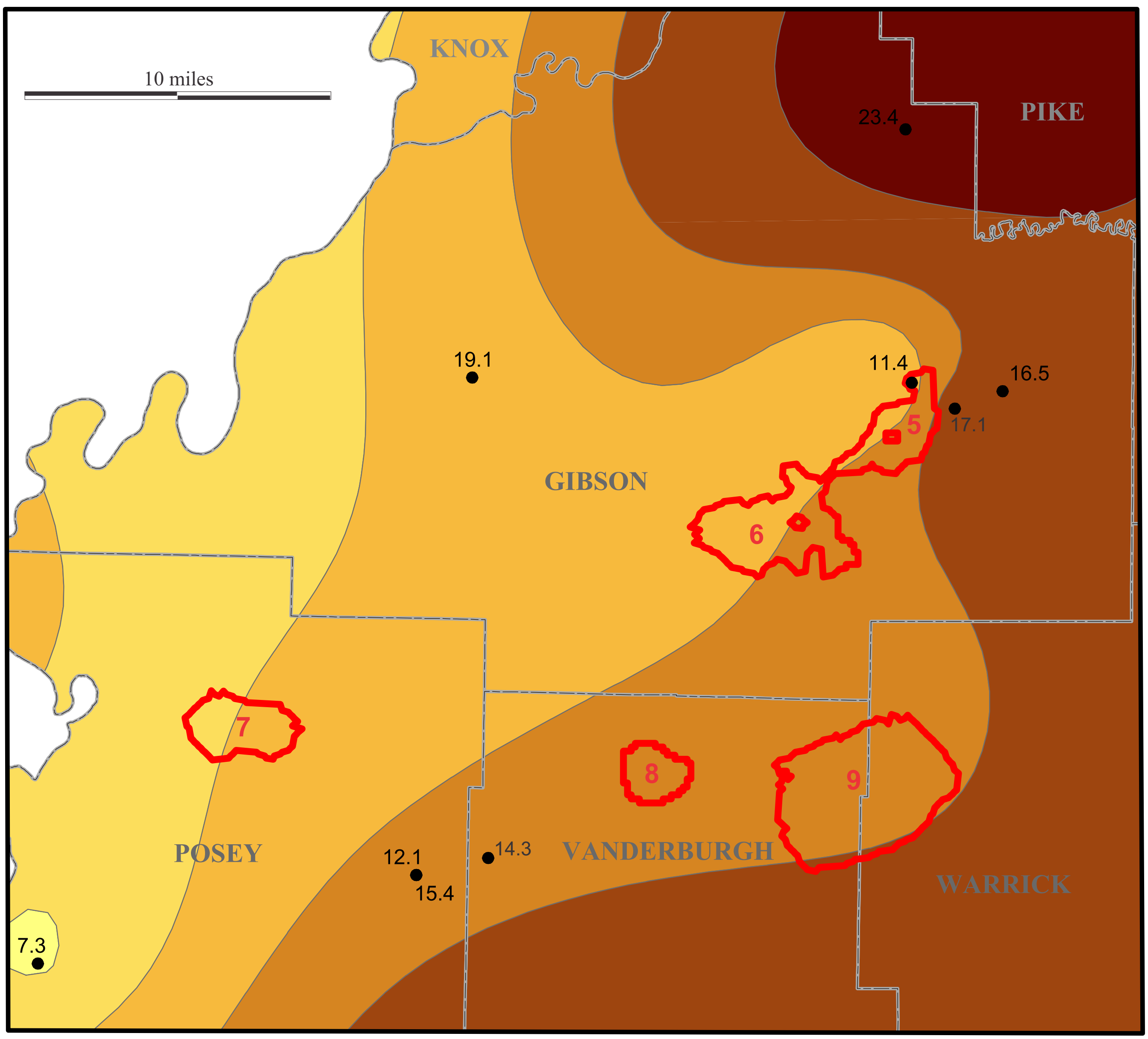
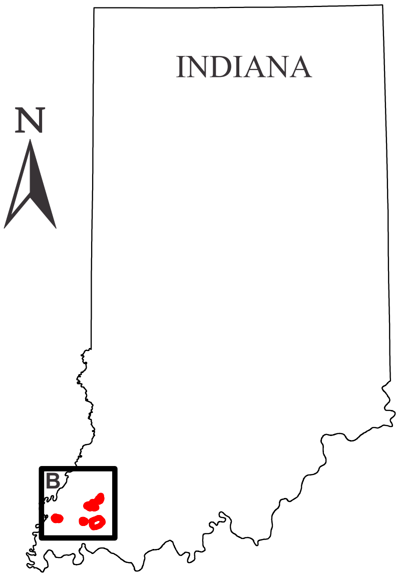
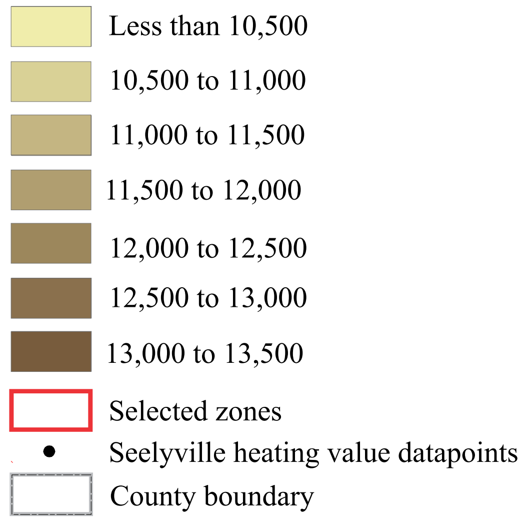


Figure 43. Map of southwestern Indiana showing ash content (dry basis) of the Seelyville Coal Member in Area B.









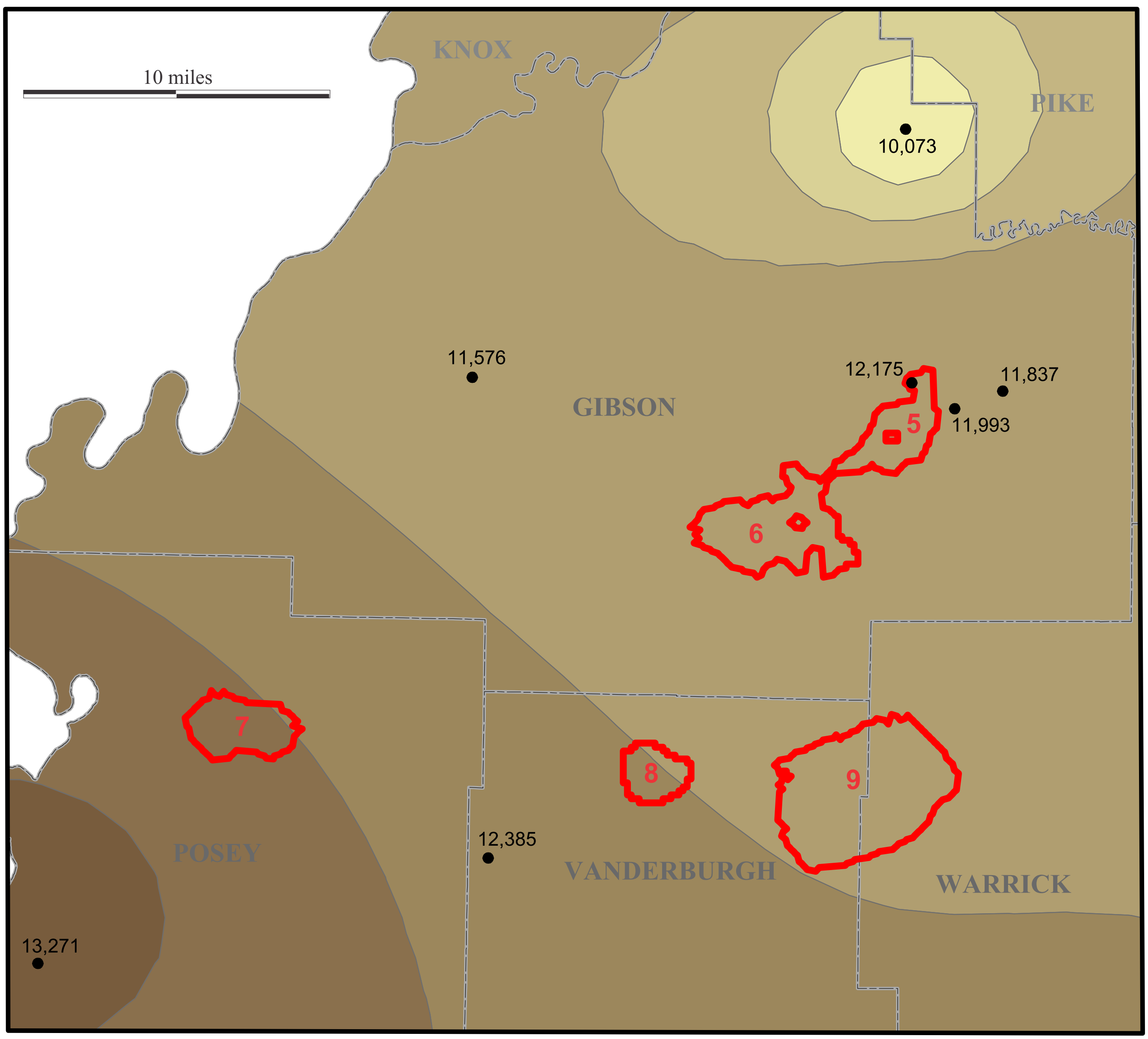


Figure 44. Map of southwestern Indiana showing heating value (Btu/lb, dry basis) of the Seelyville Coal Member in Area B.

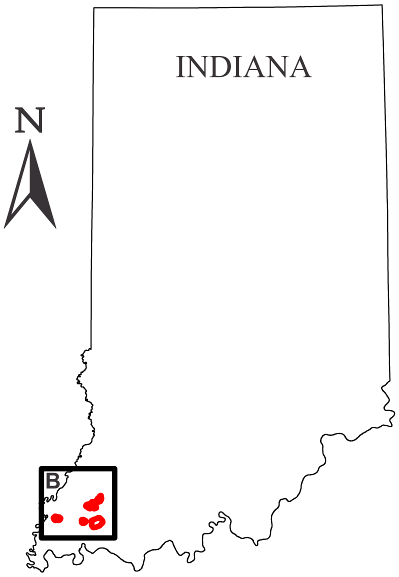


Figure 45. Map of southwestern Indiana showing total sulfur content (dry basis) of the Seelyville Coal Member in Area B.

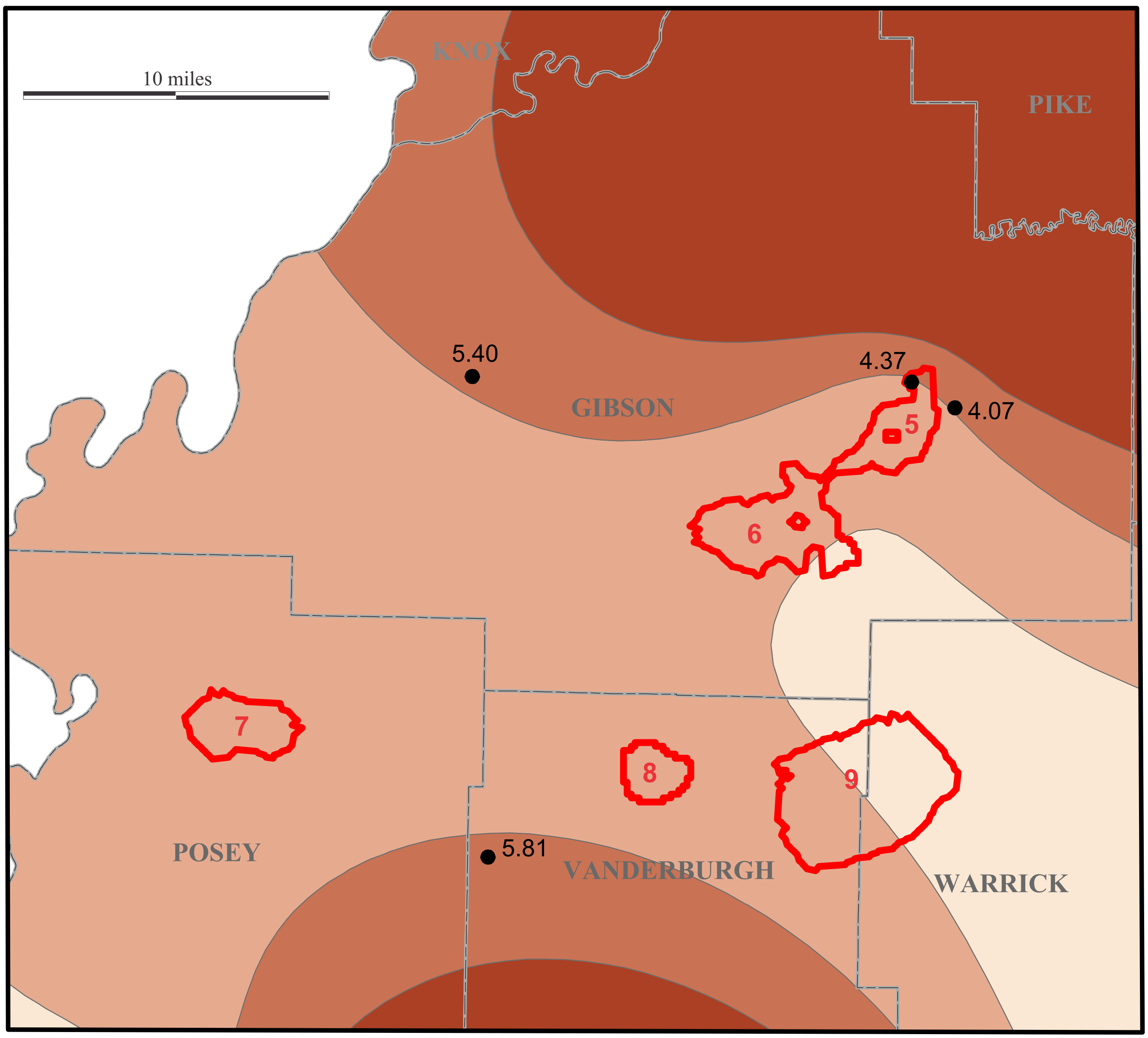
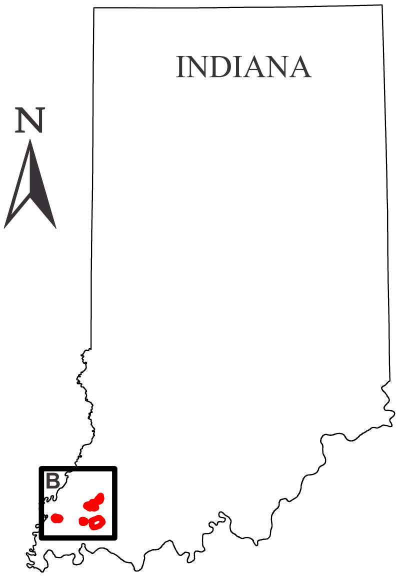


Figure 46. Map of southwestern Indiana showing petrographic composition of the Seelyville Coal Member in Area B.



Extent of the Seelyville Coal Member

Selected zones

Seelyville petrographic composition datapoints

County boundary

V - vitrinite (volume %)
L - liptinite (volume %)
I - inertinite (volume %)
MM - mineral matter (volume %)

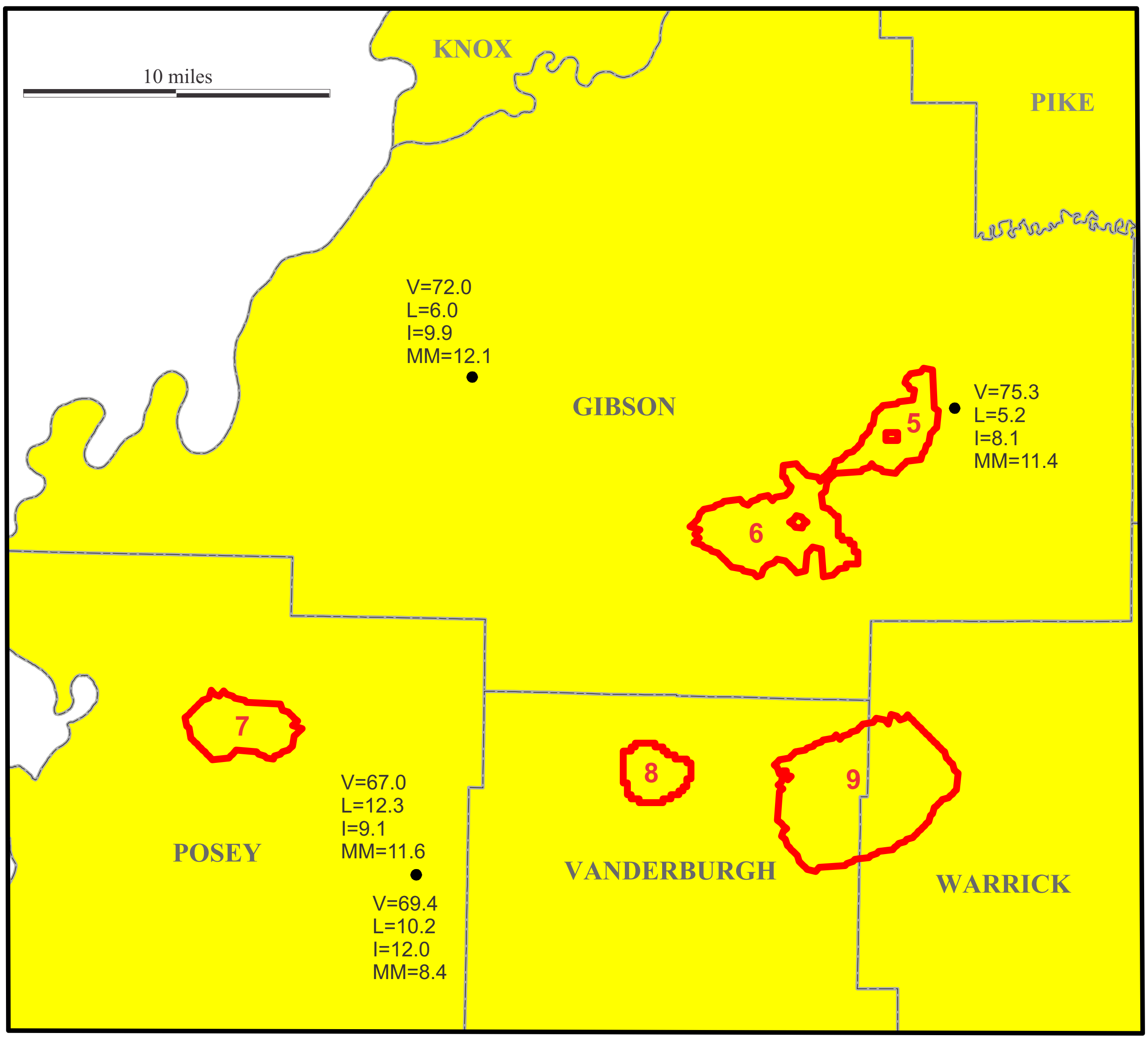


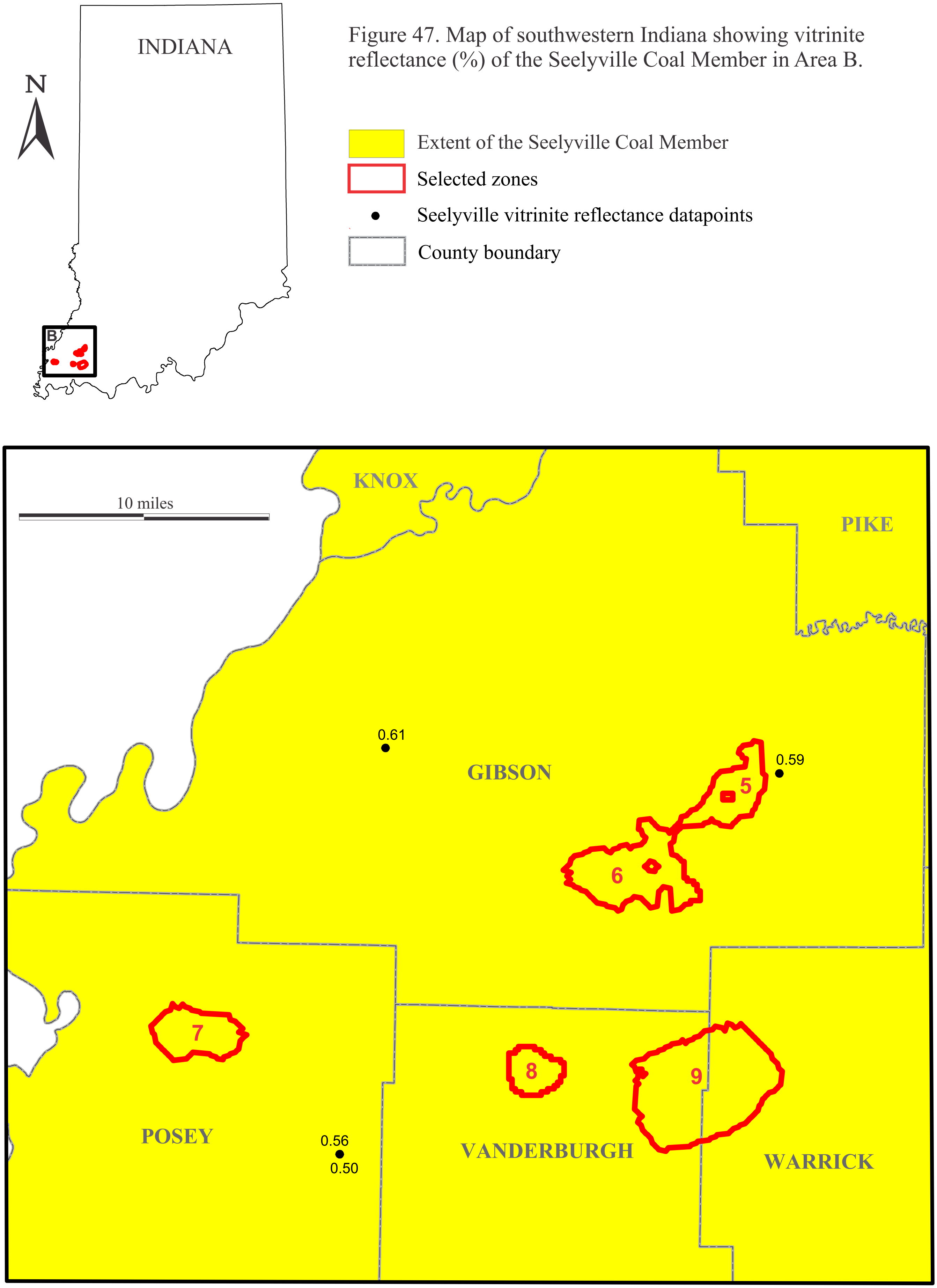
Figure 47. Map of southwestern Indiana showing vitrinite reflectance (%) of the Seelyville Coal Member in Area B.

Extent of the Seelyville Coal Member

Selected zones

Seelyville vitrinite reflectance datapoints

County boundary



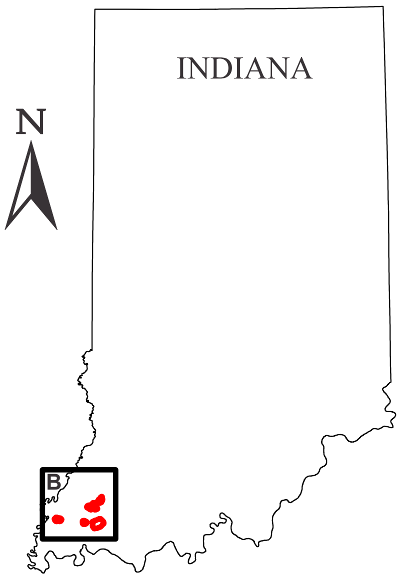


Figure 48. Map of southwestern Indiana showing ultimate carbon content (dry basis, %) of the Seelyville Coal Member in Area B.

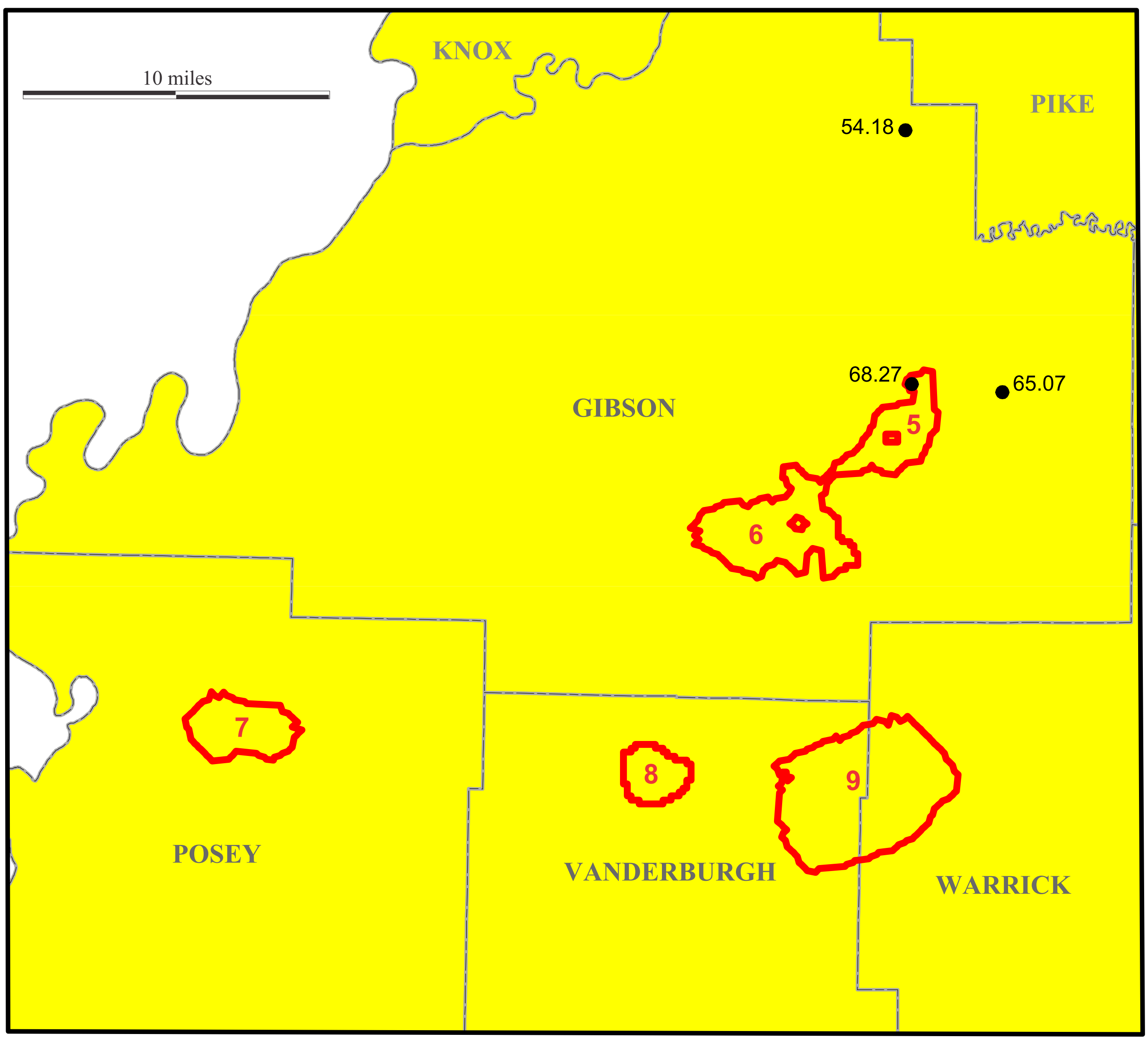
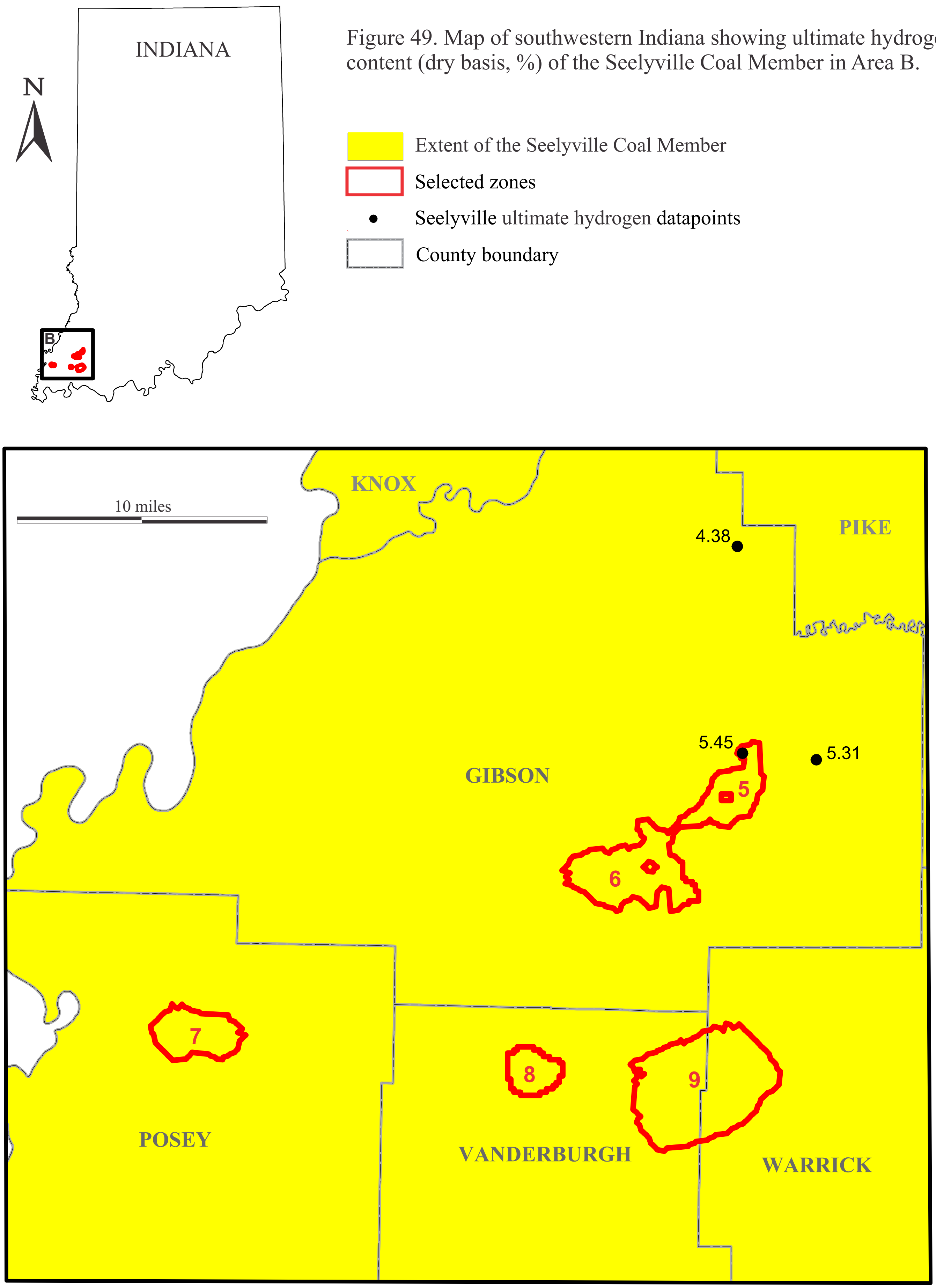


Figure 49. Map of southwestern Indiana showing ultimate hydrogen content (dry basis, %) of the Seelyville Coal Member in Area B.



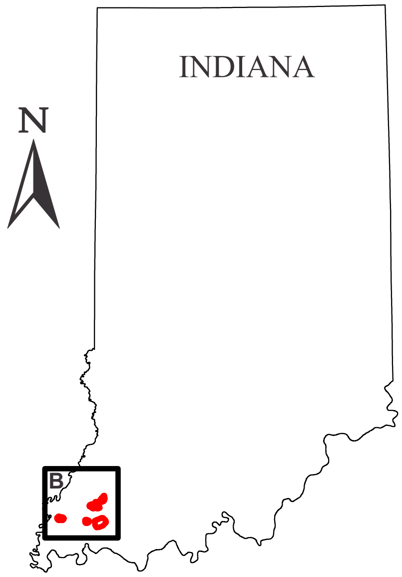


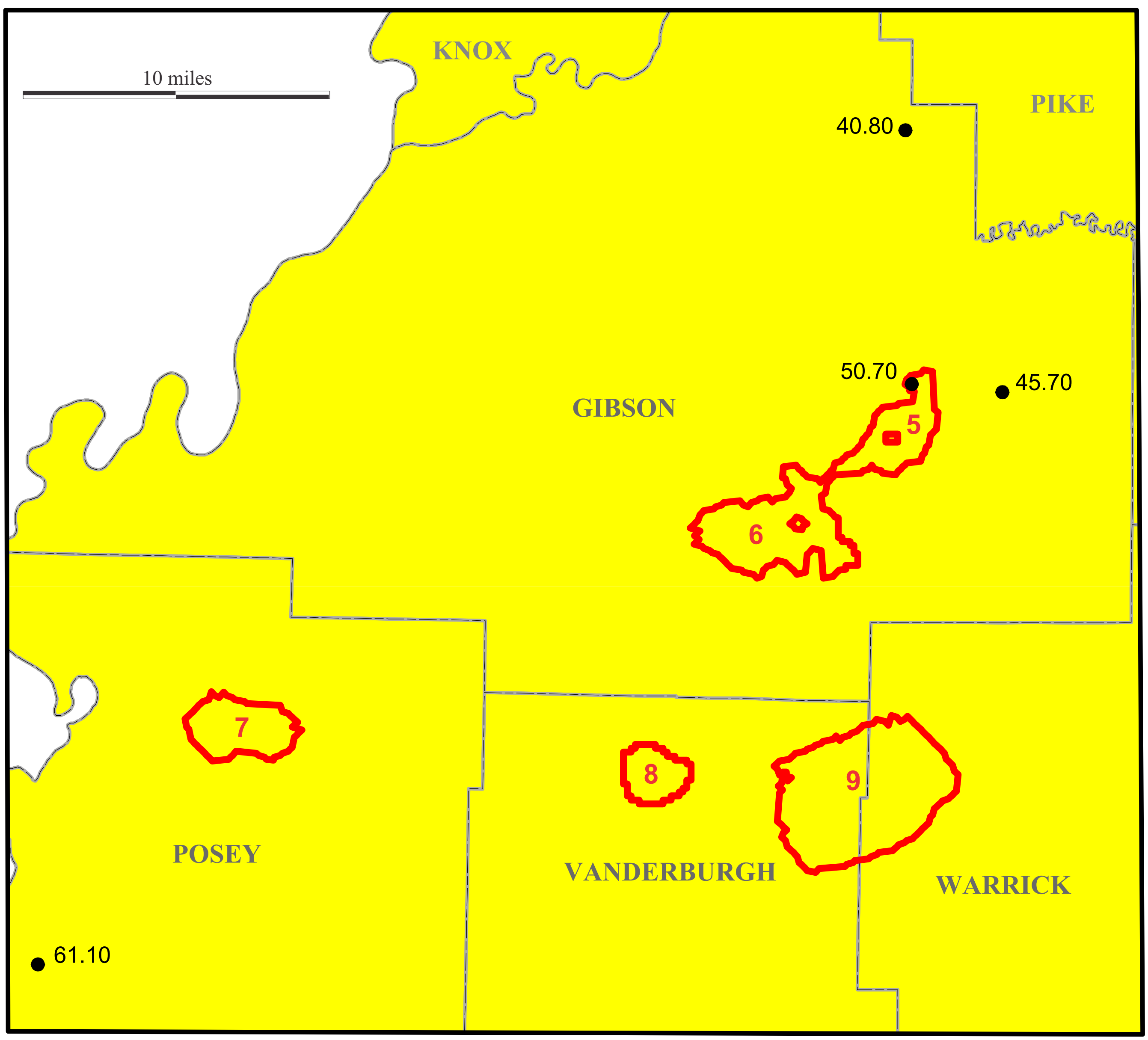
Figure 50. Map of southwestern Indiana showing fixed carbon content (dry basis, %) of the Seelyville Coal Member in Area B.

Extent of the Seelyville Coal Member

Selected zones

Seelyville fixed carbon datapoints

County boundary



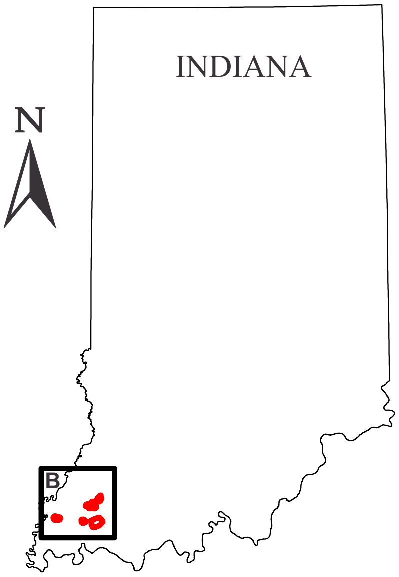
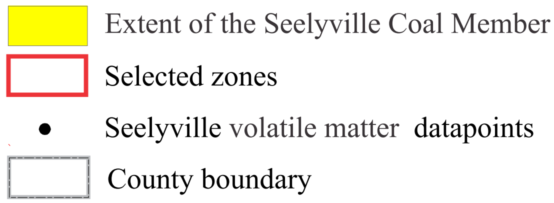
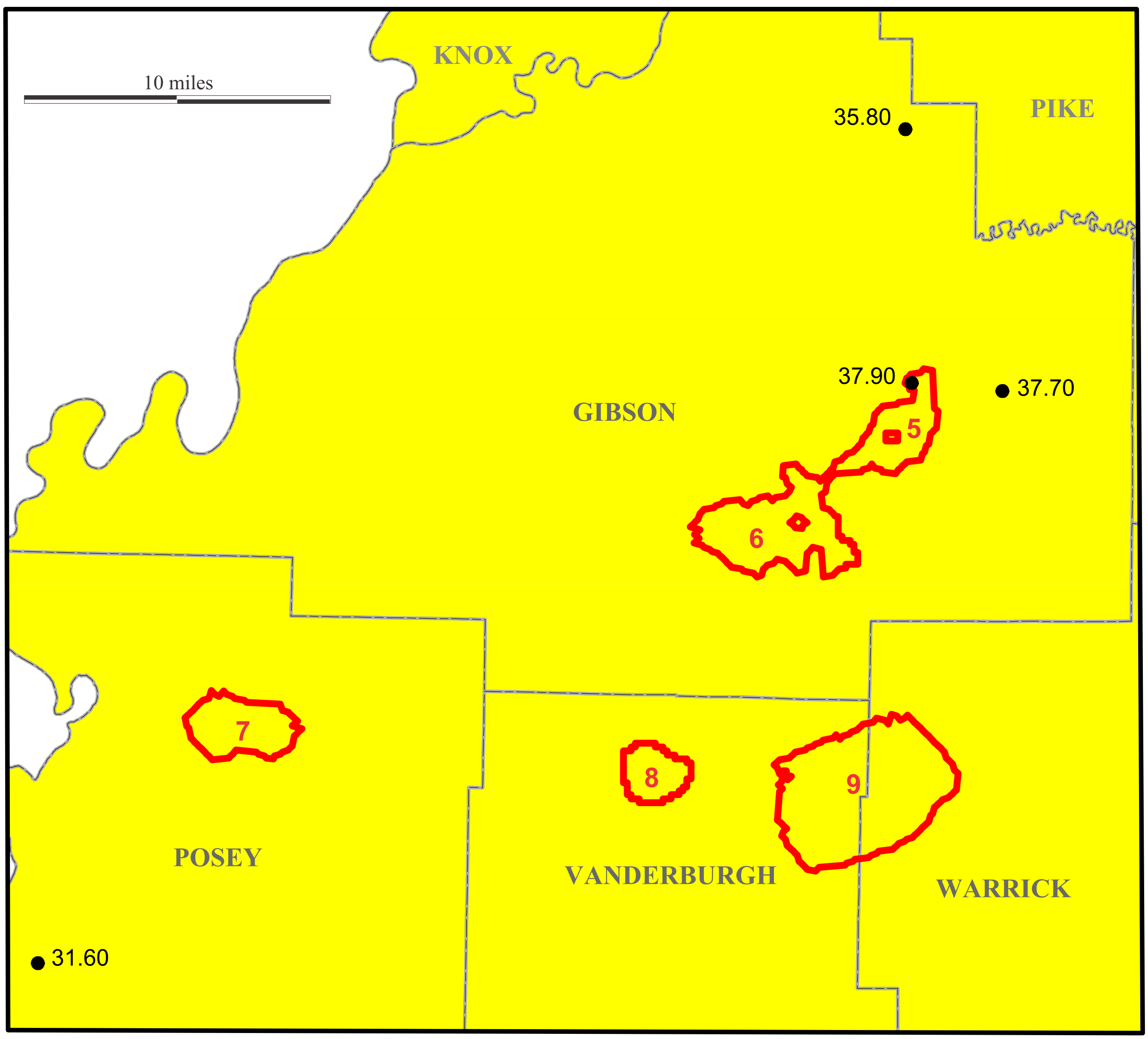


Figure 51. Map of southwestern Indiana showing volatile matter content (dry basis, %) of the Seelyville Coal Member in Area B.





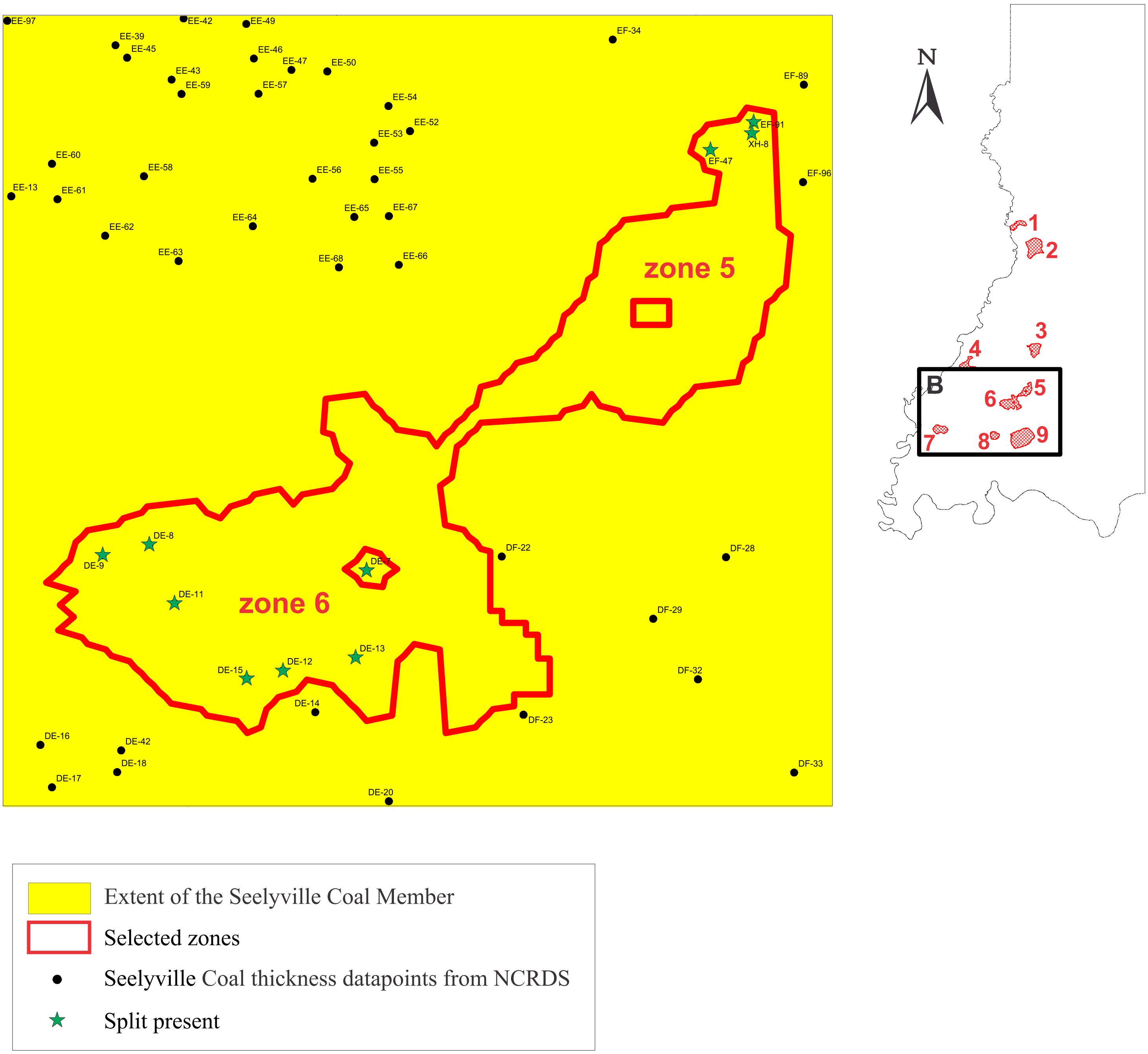


Figure 52. Map of southwestern Indiana showing distribution of thickness datapoints of the Seelyville Coal Member and presence of splits in zones 5 and 6 (Area B). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE! Thc. - thickness.

Table is on the next page

Figure 52. Continued.

Well ID	Top [ft]	Bottom [ft]	Thc. [ft]	Lithology	Notes	Parting thicker than 3.28 ft (1m)	Total coal thc.	Total splits thc.	**% of coal**
EF-47	483.9	487.7	3.8	COAL					
EF-47	487.7	488.0	0.3	Shale	Parting	NO			
EF-47	488.0	488.3	0.3	Underclay	Parting	NO	8.5	1.0	**89.5**
EF-47	488.3	488.7	0.4	Underclay	Parting	NO			
EF-47	488.7	493.4	4.7	COAL					
EF-91	535.5	536.8	1.3	COAL					
EF-91	536.8	537.3	0.5	Shale	Parting	NO			
EF-91	537.3	539.4	2.1	COAL			7.1	1.1	**86.6**
EF-91	539.4	540.0	0.6	Shale	Parting	NO			
EF-91	540.0	543.7	3.7	COAL					
XH-8	503.9	504.0	0.1	COAL					
XH-8	504.0	504.7	0.7	Shale	Parting	NO			
XH-8	504.7	504.8	0.1	COAL			10.1	1.6	**86.3**
XH-8	504.8	505.7	0.9	Shale	Parting	NO			
XH-8	505.7	515.6	9.9	COAL					
DE-11	584.0	587.0	3.0	COAL					
DE-11	587.0	589.0	2.0	No record	Parting	NO	7.0	2.0	**77.8**
DE-11	589.0	593.0	4.0	COAL					
DE-12	554.0	557.0	3.0	COAL					
DE-12	557.0	560.0	3.0	No record	Parting	NO	7.0	3.0	**70.0**
DE-12	560.0	564.0	4.0	COAL					
DE-13	518.0	522.0	4.0	COAL					
DE-13	522.0	525.0	3.0	No record	Parting	NO	9.0	3.0	**75.0**
DE-13	525.0	530.0	5.0	COAL					
DE-15	576.0	579.0	3.0	COAL					
DE-15	579.0	582.0	3.0	No record	Parting	NO	7.0	3.0	**70.0**
DE-15	582.0	586.0	4.0	COAL					
DE-8	611.0	615.0	4.0	COAL					
DE-8	615.0	617.0	2.0	No record	Parting	NO	8.0	2.0	**80.0**
DE-8	617.0	621.0	4.0	COAL					
DE-9	611.0	614.0	3.0	COAL					
DE-9	614.0	617.0	3.0	No record	Parting	NO	7.0	3.0	**70.0**
DE-9	617.0	621.0	4.0	COAL					
DE-7	532.0	535.0	3.0	COAL					
DE-7	535.0	537.0	2.0	No record	Parting	NO	6.0	2.0	**75.0**
DE-7	537.0	540.0	3.0	COAL					

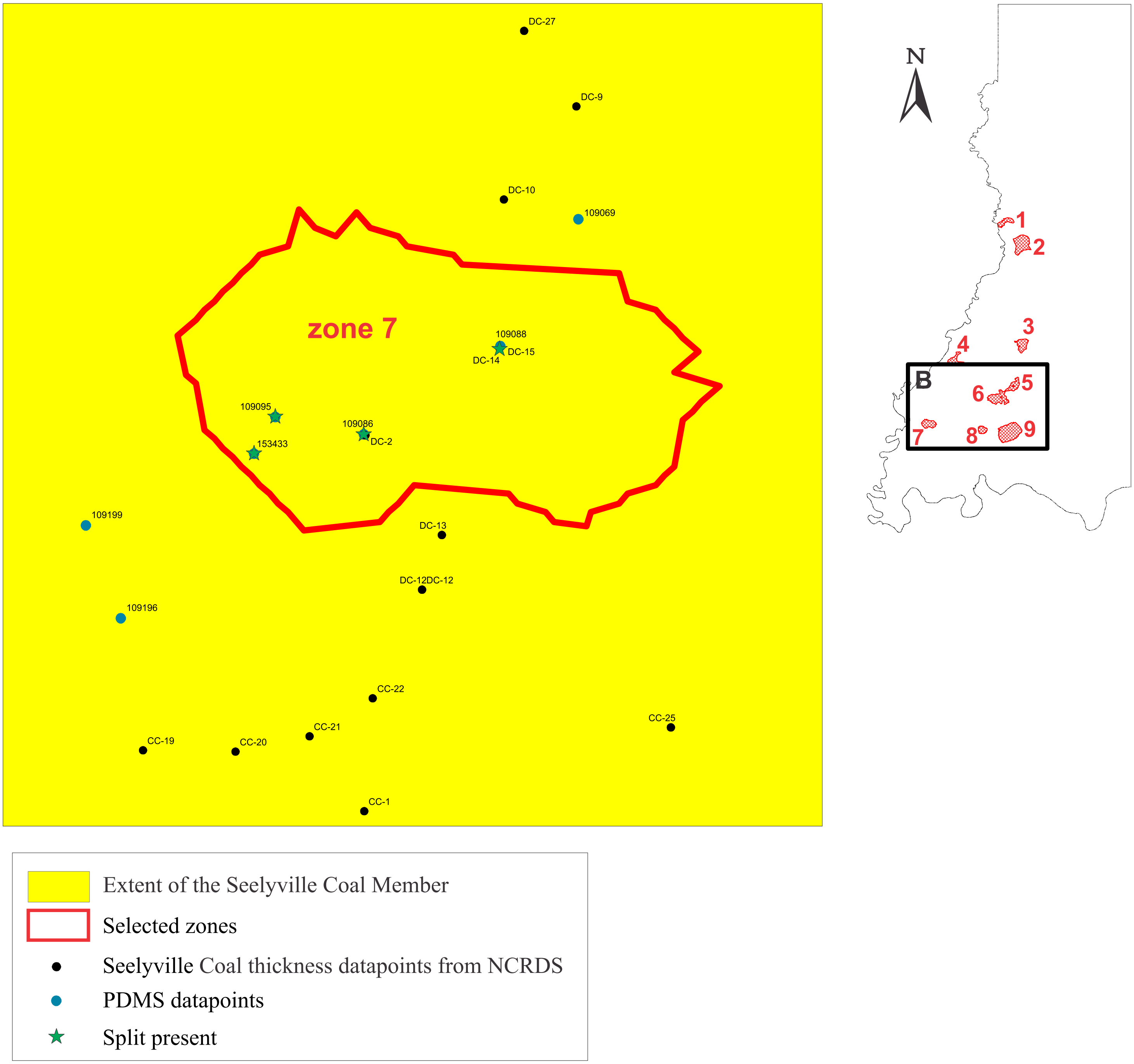


Figure 53. Map of southwestern Indiana showing distribution of thickness datapoints of the Seelyville Coal Member and presence of splits in zone 7 (Area B). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE! Thc. - thickness.

Well ID	Top [ft]	Bottom [ft]	Thc. [ft]	Lithology	Notes	Parting thicker than 3.28 ft (1m)	Total coal thc.	Total splits thc.	**% of coal**
DC-15	956.0	959.5	3.5	COAL					
DC-15	959.5	961.0	1.5	No record	Parting	NO	7.5	1.5	**83.3**
DC-15	961.0	965.0	4.0	COAL					
109088	950.0	954.0	4.0	unknown		unknown			
109086	933.0	944.0	11.0	unknown		unknown			
109095	935.0	941.0	6.0	unknown		unknown			
153433	unknown	unknown	unknown	unknown		unknown			

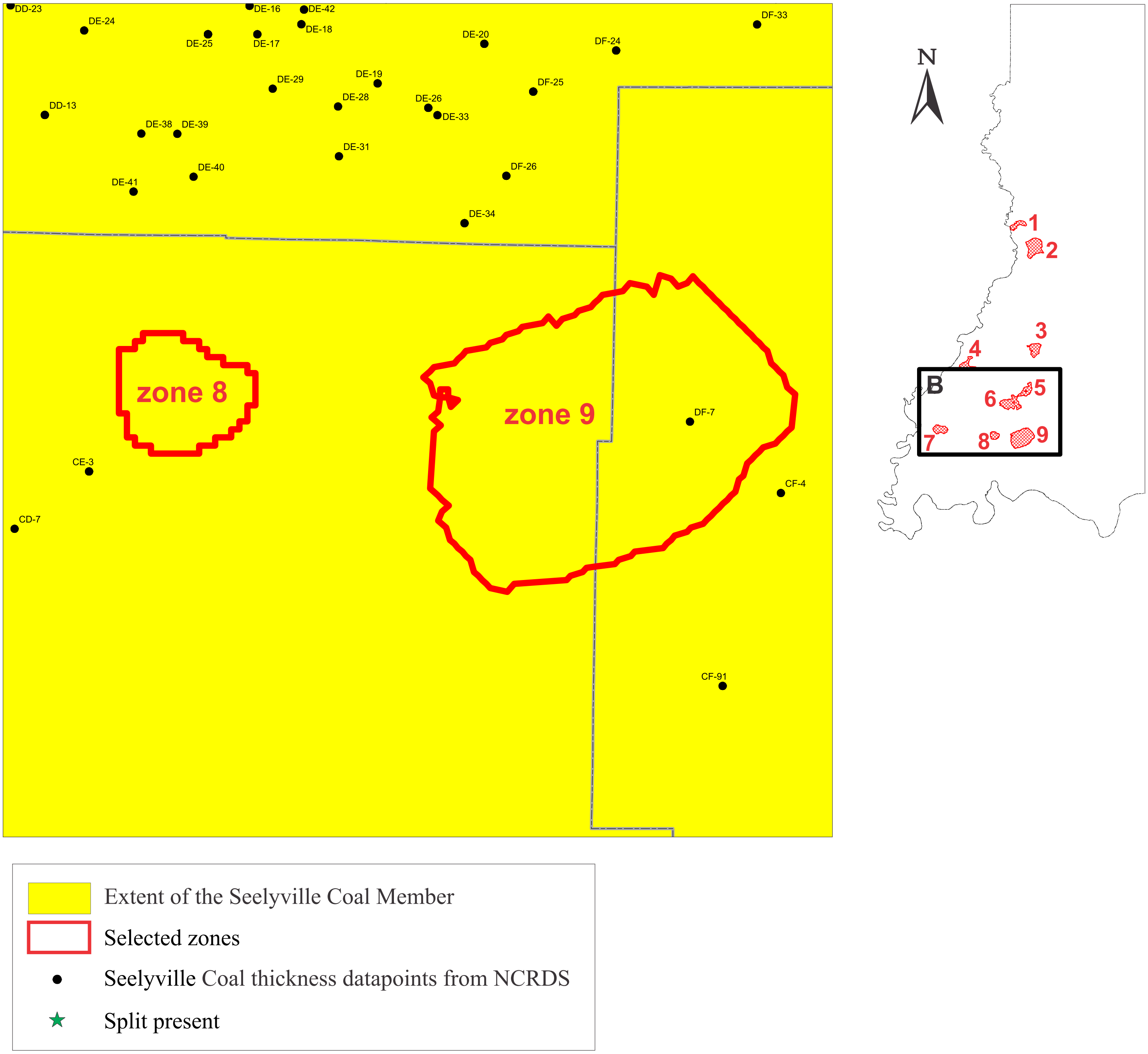
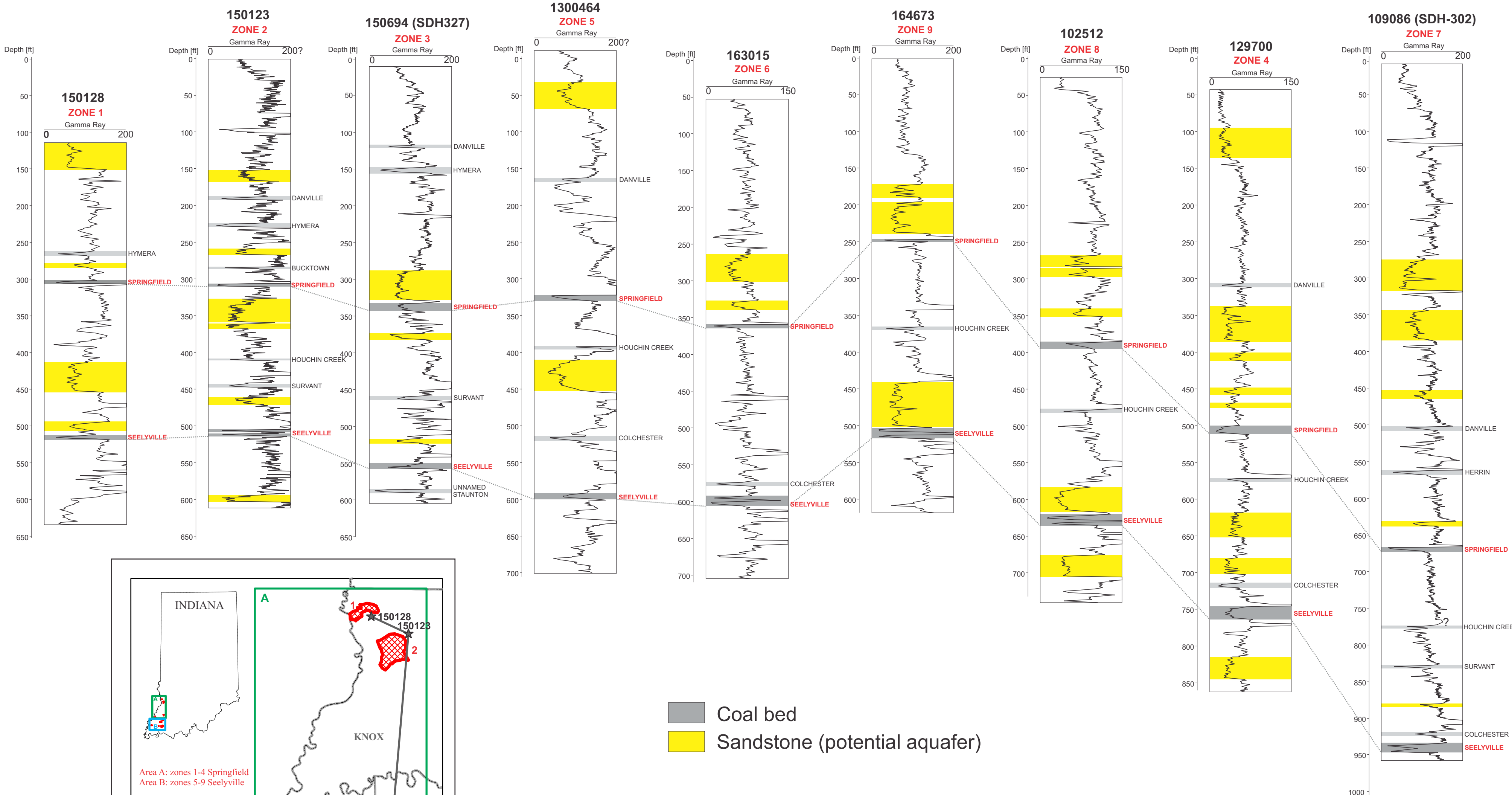


Figure 54. Map of southwestern Indiana showing distribution of thickness datapoints of the Seelyville Coal Member and presents of splits in zones 8 and 9 (Area B). Note: SPLITS WERE INVESTIGATED ONLY WITHIN THE SELECTED ZONE!



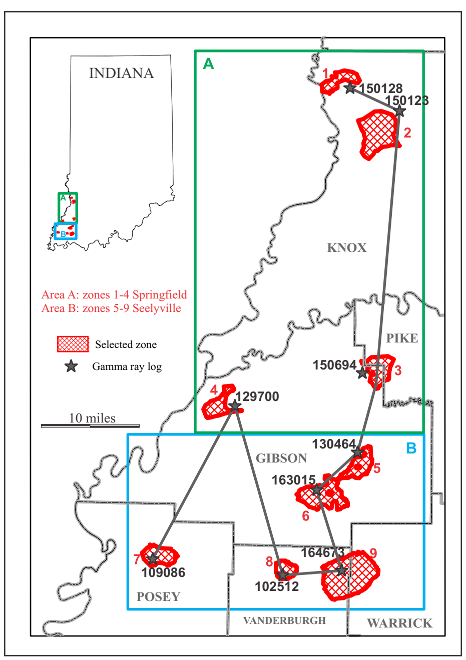


Figure 55. Geophysical logs (Gamma Rays) in or in close proximity to the zones studied. Possible aquifers are indicated in yellow. The Springfield Coal is the target seam for UCG in zones 1-4, and the Seelyville Coal is the target seam in zones 5-9. Appendix 1 presents the figure in a larger scale.

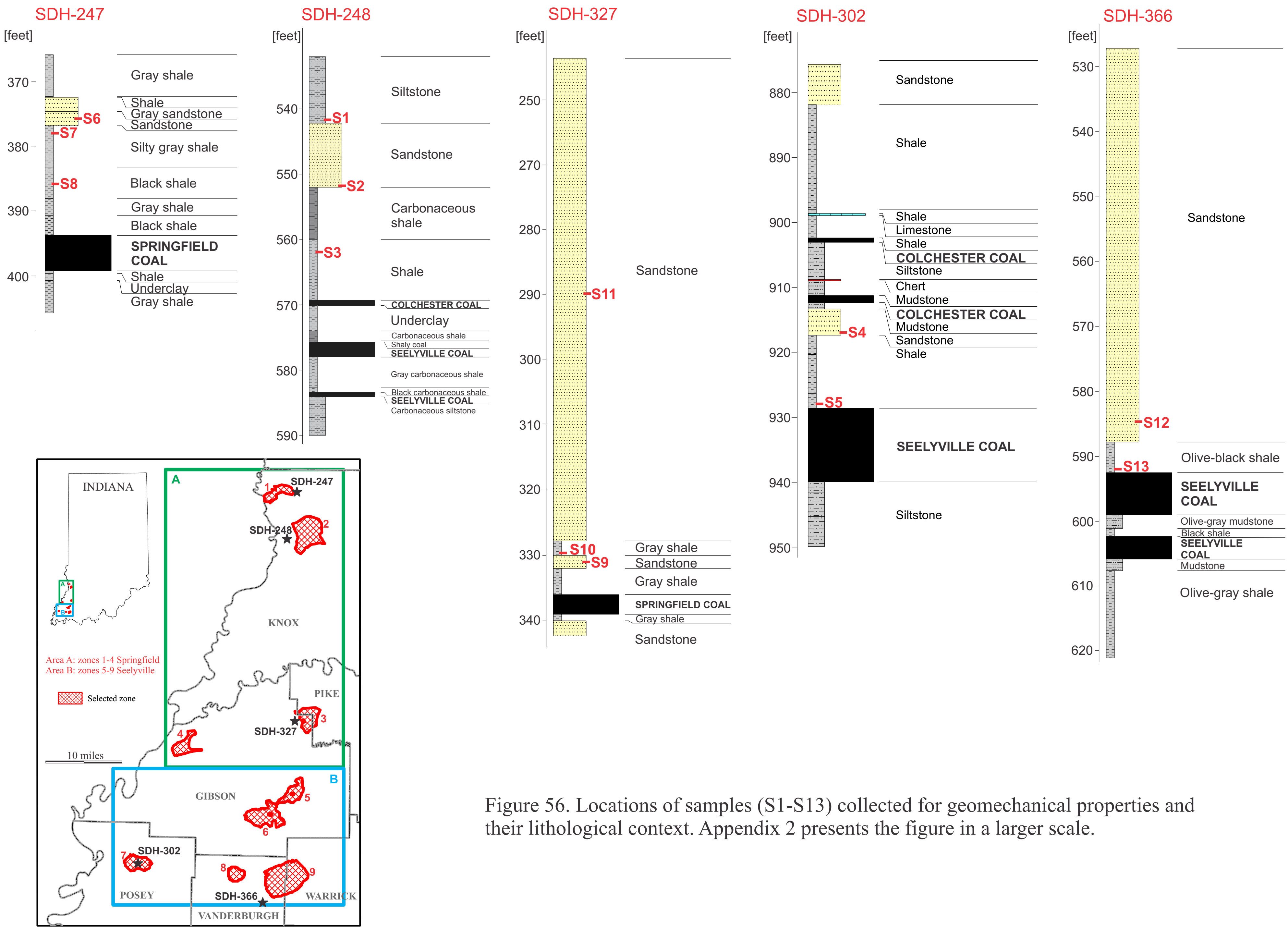


Figure 56. Locations of samples (S1-S13) collected for geomechanical properties and their lithological context. Appendix 2 presents the figure in a larger scale.

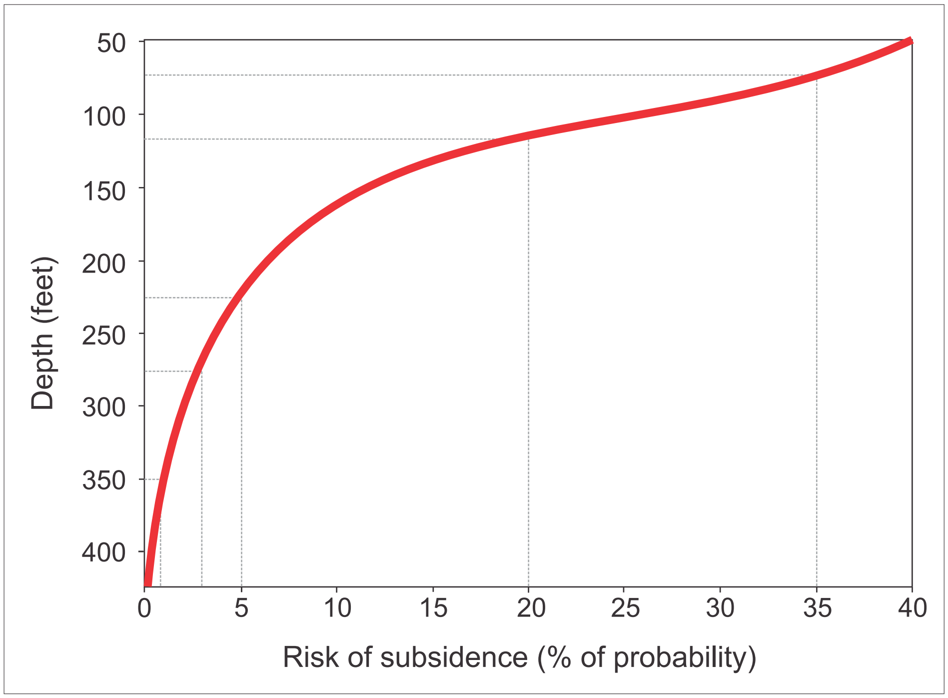


Figure 57. Diagram showing a risk of subsidence (% of probability) versus depth of an underground mine.