CONTRIBUTIONS TO THE STUDY OF COAL

Influence of Structural Irregularities upon the Chemical Character of No. 6 Coal in Franklin and Williamson Counties, Illinois

BY

E. T. BENSON AND G. H. CADY

Distribution of Sulfur in Illinois Coals and its Geological Implications

BY

G. H. CADY

URBANA, ILLINOIS
1935

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INFLUENCE OF STRUCTURAL IRREGULARITIES UPON THE CHEMICAL CHARACTER OF NO. 6 COAL IN FRANKLIN AND WILLIAMSON COUNTIES, ILLINOIS

By Edmund T. Benson and Gilbert H. Cady

INTRODUCTION

Within the large area of the Illinois coal basin, the rank of coals varies through almost the entire range of the high-volatile group, in general increasing southward or southeastward across the basin. The rate of variation within the greater part of the area is so gradual that the chemical character of any bed is well represented by average values for fairly large areas, such, for example, as are represented by individual counties. This is particularly true of the calorific value for the dry, mineral matter-free coal—what has been designated the "unit coal calorific value." County average unit coal values have for several years been recommended by the State Geological Survey as generally applicable to the coal in individual mines in any county.

It has been known for some time, however, that the rate of variation in rank is considerably more rapid across the counties lying along the southern margin of the coal basin than across the counties to the north, so that in Franklin, Williamson, Jackson, Saline and Gallatin counties, analyses of individual samples are likely to vary more from county averages than is the case north of the border belt. Inasmuch as structural conditions affecting the coal beds are more irregular in this marginal belt than elsewhere in the State it has been suspected that variations in the chemical character of the coal, indicative of variations in rank, would eventually, with the accumulation of sufficient analytical and structural data, be found definitely related to structural irregularities. It was also realized that the discovery of such relationships would probably necessitate the eventual abandonment of county average values as the basis for standardization and the adoption of values based upon the character of the coal bed within more natural structural units.

The number of chemical analyses of No. 6 bed coal in Franklin and Williamson counties and the knowledge of the structure of this bed

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1 Assistant Geologist, Coal Division.
2 Senior Geologist and Head of the Coal Division.
are now sufficiently comprehensive to permit interpretation of the relationship between structure and chemical variations within the area of these two counties. The present paper is an attempt at such an interpretation.

POSITION OF THE AREA AND THE AVAILABLE DATA

That part of Williamson County involved in this study with Franklin County constitutes an area of between 600 and 625 square miles lying north of the outcrop of No. 6 coal bed near the south border of the Illinois coal field. Saline and Hamilton counties lie on the east and Perry and Jackson counties on the west. It contains the most important mining district of the State.

The number of mines in the two counties for which two or more analyses of face samples are available is 56, including a considerable number of abandoned mines, mainly in Williamson County. These analyses, which number 241, represent nearly all the shipping mines in the area that have been in operation at one time or another since about 1908. The chemical data under consideration consist of proximate analyses only, representing the determination in each case of one of three laboratories—the University of Illinois Chemical Testing Laboratory, the U. S. Bureau of Mines Experiment Station, Pittsburgh, Pennsylvania, and the Analytical Laboratory of the State Geological Survey. These analytical data have been assembled through a period of more than 20 years.

The structural information in regard to No. 6 coal bed used in this study consists of the records of hundreds of drill holes and numerous mine shafts, most of which have been instrumentally located, the determination of coal bed altitude at drill holes and by mine levels, and the examination of surface outcrops. These data have been compiled in the form of a detailed structure map of the coal bed within the area of the counties, and this map, as is explained below, provides the basis of structural interpretation of the chemical variations of the coal.

BASIS OF CHEMICAL DATA

In order to be readily comparable, chemical data are presented herein on the unit coal basis which is essentially a moisture and mineral matter-free basis. The values which can be so presented are only volatile matter, fixed carbon, and B.t.u. The moisture values are presented, except as indicated, on the mineral matter-free basis in order to eliminate the irregularities due to variations in mineral matter.

UNIT COAL VALUES FOR NO. 6 BED COAL IN SOUTHWESTERN ILLINOIS

For more than twenty years the Illinois State Geological Survey has advocated the use of unit coal values as a basis for comparing coals, having found by experience that these values are notably uniform for unit areas as large as counties or even for larger areas in some instances. The county average unit coal calorific values of coal No. 6 in the entire region west of the DuQuoin anticline (Fig. 1) in southwestern Illinois, that is, southern Sangamon, Christian, Macoupin, Montgomery, Madison, Bond, Clinton, St. Clair, Randolph, Washington, and western Perry counties, varies only between 14,239 and 14,389 B.t.u. (a range of 150 units), except in St. Clair and Randolph counties where values are somewhat higher but do not exceed 14,458 units. In six of these counties the average values are between 14,329 and 14,389 (a range of 60 units). Inasmuch as the range of county averages for the State is about 900 B.t.u., the condition in southwestern Illinois, therefore, is one of great uniformity.

In the case of unit fixed carbon values the county averages of seven of the counties listed is between 50.7 and 52.7 per cent and of the other four between 53.9 and 54.6 per cent. In view of the total range of county averages in Illinois from 47.2 to 58.5 per cent, the narrow range in southwestern Illinois is remarkable.

Moisture values, even on an "as received" basis are also very uniform for No. 6 bed coal in southwestern Illinois. In the northern half of the area (Sangamon, Christian, Macoupin, Montgomery, Madison, Bond and Clinton counties), moisture values vary from 11.9 to 13.3 per cent (a range of 1.4 per cent), and in the southern half of the area (St. Clair, Randolph, Washington, and western Perry counties) from 10.1 to 11.1 per cent (a range of 1.0 per cent). This indicates remarkable uniformity in view of a range of variation of county average values from 4.9 to 17.2 per cent (a range of 13.3 per cent).

Within this area in southwestern Illinois in which the chemical character of No. 6 bed coal maintains such remarkable uniformity, structural conditions are likewise very uniform, the coal bed maintaining throughout, except for minor irregularities, a gentle slope toward the trough of the Illinois basin.\(^4\)

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\(^4\) Analytical data are based largely on tables prepared by the junior author for "Illinois Coal" by A. Bement. Illinois State Geol. Survey Bull. 56, pp. 90-107, 1932. Other data are from the files of the Illinois State Geological Survey.

\(^5\) Kay, P. H., Coal Resources of District VII (Southwestern Illinois): Illinois State Geol. Survey Cooperative Mining Series Bull. 11, Plate 1, 1922.
UNIT COAL VALUES IN FRANKLIN AND WILLIAMSON COUNTIES

The uniformity of unit coal values and of moisture values and their limited range in southwestern Illinois have been described in order that the reader may have a basis for evaluating the variations and ranges of values characteristic of Franklin and Williamson counties with respect to this same coal bed. In these counties the county average "as received" moisture values are less than 10 per cent and show a variation from 9.4 to 6.7, a range of 2.7 per cent; the county average unit carbon values are more than 57 per cent and display a variation from 57 to 58.8 per cent, a range of 1.8 per cent in the two counties. The unit coal calorific values exceed 14,500. Although the county average values for unit B.t.u. show only a relatively narrow range (14,554 to 14,598), individual mine averages show a considerably greater range.

Mine averages are determined by averaging the analyses of two or more, usually three or more, face samples (Table 1). The range of mineral matter-free moisture for the mine averages in these counties is from 6 to 12 per cent, the range of unit volatile matter is from about 35 to about 45 per cent (fixed carbon from about 65 to about 55 per cent), and the range of unit B.t.u. from 14,400 to 14,800 with one extreme value recorded of 14,900.

These variations within a relatively small area, in contrast with the uniformity existing in the larger area to the west of the DuQuoin anticline and in view of the greater amount of structural irregularity existing in the Franklin and Williamson counties area, lead to the natural assumption that the incipient metamorphism indicated by the variations may be solely due to deformation. It will be well to examine other possible causes of variation before definitely accepting such an assumption as correct.

POSSIBLE CAUSES OF VARIATION OTHER THAN DEFORMATION

Variations in moisture.—Variations in moisture content of Illinois coals are due not only to variations in the relative position of coal beds with respect to lines and areas of deformation but also to differences in depth of burial. Within the Illinois coal basin, individual beds show a decrease in moisture content toward the center of the trough of deposition where the original cover was probably greatest. It is likewise generally true that the lower or older a coal in any locality, the less is its moisture content. In considering variations in moisture the possible effect of variations in cover should be taken into consideration.
Table 1—Analytical data (a)

Franklin County

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<th>Unit fix. carbon</th>
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|            |                  |                          |                            |                |                |                                |            |
| Grand average |                  | 10.25                     | 40.03                      | 59.97          | 13086          | 14580                          |            |

(a) All values given are mine averages of individual analyses of face samples, no values based on composites of several samples being used.
(b) Mine numbers used in Cooperative Mining Series Bulletins 3 and 27.
(c) Mines having analyses in addition to analyses appearing in Cooperative Mining Series Bulletin 27.
(d) Mine numbers not used in Cooperative Mining Series Bulletin 27.
(e) Only one B.t.u. determination.
(f) Analysis not included in Figs. 4, 5 and 6.

Variations in volatile matter and fixed carbon.—Variations in volatile matter and fixed carbon are commonly regarded as indicative of variations in the stage of coalification, that is, the rank of a coal. Whether these values are used or some combination of them, such as the fuel ratio (fixed carbon divided by volatile matter), there is, generally speaking, an increase in fixed carbon or fuel ratio toward the southern part of the State. The highest fixed carbon and the highest fuel ratio are in the southern end of the coal basin in the Eagle Valley (Fig. 1) region of southern Gallatin County. On the other hand, the lowest fixed carbon values are in the northwestern part of the State farthest from the region of greatest instability. 6

Table 1—Analytical data (a)

**Williamson County**

<table>
<thead>
<tr>
<th>Mine No.</th>
<th>Date of analysis</th>
<th>Number of samples averaged</th>
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</tr>
<tr>
<td>1921</td>
<td>3</td>
<td>8.35</td>
<td>38.34</td>
<td>61.06</td>
<td>13458</td>
<td>14962</td>
<td></td>
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<tr>
<td>1921</td>
<td>3</td>
<td>9.77</td>
<td>39.34</td>
<td>60.96</td>
<td>13456</td>
<td>14903</td>
<td></td>
</tr>
<tr>
<td>BM 23</td>
<td>2</td>
<td>9.72</td>
<td>35.54</td>
<td>64.46</td>
<td>13275</td>
<td>14704</td>
<td></td>
</tr>
<tr>
<td>BM 25</td>
<td>2</td>
<td>9.72</td>
<td>35.54</td>
<td>64.46</td>
<td>13275</td>
<td>14704</td>
<td></td>
</tr>
<tr>
<td>BM 26</td>
<td>2</td>
<td>8.23</td>
<td>37.93</td>
<td>62.07</td>
<td>13452</td>
<td>14612</td>
<td></td>
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<tr>
<td>BM 28</td>
<td>8</td>
<td>10.67</td>
<td>39.49</td>
<td>60.51</td>
<td>13045</td>
<td>14555</td>
<td></td>
</tr>
<tr>
<td>BM 69</td>
<td>4</td>
<td>10.47</td>
<td>38.74</td>
<td>61.26</td>
<td>13045</td>
<td>14604</td>
<td></td>
</tr>
</tbody>
</table>

Grand average: 8.93 39.44 60.56 13339 14647

(a) All values given are mine averages of individual analyses of face samples, no values based on composites of several samples being used.
(b) Mine numbers used in Cooperative Mining Series Bulletin 3 and 27.
(c) Mines having analyses in addition to analyses appearing in Cooperative Mining Series Bulletin 27.
(d) Mine numbers not used in Cooperative Mining Series Bulletin 27.
(e) Only one B.t.u. determination.
(f) Analysis not included in Figs. 4, 5 and 6.

Fixed carbon and fuel ratio, like moisture content, may reasonably be expected to vary with depth of original cover. This relationship probably exists in the Illinois coal basin although data essential for definite proof are possibly not available.
An additional possible source of irregularity in the content of fixed carbon and volatile matter and the fuel ratio lies in the variations in the physical constitution, that is, the type of the coal. There is undoubtedly some variation in the relative amount of each of the banded ingredients—vitrain, clarain, durain, and fusain—in Illinois coals. Examination of about 30 columnar sections of No. 6 coal bed collected in southern and southwestern Illinois has shown that the amount of vitrain varies systematically between Macoupin and Franklin counties,\(^7\) the coal consisting of 15 per cent or less of vitrain bands in the former county and commonly more than 20 per cent in Franklin and Williamson counties. Furthermore, Illinois coals, and particularly No. 6 coal bed, very commonly contain bands of cannel coal, the presence of which would tend to increase the volatile content of the coal. Such variations in the type of coal present in the bed may account for certain anomalies in the distribution of variations in volatile matter in this as well as in other regions.

Variations in calorific value.—Variations in calorific value will arise for the same reasons that cause variations in the proportions of fixed carbon and volatile matter. Ordinarily an increase in fixed carbon is accompanied by an increase in calorific value, but since the calorific value of hydrogen is considerably greater than that of carbon, the effect of variations in fixed carbon due to regional coalification may be more or less modified by variations in the hydrogen content due to variations in the type of the coal. This is probably a real source of some variation in the calorific value.

STRUCTURAL FEATURES OF FRANKLIN AND WILLIAMSON COUNTIES

The position of the general structural features in Franklin and Williamson counties are indicated in the small maps accompanying this paper (Figs. 2 and 3). These maps are based upon a recently completed revision by the senior author of a structure map of No. 6 coal bed in District VI prepared about 20 years ago by the junior author.\(^8\) Space does not permit its publication at the present time but early publication is planned.

The Franklin-Williamson mining district of No. 6 coal extends northward from the line of outcrop of the coal bed in northern Williamson County, across all of Franklin County to an undetermined distance in Jefferson County. It also includes a small part of both Perry and

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\(^7\) Cady, G. H., Distribution of sulfur in Illinois coals and its geological implications: Table 2. Paper read before Society of Economic Geologists, Dec., 1933. This report pp. 23-41.

\(^8\) Cady, G. H., Coal Resources of District VI: Illinois State Geol. Survey Cooperative Mining Investigations Bull. 15, Plate V, 1917.
Fig. 2—Structure map of coal No. 6 in Franklin and Williamson counties showing distribution of Unit B.t.u. values.
Fig. 3—Outline map showing general relationships of structural deformation and variations of heat value.
Jackson counties east of the DuQuoin anticline not embraced in these studies. Jefferson County is also omitted from consideration because there is only a single mine, long idle, in the county. There are no mines in the eastern tier of townships in Franklin and Williamson counties except in the southeast township of the area. The available chemical data in regard to No. 6 bed coal with which this investigation is concerned applies only to a region about three townships wide from east to west and five long from north to south. As stated, structural data in this area are based upon mine levels, drill hole records and elevations, and upon observations at surface outcrops.

No. 6 coal bed dips north to northeast from its line of outcrop toward the trough of the Illinois Basin which lies beyond the east boundary of the area. The altitude of the coal decreases from between 450 and 500 feet above sea-level at its outcrop to 375 feet below sea-level in the northeast part of Franklin County. In the northeast part of the area the strike of the beds is nearly north and south. To the south the strike gradually swings around to a nearly east and west direction along the line of outcrop of the coal bed in Williamson County. The west boundary of the district is the DuQuoin anticline.

There are three local structural features of importance in this study: (1) From the outcrop of the bed northward to the Campbell Hill–Cottage Grove belt of deformation in southern Franklin County on the west and northern Williamson County on the east there is an area of comparatively steep northward dip; (2) a line or belt of structural irregularity consisting of faults and reverse dips extends slightly north of west from about six miles south of the north line of Williamson County on the east to about the common corner of the two counties on the west side of the area. This line of deformation is along the eastward projection of the Campbell Hill anticline on the west9 and the westward projection of the Cottage Grove10 or Harrisburg fault on the east; (3) a third belt of minor deformation extends slightly west of north from central Williamson County through the northern part of Williamson County to a position west, but about the latitude, of Benton. The belts of irregularity intersect northwest of Johnston City.

Within these belts of structural irregularity the characteristic deformation is faulting accompanied by a general sharp decrease in the altitude of the coal bed north and east of the two belts. In the case of the north-south aligned area the deformation appears to extend northward from the most northerly reported faults in a moderately inclined monoclinal dip to the east.

INTERPRETATION OF CHEMICAL VARIATIONS

Intercorrelation of variations.—Determination of any possible relationship among the three values, moisture, B.t.u., and volatile matter (or fixed carbon) was desirable and to this end the three values were plotted against one another in various ways. Calorific value was plotted against moisture (Fig. 4) and against fixed carbon (Fig. 5) and moisture against fixed carbon (Fig. 6). These graphs failed to show that any consistent relationship existed among these values except that certain coals from the southeast portion of the area in Williamson County appeared to possess both low moisture and high volatile content. In general there was an increase in calorific value in the southeast portion of the area. The charts gave no indication that moisture decreases systematically as B.t.u. values increase or that fixed carbon systematically increases with calorific value. In view of such results it was obviously undesirable to combine the B.t.u. value and moisture value to provide what might be called a moist unit B.t.u. value since the result would be a value more irregular than either value by itself (Table 1, Col. 5).

An incidental result of the study of the distribution of moisture values was the discovery of a distinct difference between values determined before and later than 1920 (Fig. 4 and Table 1). All but three of the values plotted above the line of 9.5 per cent moisture were determined before 1920, whereas all moisture determinations made since that date lie at positions below that line except the three previously
noted. Except for certain analyses of coals from mines located in the southeastern part of the area showing moisture values less than 8 per cent, there appears to be no reason why certain of the coals of one group should consistently have higher moisture content than coals of the other group. We are not aware that any significant changes in methods of analysis were made about 1920, but differences in analytical procedure is the most obvious explanation of this variation in moisture value. The matter is mentioned to call attention to one of the uncertainties that may prevent correct interpretation of variations in the items of the proximate analysis for a group of coals when values involved in the study represent results obtained through an extended period of years. Real differences or similarities may be obscured by variations due to slight changes in analytical procedure, or even changes in

![Figure 5](image-url)
laboratory personnel, the effects of which or even the existence of which were unperceived at the time the analyses were run.

This graphical study of the relationships of moisture, volatile matter, and calorific values indicates that the coal from that part of the bed in the southeastern portion of Williamson County is distinctly different from the coal in other parts of the area. The moisture and volatile matter chart (Fig. 6) shows rather distinctly two groups of coals, one with low moisture and fairly high volatile matter and a much larger group with moisture content in excess of 8 per cent. Within each of these groups there may be a tendency of the moisture to increase with the volatile matter. This is little more than a suggestion of a possible relationship. The relatively high volatile character of the coals in the southeastern part of the area may be due to a difference in type as compared with coals in the central part of the area. This possibility will be discussed further in a later paragraph. The general decrease in moisture content seems to be toward the east, that is, toward the trough of the basin, but this does not accord entirely with the decrease in volatile matter as it might be expected to do. Similarly, a systematic increase in calorific value does not accompany the due eastward decline in moisture values.

Correlation of variations in chemical values with structure.—In order to determine possible relationships between variations in chemical values and structure, the three values were plotted on the large structure

![Fig. 6—Relation of unit volatile matter and mineral matter-free moisture.](image-url)
map and contours were constructed to indicate the distribution of variations of each value. The procedure failed to reveal definite agreement in the distribution of variation among the values with respect to their relationship to the structure and only in the case of the variations in B.t.u. values did there appear to be definite correlation with the structure. The iso-caloric maps (Figs. 2 and 3), reproduced from the larger map used in the compilations, illustrate the relationship. It may be observed that the line of 14,600 B.t.u. fairly definitely coincides with the north side of the belt of east-west deformation in the east part of the area, bending northward along the belt of north-south deformation to about the position of Sesser from which point it bends southward and follows the west side of the north-south belt of deformation until it again bends toward the west along the north side of the east-west belt of deformation. The coal everywhere north of this line in this area is characterized by less than 14,600 units in heat value on a unit coal basis. In general the coal south of this line has a unit coal B.t.u. content of at least 14,600 units, except near the outcrop of the bed in the west part of Williamson County. In east Williamson County, towards the outcrop of the bed, the calorific value of No. 6 coal rises to above 14,700 B.t.u., one mine in this part of the area having an average B.t.u. value of over 14,900 units. This distribution of variations of calorific values in the area is clearly in accord with the distribution of zones of deformation and likewise responds to approach to the adjacent area of the Ozark uplift.

Certain anomalous values were observed. Within Williamson County, in which the unit calorific value of the coal is generally in excess of 14,600 B.t.u. there are mines (Nos. 156, 158) for which average values less than 14,500 B.t.u. are recorded. These values are based on analyses determined by the same laboratory at about the same time. The mines are practically surrounded by others having values above 14,600. It has been impossible to check the analytical values as the mines have been temporarily or permanently abandoned. However, four face samples collected and analyzed in February, 1934, from an adjacent active mine (No. 155, Table 1) which by earlier analysis showed an average unit B.t.u. value of 14,465 gave an average of four recent analyses of 14,645, an increase of 180 units over the previous value for this mine. Since this new value is in agreement with the regional average it seems probable that the earlier results are not correct. The inference is that the low values recorded for the two mines noted early in the paragraph may also be wrong, but unfortunately this cannot now be determined by check analyses.
With respect to either moisture or volatile matter (or fixed carbon) values no systematic relationship to the structural features can be discovered. There is possibly a general decline in moisture content toward the east, possibly due to the probable increase in depth of original cover in that direction. Variations in volatile matter content are erratic, due possibly to slight variations in the constitution, that is, the type of the coal from place to place in the area. In general, it will doubtless be recalled, No. 6 coal bed is very thick—up to 14 feet—in certain parts of Franklin County, and that an area in which the coal is more than 8 feet thick occupies a large part of the west half of Franklin County, extending southward in a V-shaped area into Williamson County, practically to the outcrop of the coal between Carterville and Marion. Outside of this area in which the bed is thick it is commonly not more than 6 feet in thickness. Inasmuch as the same benches of the bed are persistent across the entire area, having individually greater thickness in the thick coal portion of the area, it is suggested that in this latter area a greater proportion of the woody components of the organic debris was probably preserved, resulting in coal with higher vitrain content. It is undoubtedly desirable to test this probability by more detailed measurements of the bed than have hitherto been undertaken. The only information now available has been obtained from mines located within the area in which the coal is thick and from a single mine located close to the border of the thick coal area in which mine the bed has a thickness of about 8 feet. In this latter mine, measurement of one column showed 19 per cent of vitrain as compared with about 25 per cent in a mine within the area of thick coal. The proportion of other ingredients, particularly fusain, is also important, but there is little information available concerning the regional variations in the proportions of the ingredients in the coal bed.

CONCLUSION

The iso-calorific lines on the unit coal basis in Franklin and Williamson counties for No. 6 bed coal have a definite relation to structural features. Within these counties such iso-calorific lines define areas of uniform calorific value of the pure coal material within rather narrow limits. The values within such areas are more uniform than values within the county as a whole, hence such a map is a definite improvement in information over a county average. Furthermore, it makes possible easy understanding of the nature of variations within the area. In other counties in southern Illinois, or elsewhere in the State, character-

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ized by rapid variations in the character of the coal bed, similar maps will undoubtedly yield similar results and will eventually be prepared, so that more natural units of uniform value can be substituted for the county units now employed. Irrespective of the value to be placed upon the conclusions reached in this paper it is believed that the information provided by the map presented in Figure 2 (summarized in Fig. 3) will be found useful in checking analyses and in determining the distribution of standard values for No. 6 bed coal in this important mining district.
DISTRIBUTION OF SULFUR IN ILLINOIS COALS AND ITS GEOLOGICAL IMPLICATIONS

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[23]
Fig. 1—County average sulfur content of face samples of Illinois coals (ash and moisture free basis). (Based on data in Illinois State Geol. Survey Bull. 56.)
INTRODUCTION

It is the purpose of this paper to summarize the available information relative to the occurrence of sulfur in Illinois coals, to indicate certain geological relationships pertinent to the sulfur problem, and to suggest a possible explanation of certain phases of sulfur distribution.

Most of the available knowledge in regard to the distribution and occurrence of sulfur can be shown briefly in graphic or tabular form. Conclusions are drawn directly from such delineations and tables, omitting unnecessary elaboration of the facts shown by the diagrams. The more significant geological data can likewise be shown graphically. Such procedure eliminates some desirable comment and explanation, but since the discussion is based on generalizations, details are preferably avoided. This procedure, however, does not justify the implication that the generalizations may be ill-founded, as the author believes that careful inspection of the data presented will establish their validity.

In the discussion that follows, all values are expressed on an ash and moisture free basis except as noted in the text.

DISTRIBUTION OF TOTAL SULFUR

Chemical analyses of coal rarely give more information in regard to the sulfur present than the figure indicating the percentage of total sulfur. Knowledge of the distribution of sulfur in Illinois coals is largely dependent upon such total sulfur values. From such values are derived well supported county averages\(^2\) (Fig. 1) which provide the basis for the following generalizations in regard to the distribution of total sulfur in Illinois coals:

1. The total sulfur content of most Illinois coals is high, averaging 4.37\(^1\) on an ash- and moisture-free basis (3.4 on an as received basis).

2. In relatively small areas the total sulfur content is notably below average, there being but little coal with total sulfur content intermediate between that of the low- and high-sulfur coals.

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\(^1\)Senior Geologist and Head of the Coal Division.

(3) The distribution of total sulfur values is very erratic both geographically and from seam to seam.

(4) The erratic distribution of total sulfur values makes difficult any interpretation of the sulfur distribution.

VARIETIES OF SULFUR

Three varieties of sulfur are generally recognized by chemists when a report is desired in greater detail than in the form of total sulfur. These are sulfate sulfur, pyritic sulfur, and organic sulfur. It is assumed herein that these distinctions are geologically valid. Unfortunately the amount of information in regard to the forms of sulfur in Illinois coals is small. About 200 analyses of a considerable number of Illinois coals have been made recently, partly by the State Geological Survey and partly by the U. S. Bureau of Mines Experiment Station at Pittsburgh. These analyses provide the main basis for this discussion.

Sulfate Sulfur

Sulfate sulfur is thought to represent mainly the gypsum in the coal. Analytical results indicate that the amount of such sulfur in Illinois coals is very small, rarely more than one-half of one per cent and usually less than one-quarter of one per cent. This indicates that gypsum as a coal mineral is unimportant. In this study it is believed that the amount of sulfate sulfur can be ignored without vitiating the conclusions reached.

Pyritic Sulfur

This immediate discussion concerns the pyritic sulfur as determined by chemical analysis of standard samples from which discardable pyrite (or marcasite) has been removed.

Pyritic sulfur is very erratic in its occurrence (Fig. 2) but in the 200 samples of coal recently analyzed the pyritic sulfur rarely exceeded 4 per cent (ash- and moisture-free). Two classes of coal exist with respect to pyrite content: (1) Coals having less than 3 per cent, and (2) those having more than 3 per cent total sulfur. The coals containing more than 3 per cent commonly show great variation in pyritic sulfur content between about one and about 4 per cent. Coals with low total sulfur content have less variation in their content of pyritic sulfur, but within the small limits of variation there are erratic differences.

The chemical determinations of the amount of pyritic sulfur do not tell the whole story in regard to the amount of such sulfur present in the coal as more or less pyrite is discarded in collecting face samples.
Fig. 2—Amounts of pyritic and organic sulfur in about 200 samples of Illinois coals.

The probable amount of such pyrite is, therefore, of interest. It may be concluded from tabulation of measurements of the coal and included sulfur layers and lenses made in eight representative counties (Table 1), that the amount of discardable pyrite, if included in the face sample, would rarely increase the sulfur content more than 2 per cent and commonly not more than 1 per cent of the coal. The discardable pyrite would in general tend to increase the irregularity in the sulfur content of the high-sulfur coals more than that of the low-sulfur coals.

The general conclusion from a study of the pyritic sulfur content of Illinois coals is that the irregularities are similar in kind and amount to the irregularities characteristic of the total sulfur content.
CONTRIBUTIONS TO THE STUDY OF COAL.

Fig. 3—Minimum and maximum values for organic sulfur in the coal in various counties (in per cent).
DISTRIBUTION OF SULFUR IN ILLINOIS COALS

Table 1—Combined thickness of coal and pyrite sheets and lenses measured in certain counties with ratio of pyrite to coal by thickness and of sulfur to coal by weight

<table>
<thead>
<tr>
<th>County</th>
<th>Coal number</th>
<th>Total thickness of coal (Inches)</th>
<th>Total thickness pyrite (Inches)</th>
<th>Ratio pyrite to coal (thickness)</th>
<th>Approximate ratio sulfur in pyrite to coal</th>
<th>By thickness Per cent</th>
<th>By weight (a) Per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Franklin</td>
<td>6</td>
<td>15.363</td>
<td>22.88</td>
<td>.15</td>
<td>.08</td>
<td>.08</td>
<td>.12</td>
</tr>
<tr>
<td>Macoupin</td>
<td>6</td>
<td>4.311</td>
<td>55.51</td>
<td>1.27</td>
<td>.68</td>
<td>.68</td>
<td>1.02</td>
</tr>
<tr>
<td>Madison</td>
<td>6</td>
<td>3.410</td>
<td>49.31</td>
<td>1.45</td>
<td>.78</td>
<td>.78</td>
<td>1.17</td>
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<tr>
<td>Mercer</td>
<td>1</td>
<td>921</td>
<td>6.82</td>
<td>.72</td>
<td>.39</td>
<td>.39</td>
<td>.58</td>
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<tr>
<td>Peoria</td>
<td>5</td>
<td>1.921</td>
<td>14.26</td>
<td>.74</td>
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<td>.39</td>
<td>.58</td>
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<tr>
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<td>6</td>
<td>16.417</td>
<td>116.93</td>
<td>.72</td>
<td>.27</td>
<td>.27</td>
<td>.41</td>
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<td>Sangamon</td>
<td>5</td>
<td>2.005</td>
<td>12.92</td>
<td>.495</td>
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<td>Sangamon</td>
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<td>1.504</td>
<td>20.61</td>
<td>1.27</td>
<td>.68</td>
<td>.68</td>
<td>1.02</td>
</tr>
<tr>
<td>Vermilion</td>
<td>5 (Grape Creek)</td>
<td>2.021</td>
<td>7.88</td>
<td>.39</td>
<td>.21</td>
<td>.21</td>
<td>.32</td>
</tr>
<tr>
<td>Vermilion</td>
<td>7</td>
<td>1.716</td>
<td>33.13</td>
<td>1.93</td>
<td>1.04</td>
<td>1.04</td>
<td>1.56</td>
</tr>
</tbody>
</table>

(a) Assuming that the specific gravity of sulfur is 2 and that of coal is 1.33.

Organic Sulfur

Organic sulfur is that part of the total sulfur which is neither chemically determined sulfate sulfur nor chemically determined pyritic sulfur.

Organic sulfur in Illinois coals varies less in quantity than pyritic sulfur, for it is not known to exceed 3.23 per cent of the weight of the coal nor to be present in amounts less than .4 per cent (Fig. 2). The range for each county or region is usually small—between 0.4 and 0.5 per cent—being rarely more than 1 or less than 0.2 per cent. Furthermore it is fairly characteristic in its amount in various regions and for different seams (Fig. 3). With respect to coal No. 6, at least, there is fairly systematic geographic variation. East of the DuQuoin anticline in eastern Perry County and in Franklin, Jefferson, and Williamson counties in the low sulfur area there is generally less than 1 per cent of organic sulfur present in the coal. To the west and northwest, however, the amount of such sulfur gradually increases to more than 3 per cent in Macoupin County. There is also an increase eastward from the low-sulfur area toward Saline, Gallatin, and White counties. Coals in the north half of the coal basin have an organic sulfur content intermediate between 1.25 and 2.5 per cent with local areas in Will and Woodford counties (coal No. 2) and in Vermilion County (coal No. 5, Grape Creek) where the organic sulfur content is less than 1.25 per cent.
SUMMARY OF OBSERVATIONS ON THE QUANTITATIVE OCCURRENCE OF SULFUR AND ITS FORMS

(1) Total sulfur in Illinois generally exceeds 3 per cent* and in most places and seams ranges from 4 to 6 per cent (Fig. 1). In a few local areas the sulfur content of a coal is less than 3 per cent, not uncommonly in these areas being less than 2 per cent. The counties in which these areas are located and coal beds are as follows:

Jackson County ................ Murphysboro (No. 2) coal
Will County ................. LaSalle (No. 2) coal
Woodford County .......... LaSalle (No. 2) coal
Saline County ................ Harrisburg (No. 5) coal
Vermilion County .......... Springfield (No. 5) (Grape Creek coal)
Eastern Perry, Jefferson, Franklin, and Williamson counties... Herrin (No. 6) coal

(2) Within the limits of variation of each group the amount of total sulfur is very erratic, making it difficult to discover any definite relationships.

(3) Sulfate sulfur is an unimportant constituent of Illinois coals (1/4-1/2 of 1 per cent).

(4) (a) Pyritic sulfur in coals having a low total sulfur content is necessarily low, not exceeding 2 per cent in coals containing 3 per cent or less of total sulfur, but within these limits it is variable since it may be as little as 0.25 per cent.

(b) Pyritic sulfur in coals having a total sulfur content exceeding 3 per cent varies irregularly to such an extent as to account for a 5 per cent variation in the total sulfur content, that is, from 3 to 8 per cent.

(c) Free or discardable pyrite, if included in the analytical results, would rarely increase the average sulfur values more than 2 per cent and in most cases not more than 1 per cent of the weight of the coal. Coals having a total sulfur content of less than 3 per cent probably rarely have an additional discardable sulfur content in the form of pyrite of more than 0.5 per cent.

(5) (a) Organic sulfur, in contrast to total and pyritic sulfur, displays considerable regional regularity and fairly systematic variation from place to place in certain beds. Local areas or low total sulfur are also areas of low organic sulfur.

(b) Local variation in organic sulfur is rarely more than 1 per cent (Fig. 2) and generally not more than 0.5 per cent irrespective of the locality.

*In this summary, per cent values refer to weight of the coal on an ash and moisture free basis.
(e) Low organic sulfur content (less than 1 per cent) is usually accompanied by low pyritic and total sulfur content; high organic sulfur content is usually accompanied by high pyritic (more than 2 per cent) and total sulfur (more than 3 per cent) contents.

(6) The most significant result of this examination of the occurrence of total sulfur and the chemical forms of sulfur is the conclusion that the organic sulfur is the best index of the sulfur content and that the organic sulfur content is regionally consistent for each coal bed.

VARIATIONS IN ORGANIC SULFUR IN A SINGLE MINE

The generalization in regard to the regional uniformity of organic sulfur values is in contrast with the conclusions of Yancey and Fraser after studying the occurrence of sulfur in Middle Fork mine near Benton, Franklin County, Illinois, and in two mines in Kentucky. Mainly because of the variations observed in the Illinois mine they say:

"Considering the mine as a whole, however, it cannot be said that the organic sulphur is constant and uniformly distributed, as the samples varied from this low percentage, 0.57, to as high as 2.10, thus showing the maximum variation over the mine of one and one-half per cent. The theory has been advanced that organic sulphur content of a given bed of coal may be constant over large areas and characteristic of that particular bed. The results of these investigations, however, would indicate that the uniformity of organic sulphur distribution is confined to very limited areas in the bed and that even for a single mine as a whole the variation in organic sulphur content may be considerable."

Plotting the data in regard to the organic sulfur content of the coal where sampled on a skeleton mine map (Fig. 4) it is apparent that there is a systematic distribution of high and low values. The high organic sulfur values lying in a fairly definitely outlined area between two areas in which the coal is low in organic sulfur. It is significant that this mine is located on the margin of an area of low-sulfur coal in western Franklin County (Fig. 5).

The present investigation indicates that the organic sulfur content is not uniform over very large areas but that for individual beds there is apparently greater uniformity and more systematic variation than the conclusions of Yancey and Fraser would suggest. Undoubtedly there is need for further sampling of individual mines both in areas where general uniformity of conditions are supposed to exist as well as in areas where variable conditions are suspected.

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Illinois coals are mainly composed of variable amounts of the three banded ingredients, vitrain, clarain, and fusain. Durain is unimportant. There is also only a small amount of cannel coal.

The distribution of the forms of sulfur has been determined for about 100 samples of the three important ingredients representing a fairly wide variety of coals. As in the whole coal, sulfate sulfur is unimportant. Pyritic sulfur is generally low largely because (except for

* Fusain is mineral charcoal. The banded appearance of Illinois coals is due mainly to the brilliant jet black bands of vitrain, usually 1/4 to 1/2 inch wide, lying in less bright and laminated clarain. Durain is dull splint coal and is rare.
Coal containing less than 1 per cent sulphur.

Coal containing less than 1.25 per cent sulphur.

6. 5—Areas in southern Illinois underlain by low-sulfur coal. The Big Muddy District in Jackson County has been worked out. (Cady, G. H., Low Sulphur Coal in Illinois: Illinois Geological Survey Bulletin 38, fig. 58, p. 432, 1922.)
Fig. 6—Amounts of pyritic and organic sulfur in about 100 samples of banded ingredients.
certain fusain samples) the ingredients were carefully picked to exclude mineral impurities. Certain interesting generalizations in regard to the organic sulfur seem to be warranted by the available data (Fig. 6):

1. The organic sulfur content of fusain is always less than 1 per cent irrespective of the coal; the pyritic content of fusain is very erratic. This is because its cavities may or may not be filled with mineral matter.

2. The organic sulfur content of vitrain is generally lower than that of clarain from the same coal, but it still may be relatively high.

3. The organic sulfur content of both clarain and vitrain varies with the organic sulfur content of the whole coal, some being high and some being low.

4. Increase in the relative amount of clarain in a coal would probably result in an increase in the organic sulfur content but the variations in the organic sulfur content of Illinois coals cannot be ascribed simply to variations in the relative proportions of the banded ingredients, for if all of No. 6 coal bed in Macoupin County were composed of such clarain as is found in the coals of southern Illinois it would fall far short of containing the amount of organic sulfur present in Macoupin County coal. The actual amount of variation in the relative amount of the different ingredients is relatively small (Table 2).

Table 2—Preliminary data concerning the proportions of the banded ingredients in columnar samples of coal No. 6 from mines in southwestern and southern Illinois (a)

<table>
<thead>
<tr>
<th>County</th>
<th>Columns No.</th>
<th>Vitrain Per cent</th>
<th>Clarain Per cent</th>
<th>Fusian Per cent</th>
<th>Durain Per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macoupin</td>
<td>10 and 11 b</td>
<td>14.6</td>
<td>76.8</td>
<td>4.9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1 and 2</td>
<td>15.0</td>
<td>75.0</td>
<td>10.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3 and 4</td>
<td>12.5</td>
<td>79.4</td>
<td>2.3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5 and 6</td>
<td>11.0</td>
<td>79.5</td>
<td>2.1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8 and 9</td>
<td>14.4</td>
<td>75.0</td>
<td>10.6</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>13 and 14</td>
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<td>77.2</td>
<td>9.3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>12 and 13</td>
<td>10.3</td>
<td>76.4</td>
<td>9.6</td>
<td>0</td>
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<tr>
<td></td>
<td>1 and 2</td>
<td>12.5</td>
<td>79.4</td>
<td>2.3</td>
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<td>3 and 4</td>
<td>11.0</td>
<td>79.5</td>
<td>2.1</td>
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<tr>
<td></td>
<td>18 and 19</td>
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<td>68.7</td>
<td>2.9</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>16 and 17</td>
<td>15.9</td>
<td>74</td>
<td>6.4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>20 and 21</td>
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<td>75.7</td>
<td>5.5</td>
<td>0</td>
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<tr>
<td></td>
<td>22 and 23</td>
<td>18.0</td>
<td>74.4</td>
<td>1.6</td>
<td>0</td>
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<tr>
<td></td>
<td>25 and 26</td>
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<td>74.4</td>
<td>4.4</td>
<td>1.4</td>
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<tr>
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<td>27 and 28</td>
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<td>70.4</td>
<td>1.9</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>30 and 31</td>
<td>19.1</td>
<td>75.5</td>
<td>1.4</td>
<td>3.6</td>
</tr>
</tbody>
</table>

(a) Determined by megoscopic measurements, mainly by L. C. McCabe, Coal Division.

(b) Except for No. 18, values represent averages of measurements of two columns from each mine.
CONTRIBUTIONS TO THE STUDY OF COAL

PHYSICAL FORMS OF PYRITE

The physical forms of pyrite occurring in Illinois coals have been ably described by Yancey and Fraser. Without repeating this description the writer chooses to consider the coal pyrites as of two chief forms:

(1) One form is the pyrite (or marcasite) occurring as interbedded sheets or lenses between or upon successive benches of coal. It is believed to have been deposited shortly after the accumulation of the peat represented by the bench of coal upon which it lies, and to have been buried by later deposits of coal or other material.

(2) Pyrite of a concretionary origin, that filling joint cracks and other vertical and some horizontal partings, and disseminated pyrite—in fact such pyrite as cannot be correctly assigned to type (1)—is believed to be of secondary origin and to have formed largely since the consolidation of the bed to approximately its present thickness. The lateness of its origin is indicated particularly by the fact that there is practically no evidence of differential shrinkage between the coal and pyrite such as would be inevitable if pyritization had been an early phenomenon.

GEological Implications

(1) It is apparent, since the sulfur in the coal is so largely of organic origin, that the original source of all the sulfur may have been the organic sulfur.

(2) Even if the pyritic sulfur were not derived from organic sulfur the relatively large amount of organic sulfur and the irregularities in its distribution is a problem of primary importance.

(3) It is evident that the organic sulfur originated concomitantly with the coal, and its occurrence and variations can probably not be correctly attributed to post factem causes such as the nature of the cover, thickness of the seam, thickness of overburden, and diastrophic changes.

(4) Concurrent conditions which might have effected variations in the amount and distribution of the organic sulfur are particularly:

(a) The type of vegetation
(b) Climatic conditions
(c) Ground water conditions
(d) Soil conditions
(e) Geographic conditions
(f) Geologic age

5 Yancey and Fraser, Op. cit.
The first four of these possible factors are highly speculative, there being no information upon which to base substantial hypotheses. Concerning geographic conditions and geologic age we have fairly definite information. The former particularly opens up suggestive possibilities. The matter of geological age will be considered first.

**Geologic Age**

Examination of the analytical data and general knowledge of the distribution of pyrite in the coal seams fails to produce any evidence to justify correlating variations in sulfur with geological age. It is not unreasonable to suppose that from bed to bed through the portion of the Pennsylvanian period represented by the five commercially important coal beds of Illinois there may have been differences in climatic conditions, in the type of vegetation, in ground water conditions, and in the soil conditions, but if so they were not such differences as produced an evident effect from bed to bed as a whole upon the accumulation and distribution of organic sulfur. It appears, therefore, that differences due to difference in geologic age alone can be dismissed from consideration as a possible cause of variations in the organic sulfur.

**Geographic Conditions**

The recent considerable additions to our knowledge of the details of Pennsylvanian stratigraphy due to the activities of the Stratigraphic Division of the Illinois Geological Survey under the supervision of Dr. J. Marvin Weller, in cooperation particularly with Dr. H. R. Wanless, makes it possible to delineate with much greater accuracy than formerly the areas of accumulation of our commercially important coal beds. Furthermore, it is particularly due to these stratigraphic studies that it is possible to make definite assertions in regard to the conditions existing in those portions of the basins beyond the areas of coal accumulation. The fact that the position of the coal beds in the areas where little or no accumulation took place is identifiable by widespread underclays seems to indicate that at the time of coal formation a very large part of the basin was land covered with vegetation, but that within this area were large portions where conditions favored accumulation of peat. There is no basis for assuming differences in rate of growth or of density of growth within different parts of the area, although it is not improbable that there were such differences, but it is evident that there were differences in the proportion of plant material which remained as peat.

Assuming geographic conditions as outlined with the possibility of a difference in the amount of accumulated residue from a given amount of plant growth, it seems reasonable to believe that differences in the amount of organic sulfur may have resulted. It is noteworthy
Fig. 7—Approximate known extent of areas of thick accumulation of coal beds of commercial importance in Illinois, shown by seam. Approximate margins of the areas of thick accumulation are indicated by a full or broken line; by the latter if very indefinite. Present erosional margin of each coal bed is indicated by a line of dots. (Some of the data presented are based on field studies by J. M. Weller and H. R. Wanless.)
that the areas of low sulfur (p. 9) are in general somewhat remote from the margins of the areas of accumulation (Fig. 7) whereas coals lying adjacent to these margins or in small areas nowhere remote from the margins of accumulation are regions of high sulfur. However, it is not necessary to assume that the relative amount of accumulation would be slow only in marginal areas, or fast only in interior places. That would be a matter determined largely by moisture conditions, as suggested by White.7

This hypothesis in explanation of the variations in the content of organic sulfur in Illinois coals calls for at least partial retention in the peat of the organic sulfur required by successive plants even though the greater part of the plants is not preserved as coal. Undoubtedly more or less of the sulfur would escape as hydrogen sulphide gas; on the other hand the possibility of the retention of part of the sulfur in the main body of the peat would seem to be considerable in view of the chemical activity of the sulfur compounds and the sulfur requirements of the growing vegetation.

That differences in the relative amount of accumulation existed in different parts of the areas of accumulation and in different seams is indicated by the differences in the amount of the banded ingredients in the different seams or in different parts of the same seam (Table 2). Compare, for example, the vitrain content of the Macoupin County coal with that of Franklin and Williamson counties. It is likewise noteworthy that the benched character of No. 6 coal in southern Illinois is much more noticeable along the western margin of the area of accumulation than in the central part of the basin where the low-sulfur coal is found. In this low-sulfur area and in one or two others the rate of accumulation as well as the relative amount of accumulated material was conspicuously greater than elsewhere in the areas of accumulation, due either to more rapid growth or to less loss from decay and oxidation. However, noticeably greater thickness was not always the result of a greater proportion of accumulated material as compared with the amount of growth, for in the case of coal No. 2 the thickness of the coal is not conspicuously greater than it is elsewhere.

Related Problems

The sulfur problem with respect to Illinois coals is by no means solved by the discovery of a reasonable explanation for variations in the amount of organic sulfur. Much uncertainty exists as to the nature of organic sulfur. If, as is commonly supposed, the original source of the

7 White, David. Rôle of water conditions in the formation and differentiation of common (banded) coals: Economic Geology, Vol. 28, No. 6, pp. 556-570, 1933.
organic sulfur is the proteins, an unexpectedly large quantity of organic sulfur appears in the vitrain and even in the fusain of the coals supposedly derived from woody material. At any rate one would expect to find a greater difference between clarain and vitrain than appears to exist. Again the method of derivation of the pyritic sulfur from the organic sulfur is not fully understood. For example, one finds not infrequently isolated tiny crystals or globules of pyrite embedded in vitrain. The implication is that the sulfur of such pyrite was probably derived from the surrounding vitrain, possibly by bacterial action, but the process is not fully understood. The fact that most of the pyrite found in coal appears to be of relatively late origin in the sense that it was deposited after the coal had reached essentially its present state of consolidation suggests the possibility that the coalification process is partially if not entirely responsible for the release of organic sulfur.

CONCLUSION

In presenting this interpretation of the occurrence and distribution of sulfur in Illinois coal it is the writer's first purpose to present certain well established generalizations in regard to this distribution, second to indicate certain geological relationships that seem to have a bearing on the problem, and finally to stimulate interest in the problem of occurrence and distribution of the forms of sulfur in the coal bed. The theory advanced as explanation of the variations in organic sulfur is of minor importance and one that will probably undergo modification as knowledge advances.