Analyzes of brown coal in connection with higher sulfur contents in Sokolovská uhelná

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Abstract. The field of energy raw materials, including caustobioliths, still plays a priority role in the raw materials policy of many states. One of the important areas in which these reserves are currently mined is the Sokolov Basin in the Czech Republic. The current question on this deposit is the increased sulfur content in some locations of the Antonín seam.

1. Introduction
The presence of sulfur in coal in higher proportions represents a serious technological and ecological problem limiting the use of coal. All mining organizations are legally, and customer bound to supply brown coal, which meets both contractual and legal quality limits of undesirable components.

This paper deals with the study of sulfur forms in the coal seam Antonín, in the locality of the Družba quarry. To study the problem of increased sulfur contents, 83 samples were used, coming from 8 purpose-built wells designated JP531, JP533, JP535, JP565, JP566, JP567, JP589, JP594.

2. Boreholes
Boreholes for verification the coal seam quality were drilled to the core with a yield of at least 90%. The above-mentioned boreholes were drilled with the ZIF650M mobile drilling rig, which is a medium drilling rig, installed on the chassis of the TATRA 815 lorry. The set is suitable for rotary drilling of geological - exploration bore with direct irrigation, up to the depth of about 300 m. The maximum initial bore diameter is 195 mm, final 93 mm. The samples were processed (crushing, grinding, quaternion) and then individual seps were created with the designation of technological sections No. 111 to 121.

All assessed bores are located in the northern part of the quarry, in places with a steep increase in sulfur contents [1–4]. The positions of the bores and their names are indicated in the map in Figure 1.
should be noted that the bores were intentionally placed in this part of the quarry. There are higher concentrations of sulfur in this locality, which cause considerable technological problems during mining. On the other hand, such increased sulfur contents are suitable for laboratory testing of sulfur forms. As will be seen below, some forms of sulfur in the samples make up only a very small part (practically even a hundred %), which is at the limit of detection of the selected laboratory method. The samples were analyzed according to valid standards for determination of sulfur forms ČSN ISO 157 and ČSN ISO 19579. The results of the analyzes are given in the following tables (Table 1-8).

Figure 1. Positions of special-purpose borehole JP

| Borehole | Sample No. | Level from-to [m] | A[4] [%] | S[4] [%] | S[org] [%] | S[pyr] [%] | S[SO4] [%] |
|----------|------------|-------------------|---------|--------|-----------|-----------|-----------|
| JP53     | 111        | 0,00 - 1,00       | 17,65   | 3,35   | 1,92      | 0,72      | 0,71      |
|          | 112        | 6,50 - 8,00       | 10,97   | 4,10   | 2,31      | 1,20      | 0,59      |
|          | 113        |                   |         |        |           |           |           |
|          | 114        | 8,00 - 13,00      | 9,65    | 2,22   | 1,30      | 0,57      | 0,35      |
|          | 115        | 13,00 - 17,00     | 15,14   | 4,41   | 2,51      | 1,32      | 0,58      |
|          | 116        | 17,00 - 18,55     | 24,79   | 3,93   | 2,31      | 1,03      | 0,59      |
|          | 117        | 18,55 - 23,90     | 29,89   | 3,16   | 2,33      | 0,56      | 0,27      |
|          | 118        | 23,90 - 29,20     | 48,97   | 2,59   | 1,73      | 0,57      | 0,29      |
|          | 119        | 29,20 - 34,25     | 14,79   | 7,85   | 4,90      | 2,27      | 0,68      |
|          | 120        | 34,25 - 34,45     | 87,87   | 11,10  | 6,50      | 3,98      | 0,62      |
|          | 121        | 34,45 - 39,90     | 24,68   | 11,18  | 4,45      | 5,64      | 1,09      |
| Average  |            |                   | 28,44   | 5,39   | 3,03      | 1,79      | 0,58      |
| Min      |            |                   | 9,65    | 2,22   | 1,30      | 0,56      | 0,27      |
| Max      |            |                   | 87,87   | 1,18   | 6,50      | 5,64      | 1,09      |

Table 1. Results of analyze of Borehole JP533
### Table 2. Results of analyze of borehole JP535

| Borehole | Sample No. | Level from-to [m] | $A_1[^\%]$ | $S_1[^\%]$ | $S_{org}[^\%]$ | $S_{p[r]}[^\%]$ | $S_{so4}[^\%]$ |
|----------|-------------|------------------|------------|------------|----------------|----------------|----------------|
| JP535    | 111         | 4.85 - 9.00      | 7.89       | 1.87       | 1.37           | 0.32           | 0.18           |
|          | 112         | 9.00 - 13.25     | 8.67       | 1.90       | 1.13           | 0.63           | 0.14           |
|          | 113         | 13.25 - 13.30    | 69.02      | 0.26       | 0.14           | 0.05           | 0.07           |
|          | 114         | 13.30 - 18.00    | 9.89       | 1.26       | 0.86           | 0.27           | 0.13           |
|          | 115         | 18.00 - 21.40    | 12.27      | 1.95       | 1.35           | 0.48           | 0.12           |
|          | 116         | 21.40 - 24.75    | 24.00      | 4.11       | 2.27           | 1.25           | 0.59           |
|          | 117         | 24.75 - 28.00    | 21.49      | 3.52       | 2.29           | 0.88           | 0.35           |
|          | 118         | 28.00 - 32.60    | 36.62      | 2.82       | 1.91           | 0.58           | 0.33           |
|          | 119         | 32.60 - 36.60    | 17.18      | 9.10       | 5.01           | 3.55           | 0.54           |
|          | 120         | 36.60 - 36.85    | 87.14      | 4.99       | 1.25           | 3.31           | 0.43           |
|          | 121         | 36.85 - 42.20    | 29.40      | 9.05       | 3.90           | 4.15           | 1.00           |

- Average: 29.42, 3.71, 1.95, 1.41, 0.35
- Min: 7.89, 0.26, 0.14, 0.05, 0.07
- Max: 87.14, 9.10, 5.01, 4.15, 1.00

### Table 3. Results of analyze of borehole JP531

| Bore | Sample No. | Level from-to [m] | $A_1[^\%]$ | $S_1[^\%]$ | $S_{org}[^\%]$ | $S_{p[r]}[^\%]$ | $S_{so4}[^\%]$ |
|------|-------------|------------------|------------|------------|----------------|----------------|----------------|
| JP531| 111         | 11.80 - 16.00    | 10.85      | 1.47       | 0.90           | 0.40           | 0.17           |
|      | 112         | 16.00 - 19.85    | 8.36       | 1.49       | 1.06           | 0.23           | 0.20           |
|      | 113         | 19.85 - 19.90    | 64.11      | 0.94       | 0.41           | 0.43           | 0.10           |
|      | 114         | 19.90 - 24.00    | 9.90       | 1.17       | 0.73           | 0.38           | 0.06           |
|      | 115         | 24.00 - 27.55    | 10.95      | 1.04       | 0.92           | 0.06           | 0.06           |
|      | 116         | 27.55 - 30.90    | 18.24      | 1.76       | 1.16           | 0.41           | 0.19           |
|      | 117         | 30.90 - 33.20    | 15.63      | 2.80       | 2.10           | 0.57           | 0.13           |
|      | 118         | 33.20 - 38.50    | 47.85      | 1.66       | 1.36           | 0.23           | 0.07           |
|      | 119         | 38.50 - 42.70    | 16.72      | 7.29       | 4.30           | 2.24           | 0.75           |
|      | 120         | 42.70 - 42.90    | 86.49      | 3.81       | 1.23           | 2.17           | 0.41           |
|      | 121         | 42.90 - 48.05    | 26.37      | 7.08       | 3.48           | 2.74           | 0.86           |

- Average: 28.68, 2.77, 1.60, 0.90, 0.27
- Min: 8.36, 0.94, 0.41, 0.06, 0.06
- Max: 86.49, 7.29, 4.30, 2.74, 0.86

### Table 4. Results of analyze of borehole JP565

| Borehole | Sample No. | Level from-to [m] | $A_1[^\%]$ | $S_1[^\%]$ | $S_{org}[^\%]$ | $S_{p[r]}[^\%]$ | $S_{so4}[^\%]$ |
|----------|-------------|------------------|------------|------------|----------------|----------------|----------------|
| JP565    | 111         | 11.70 - 15.00    | 8.08       | 0.46       | 0.38           | 0.06           | 0.02           |
|          | 112         | 15.00 - 19.25    | 7.88       | 0.42       | 0.33           | 0.06           | 0.03           |
|          | 113         | 19.25 - 19.30    | 80.94      | 0.05       | -              | -              | -              |
|          | 114         | 19.30 - 25.00    | 13.45      | 0.54       | 0.20           | 0.31           | 0.03           |
|          | 115         | 25.00 - 28.90    | 16.29      | 0.54       | 0.37           | 0.14           | 0.03           |
|          | 116         | 28.90 - 30.80    | 32.16      | 0.54       | 0.38           | 0.13           | 0.03           |
|          | 117         | 30.80 - 34.50    | 48.98      | 0.81       | 0.61           | 0.13           | 0.07           |
|          | 118         | 34.50 - 38.20    | 31.59      | 0.77       | 0.60           | 0.13           | 0.04           |
|          | 119         | 38.20 - 41.60    | 52.06      | 4.01       | 2.00           | 1.81           | 0.20           |
|          | 120         | 41.60 - 41.90    | 87.63      | 5.16       | 0.84           | 4.03           | 0.29           |
|          | 121         | 41.90 - 45.60    | 26.12      | 4.85       | 1.43           | 3.21           | 0.21           |

- Average: 36.83, 1.65, 0.71, 1.00, 0.10
- Min: 7.88, 0.05, 0.20, 0.06, 0.02
- Max: 87.63, 5.16, 2.00, 4.03, 0.29
### Table 5. Results of analyze of borehole JP566

| Borehole | Sample No. | Level from-to [m] | A4[%] | S4[%] | Sod[%] | Sred[%] | Sres[%] | Sso4[%] |
|----------|------------|-------------------|-------|-------|--------|---------|---------|---------|
| JP566    | 111        | 7.40 - 9.00       | 5.23  | 0.50  | 0.45   | 0.02    | 0.03    |
|          | 112        | 9.00 - 13.85      | 7.95  | 0.49  | 0.44   | 0.02    | 0.03    |
|          | 113        | 13.85 - 19.95     | 80.13 | 0.05  | -      | -       | -       |
|          | 114        | 13.95 - 20.00     | 9.20  | 0.55  | 0.46   | 0.05    | 0.04    |
|          | 115        | 20.00 - 25.20     | 15.24 | 0.89  | 0.68   | 0.18    | 0.03    |
|          | 116        | 25.20 - 27.00     | 29.45 | 0.82  | 0.52   | 0.27    | 0.03    |
|          | 117        | 27.00 - 29.50     | 10.56 | 1.38  | 0.86   | 0.45    | 0.07    |
|          | 118        | 29.50 - 34.80     | 31.10 | 1.45  | 1.13   | 0.28    | 0.04    |
|          | 119        | 34.80 - 36.60     | 31.77 | 5.15  | 2.80   | 2.06    | 0.29    |
|          | 120        | 36.60 - 36.75     | 62.51 | 2.41  | 1.09   | 1.19    | 0.13    |
|          | 121        | 36.75 - 40.25     | 16.79 | 5.76  | 2.07   | 3.55    | 0.14    |
|          | Average    |                   |       |       | 27.27  | 1.77    | 1.05    | 0.81    | 0.08    |
|          | Min        |                   |       |       | 5.23   | 0.05    | 0.44    | 0.02    | 0.03    |
|          | Max        |                   |       |       | 80.13  | 5.76    | 2.80    | 3.55    | 0.29    |

### Table 6. Results of analyze of borehole JP567

| Borehole | Sample No. | Level from-to [m] | A4[%] | S4[%] | Sod[%] | Sred[%] | Sres[%] | Sso4[%] |
|----------|------------|-------------------|-------|-------|--------|---------|---------|---------|
| JP567    | 111        | 10.40 - 15.00     | 7.05  | 1.38  | 0.82   | 0.49    | 0.07    |
|          | 112        | 15.00 - 19.35     | 8.88  | 0.54  | 0.44   | 0.08    | 0.02    |
|          | 113        | 19.35 - 19.94     | 68.43 | 1.39  | 0.53   | 0.82    | 0.04    |
|          | 114        | 19.40 - 24.00     | 9.60  | 1.56  | 0.78   | 0.71    | 0.07    |
|          | 115        | 24.00 - 27.75     | 17.63 | 0.91  | 0.71   | 0.17    | 0.03    |
|          | 116        | 27.75 - 29.60     | 25.43 | 1.00  | 0.70   | 0.26    | 0.04    |
|          | 117        | 29.60 - 32.45     | 15.04 | 1.06  | 0.77   | 0.24    | 0.05    |
|          | 118        | 32.45 - 38.50     | 38.91 | 1.63  | 1.05   | 0.49    | 0.09    |
|          | 119        | 38.50 - 42.55     | 17.21 | 6.06  | 3.21   | 2.57    | 0.28    |
|          | 120        | 42.55 - 42.75     | 88.43 | 4.74  | 0.50   | 3.94    | 0.30    |
|          | 121        | 42.75 - 47.20     | 27.46 | 6.70  | 2.19   | 4.28    | 0.23    |
|          | Average    |                   |       |       | 29.46  | 2.45    | 1.06    | 1.28    | 0.11    |
|          | Min        |                   |       |       | 7.05   | 0.54    | 0.44    | 0.08    | 0.02    |
|          | Max        |                   |       |       | 88.43  | 6.70    | 3.21    | 4.28    | 0.30    |

### Table 7. Results of analyze of borehole JP589

| Borehole | Sample No. | Level from-to [m] | A4[%] | S4[%] | Sod[%] | Sred[%] | Sres[%] | Sso4[%] |
|----------|------------|-------------------|-------|-------|--------|---------|---------|---------|
| JP589    | 111        | 15.40 - 20.00     | 6.21  | 1.06  | 0.78   | 0.25    | 0.03    |
|          | 112        | 20.00 - 24.80     | 7.37  | 0.58  | 0.45   | 0.09    | 0.04    |
|          | 113        | 24.80 - 24.85     | 76.07 | 0.08  | -      | -       | -       | -       |
|          | 114        | 24.85 - 30.00     | 8.58  | 0.59  | 0.50   | 0.07    | 0.02    |
|          | 115        | 30.00 - 33.50     | 15.35 | 1.15  | 0.75   | 0.36    | 0.04    |
|          | 116        | 33.50 - 36.40     | 27.17 | 0.73  | 0.59   | 0.11    | 0.04    |
|          | 117        | 36.40 - 38.10     | 13.63 | 1.20  | 0.88   | 0.26    | 0.06    |
|          | 118        | 38.10 - 42.75     | 38.70 | 1.01  | 0.81   | 0.14    | 0.06    |
|          | 119        | 42.75 - 46.45     | 20.91 | 5.28  | 3.17   | 1.83    | 0.28    |
|          | 120        | 46.45 - 46.65     | 86.41 | 6.21  | 0.37   | 5.49    | 0.35    |
|          | 121        | 46.65 - 51.50     | 27.29 | 5.05  | 2.20   | 2.67    | 0.18    |
|          | Average    |                   |       |       | 29.79  | 2.09    | 1.05    | 1.13    | 0.10    |
|          | Min        |                   |       |       | 6.21   | 0.08    | 0.37    | 0.07    | 0.02    |
|          | Max        |                   |       |       | 86.41  | 6.21    | 3.17    | 5.49    | 0.35    |
Table 8. Results of analyze of borehole JP594

| Borehole | Sample No. | Level from-to [m] | $A^{d}$[%] | $S^{d}$[%] | $S_{org}$[%] | $S_{pyr}$[%] | $S_{SO4}$[%] |
|----------|------------|-------------------|-----------|-----------|-----------|-----------|-----------|
| JP594    | 111        | 13,40 –18,00      | 7,16      | 0,91      | 0,67      | 0,20      | 0,04      |
|          | 112        | 18,00 - 22,60     | 8,73      | 0,53      | 0,40      | 0,12      | 0,01      |
|          | 113        | -                 | -         | -         | -         | -         | -         |
|          | 114        | 22,60 - 27,00     | 8,99      | 0,53      | 0,45      | 0,06      | 0,02      |
|          | 115        | 27,00 - 30,90     | 15,18     | 0,69      | 0,55      | 0,06      | 0,08      |
|          | 116        | 30,90 - 33,10     | 28,85     | 0,63      | 0,42      | 0,14      | 0,07      |
|          | 117        | 33,10 - 36,40     | 15,25     | 0,88      | 0,67      | 0,09      | 0,12      |
|          | 118        | 36,40 – 38,15     | 25,56     | 0,87      | 0,68      | 0,07      | 0,12      |
|          | 119        | 38,15 - 42,15     | 17,53     | 4,24      | 2,72      | 0,90      | 0,62      |
|          | 120        | 42,15 – 42,40     | 85,75     | 5,40      | 0,30      | 4,61      | 0,49      |
|          | 121        | 42,40 – 48,00     | 20,83     | 3,99      | 1,83      | 1,79      | 0,37      |

Average 23,38 1,87 0,87 0,80 0,19  
Min 7,16 0,53 0,30 0,06 0,01  
Max 85,75 5,40 2,72 4,61 0,62

3. Results
A set of 83 samples obtained from the bore JP531, JP533, JP535, JP565, JP566, JP567, JP589, JP594 provided information on the horizontal and vertical distribution of sulfur forms in coal. It was found that organic sulfur is the most abundant and also causes of rapid increase of sulfur content around lane No. 30, i.e. around technological section No. 119, were found. Mining around section No. 119 is very problematic due to increased sulfur contents, disulfide sulfur contents are increasing rapidly (mainly the presence of pyrite) around it. Pyrite is the main cause of increased emissions at coal combustion in power generators and is therefore a reason for complaints about the quality of coal supplies and related sanctions to suppliers. However, this applies only to the northern area, which should be mined within two years, and the mining organization would have to deal with sulfur anomalies to a minimum.

The data for all bores provided the following statistics: The average total sulfur content is 2.79%, organic sulfur 1.42%. Pyrite sulfur with an average of 1.14% and with the lowest sulphate value 0.23%.

Minimum extremes: For total sulfur the minimum content is 0.26%, for organic sulfur 0.14%. Pyrite sulfur with a minimum content of 0.02% and sulphate sulfur with 0.01%.

Maximum extremes: For total sulfur the maximum content is 11.18%, for organic sulfur 6.5%. Pyrite sulfur with a minimum content of 5.64% and sulphate sulfur with 1.09%.

The analyzes provided information on the distribution of sulfur forms in the coal component as well as in technological sections No. 111 - 122. Figure 2 suggests a possible addition to the mathematical model of the analysis data to provide up-to-date information on the quality of mined coal to the crew of the mining machine, according to the current position of the wheel to the seam cut, using GPS.
In the bores JP533 and JP535 the highest sulfur contents were recorded. These data were processed into histograms as shown in Figure 3. The left column shows the ash content of Ad, as well as the total sulfur, organic, pyrite, and sulphate (%) contents from the left.

Isolines maps of all three types of sulfur forms were compiled for technological sections with the highest sulfur contents Nos. 119 and 120. The trend is shown in Figure 4.

**Figure 2.** Technological sections 111 -122

**Figure 3.** Histogram of maximum ash and sulfur forms of bores JP533 and JP535
Figure 4. Trend maps of sulfur content for sections 119 and 120

4. Conclusions
The study concludes that in deeper parts sulfur concentrations are increased. A large increase in the sulfur content from the uppermost parts is gradual, with a large increase in section 119, which is located near lane No. 30. Below the lane level 30, the sulfur values are already maximal (up to 12% according to laboratory findings). Section No. 119 is therefore the most sulfurous section of the Antonín seam.

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