Proposed Cleaning Potential Gradient Based on a Study of Coals from Three Exploration Areas in Shanxi Province, China

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1. INTRODUCTION

Coal plays a crucial role in energy supply worldwide, especially in China. In 2019, China’s coal consumption and production accounted for about 57.7% and 68.6% of domestic energy consumption and production, respectively. Currently, China remains the largest producer and consumer of coal in the world, with about 47.6% of global coal production and 52.9% of global coal consumption in 2019. At the end of 2019, the reserve-to-production ratio of China’s coal resources was 37, which means that the remaining reserves could be mined for about 37 years, assuming that future production would be at the same annual rate as in 2019. Although the proportion of coal in the diversified Chinese energy structure has been declining gradually year by year, the characteristics of China’s energy resources and development status suggest that coal is not only still the main energy source in China, it will likely remain so for the foreseeable future. The extensive use of coal has resulted in a range of environmental issues, including acid rain caused by SO2/NOx emissions during combustion, fly ash emission, formed by fine particulate emission from coal utilization, i.e., PM2.5 and PM10, and endemic diseases caused by hazardous trace elements emitted during coal combustion. In addition, byproducts from mining, preparation, and utilization of coals, such as coal waste piles, flue gas desulfurization (FGD) gypsum, heavy metals, etc., will also cause many potential environmental problems. One method to reduce these environmental impacts is to wash or clean the coal to remove the impurities. Cleaning potentials refer to the removal potentiality of these impurities through washing or cleaning including physical and chemical cleaning. Producing near zero ash coals through chemical (i.e., solvent extraction) or physical (e.g., flotation) processes is also a very important theme in the coal cleaning research. Here, we put focus on cleaning potentials during physical cleaning (floatation). To evaluate regional trends in the cleaning potential of coals is one of the major research components of clean coal geology. These evaluations are also basic to controlling the environmental issues associated with coal utilization. Evaluation of cleanability, or the cleaning potential, of coal resources is the key to controlling coal pollution from the source and to achieving high-efficient mining and utilization of coal resources. The ash yields and sulfur contents of Chinese coal resources were measured and graded during the third national coalfield
assessment.37 The concept of high-quality coal was proposed, based on parameters such as ash yield, sulfur content, calorific value, and washability.37,38 In a study of coal resources in western China, the concept of high-quality coal was redefined and classified by Li et al., and the high-quality coal resources in Ordos Basin were evaluated.39 Based on these previous works,37−39 the evaluation systems for quality and cleaning grade of coal were established to evaluate coal resources as part of the latest resource evaluation of national coals.40−42 A new method to evaluate coals according to cleanability proposed in a later study43 was used in this study, which could accurately reflect the cleaning potential of coal resources based on the removal ratio of hazardous impurities from coals during coal preparation.

To promote the development of clean coal geology35,36 and to have a systematic study of the cleaning potential of coals, studies on the cleaning potential of selected coals in Shanxi province, China were carried out. Before the present study, we analyzed the effects of geological factors, including depositional environment and local geological features, on the cleaning potentials of coals in three general exploration areas of Shanxi. The depositional environment of coals plays an important role in their cleanabilities. We also calculated the distribution area of coals with different cleanabilities in the previous study.44 In the present study, we extend that work, based on the previous study, to an estimate of the resources of coals with different cleaning potentials in those areas, with regard to coal quality, calculated cleanability values, and cleaning grade. In addition, we proposed a cleaning potential gradient to predict the proportion of coals with different qualities after the flotation process. Overall, the present study not only provides a reference for the utilization of coals with different cleaning potential characteristics but also adds to the conceptual basis of the field of clean coal geology.

2. RESEARCH SETTING

The present study focused on three general exploration areas (Anping, Xizhuang, and Yitang) of Shanxi province, shown in Figure 1, which is one of the major coal-producing provinces in China. Two seams were selected for study in each of the three areas. They were the No. 2 and No. 10 seams in Anping, No. 3 up and No. 3 seams in Xizhuang, and No. 3 and No. 9 seams in Yitang. They have been described, along with relevant geological information and analytical data, by Tang et al.44 The detailed information about these six coal seams is shown in Table 1. For each coal seam, the coal samples (core samples) were collected from wells with one sample for each well. There are 39 wells in the three areas, 15 in Anping, 14 in Xizhuang, and 10 in Yitang.

Coal reserves in Shanxi have declined steadily, as a result of sustained, large-scale coal production in this province, which also results in leaving poorer quality coal to be mined now and in the future. An evaluation of coal resources, in terms of cleaning potential, in these three exploration areas could provide a reference for the regional delineation of coal resources with different qualities and their clean and effective utilization.
3. EVALUATION METHOD

The evaluation systems of quality and cleanability were used in this study. In the quality evaluation system, coal quality values (the comprehensive index) were calculated based on ash yields and sulfur contents using the generalized weighted contrast scaling exponent method. According to the comprehensive index, coal qualities were divided into six grades.41,42 As for the cleanability evaluation system, cleanability values were calculated based on the removal ratios of ash and sulfur through coal preparation. Cleanabilities were graded into five levels based on cleanability values.43 The detailed introduction to these two methods can also be found in ref 44. The generalized weighted contrast scaling exponent method40−42 was also used in the present study, which can also appropriately indicate the cleaning grade of float coal. In this method, the comprehensive index (Table 2) is calculated using the quality grade evaluation software (2019SR1040902) of coal resources proposed by Tang et al.,42 according to the ash yields and sulfur contents of float coal (cleaned coal). The classification systems (Table 2) of cleaning grade of float coal are established according to the comprehensive index, which is similar to the classification systems of coal quality.

The distribution maps of coals with different cleaning potentials were prepared using the mapping and geographical information software (MAPGIS), which can be used to prepare various geological maps based on the related data. An introduction and further information about the use of MAPGIS are provided in ref 45. On the basis of the distribution maps of coals with different cleanabilities, the reserves of differently cleanable coals were predicted using the

Table 2. Classifications for the Cleaning Grade of Float Coal (Modified with Permission from ref 44. Copyright 2020 American Chemical Society)

| symbol | comprehensive index (A) | classification | remarks (S<sub>t,d</sub> %; A<sub>d</sub> %) |
|--------|--------------------------|----------------|----------------------------------|
| I      | A ∈ (−∞, 0.186]          | scarce excellent-clean coal | S<sub>t,d</sub> ≤ 0.5 and A<sub>d</sub> ≤ 5 |
| II     | A ∈ (0.186, 0.437]        | excellent-clean coal       | 0.5 < S<sub>t,d</sub> ≤ 1.0 and A<sub>d</sub> ≤ 10 or S<sub>t,d</sub> ≤ 1.0 and 5 < A<sub>d</sub> ≤ 10 |
| III    | A ∈ (0.437, 0.636]        | good-clean coal            | 1.0 < S<sub>t,d</sub> ≤ 1.5 and A<sub>d</sub> ≤ 20 or S<sub>t,d</sub> ≤ 1.5 and 10 < A<sub>d</sub> ≤ 20 |
| IV     | A ∈ (0.636, 0.763]        | fair-clean coal            | 1.5 < S<sub>t,d</sub> ≤ 2.0 and A<sub>d</sub> ≤ 30 or S<sub>t,d</sub> ≤ 2.0 and 20 < A<sub>d</sub> ≤ 30 |
| V      | A ∈ (0.763, 0.887]        | poor-clean coal            | 2.0 < S<sub>t,d</sub> ≤ 3.0 and A<sub>d</sub> ≤ 40 or S<sub>t,d</sub> ≤ 3.0 and 30 < A<sub>d</sub> ≤ 40 |
| VI     | A ∈ (0.887, +∞]          | bad-clean coal             | S<sub>t,d</sub> > 3.0 or A<sub>d</sub> > 40 |

*S<sub>t,d</sub>, total sulfur content on dry basis; A<sub>d</sub>, ash yield on dry basis; and comprehensive index A is calculated using the quality grade evaluation software of coal according to the sulfur contents (dry basis) and ash yields (dry basis) of float coal.

Figure 2. Distribution of coals with different coal qualities (Reprinted with permission from ref 44. Copyright 2020 American Chemical Society).
geological block method. According to the geological reports and the relevant standards, the complexity degree of the geological structure in the three general exploration areas belonged to the simple type. The coal reserves were calculated using the pseudo thickness, the horizontal projected area, and the apparent density of coal seams. The equation was as follows:

\[ Q = \sum Q_n \times S_n \times M_n \times D_n \]  

where \( Q \) represents the predicted reserves (t); \( n \), the code of each block (1, 2, 3, etc.); \( Q_n \), the reserve of coal in each block (t); \( S_n \), the area of each block (m²); \( M_n \), the average thickness of coal seams in each block (m); and \( D_n \), the average apparent density of coal seams in each block (t/m³).

4. RESULTS AND DISCUSSION

In the present study, resource evaluation of coals was estimated in terms of three aspects: coal quality, cleaning grade, and cleanability. Distribution maps (Figures 2–4) of coal resources with different cleaning potential characteristics were prepared. In these distribution maps, “a” and “b” refer to the No. 2 seam and the No. 10 seam in the Anping exploration area; “c” and “d”, to the No. 3 seam in the Xizhuang exploration area; and “e” and “f”, to the No. 3 seam and the No. 9 seam in the Yitang exploration area, respectively. Based on these distribution maps, the reserves of differently cleanable coals were predicted using the geological block method. That is the reserves of coals were calculated through eq 1 using the pseudo thickness, the horizontal projected area, and the apparent density of coal seams.

4.1. Coal Quality. Coals with different qualities in the three exploration areas are shown in Figure 2, modified from Tang et al. According to these distribution maps, the predicted reserves and proportions of coals with different qualities were calculated and are shown in Table 3.

The coal of the No. 2 seam in the Anping exploration area includes good, fair, and poor-quality coal. The reserves of good, fair, and poor-quality coals are about 38.9, 182.9, and 80.3 million tonnes, accounting for about 12.9, 60.5, and 26.6%, respectively. The No. 10 seam in the Anping area contains poor and bad-quality coal. The reserves of poor and bad-quality coals are about 73.7 and 175.1 million tonnes, with proportions of about 29.6 and 70.4%, respectively. The coal of the No. 3 upper seam in the Xizhuang exploration area is mostly of good and fair quality with minor amounts of poor-quality coal. The proportions of good, fair and poor-quality coal are about 62.7, 36.1, and 1.2%, with reserves of about 130.8, 75.4, and 2.5 million tonnes, respectively. The coal of the No. 3 seam in the Xizhuang exploration area includes excellent, good, fair and poor-quality coals, with reserves of about 10.0, 140.4, 42.4, and 33.9 million tonnes, respectively. The proportions of them are about 4.4, 61.9, 18.7, and 14.9%, respectively. The quality of the No. 3 seam in the Yitang exploration area is of good, fair, and poor-quality. The reserves of good, fair and poor-quality coal are about 103.3, 141.0, and 19.8 million tonnes,
accounting for about 39.1, 53.4, and 7.5%, respectively. In the No. 9 seam of the Yitang area, the fair-quality coal is accounting only for about 2.6%, with reserve of about 5.6 million tonnes. Coal with poor and bad quality is abundant, representing about 22.4 and 75.0%, and with reserves of about 47.7 and 159.8 million tonnes, respectively.

4.2. Cleaning Grade. A distribution map of coal with different cleanabilities is shown in Figure 3. The predicted reserves and proportions of coal with different cleanabilities in the three exploration areas were calculated based on these distribution maps and are shown in Table 4.

The cleaning grades of the float coal from the No. 2 coal seam in the Anping area include excellent and good-cleaning float coal. Resources of excellent-clean float coal occur most frequently in this area, with a proportion of about 81.0%. Resources with good-clean float coal are distributed in the north-central and south parts of the area, accounting for about 19.0% (Figure 3 and Table 4). Coals with fair and poor characteristics do not occur here. The proportion of coal with

| exploration area | coal seam | R/P | I | II | III | IV | V | VI | total |
|------------------|-----------|-----|---|----|-----|----|---|----|-------|
| Anping No. 2     | R         | R   | R | R  |     |     |   |    |       |
|                  | P         |     |   |    |     |     |   |    |       |
| No. 10           | R         |     |   |    |     |     |   |    |       |
|                  | P         |     |   |    |     |     |   |    |       |
| Xizhuang No. 3   | R         | R   | R | R  |     |     |   |    |       |
|                  | P         |     |   |    |     |     |   |    |       |
| No. 3            | R         |     |   |    |     |     |   |    |       |
|                  | P         |     |   |    |     |     |   |    |       |
| Yitang No. 3     | R         | R   | R | R  |     |     |   |    |       |
|                  | P         |     |   |    |     |     |   |    |       |
| No. 9            | R         |     |   |    |     |     |   |    |       |
|                  | P         |     |   |    |     |     |   |    |       |

Figure 4. Distribution of coals with different cleanabilities (Reprinted with permission from ref 44 Copyright 2020 American Chemical Society).

Table 3. Predicted Reserves (R, million tonnes) and Proportions (P, %) of Coals with Different Qualities in the Three Exploration Areas

1.00–2.99 Poor cleanability coal
3.00–5.69 Fair cleanability coal
5.70–8.4 Good cleanability coal
>8.4 Proficient cleanability coal

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good characteristic increases slightly, whereas the proportion of coal with excellent characteristic increases significantly after coal preparation (Tables 3 and 4). The cleaning grades of the float coal from the No. 10 coal seam in the Anping area represent fair, poor, and bad-clean float coal. Resources with fair-clean float coal are distributed near the B1301 well in the north-central part of this area, with a proportion of only about 2.2%. Resources with poor-clean float coal are distributed in the central and north-central parts of the area, representing about 26.8%. Resources with bad-clean float coal are widely distributed in the south and north areas, accounting for about 71.0% (Figure 3 and Table 4). Preparation of the raw coal results in coal with fair characteristic occurring only slightly, and a small decrease in the proportion of coal with poor characteristic (Tables 3 and 4). Unusually, the proportion of coal with bad characteristic increases to a small extent (Tables 3 and 4), which may be a consequence of the high-organic-sulfur content, as discussed in our earlier publication.44

The cleaning grades of the float coal from the No. 3up coal seam in the Xizhuang area consist of excellent and good-clean float coal. Resources with excellent-clean float coal occur most frequently in this area, with a proportion of about 89.7%. Resources with good-clean coal occur near the L0501, S502, and S503 wells in the south-central part of the area, accounting for about 10.3% (Figure 3 and Table 4). The cleaning grades of the float coal from the No. 3 coal seam in the Xizhuang area include excellent and good-clean float coal, with proportions of about 86.2 and 13.8% (Table 4), respectively. Both the low ash yield and the low sulfur content are responsible for this. Resources with excellent-clean float coal are most abundant in the area, while resources with good-clean float coal are distributed to a lesser extent near the S102 and S302 wells in the south area and the L1301 well in the north area (Figure 3). For both the No. 3up and the No. 3 seams, the proportion of coal of excellent characteristic increases significantly and that of coal with good, fair, and poor characteristics decrease dramatically during preparation (Tables 3 and 4), with the low sulfur content being most responsible for this, again in accord with our earlier publication.44

The cleaning grades of float coal from the No. 3 coal seam in the Yitang area contain excellent and good, primarily excellent, clean float coal. Resources with excellent-clean float coal, good characteristic increases slightly, whereas the proportion of coal with excellent characteristic increases significantly after coal preparation (Tables 3 and 4). The cleaning grades of the float coal from the No. 10 coal seam in the Anping area represent fair, poor, and bad-clean float coal. Resources with fair-clean float coal are distributed near the B1301 well in the north-central part of this area, with a proportion of only about 2.2%. Resources with poor-clean float coal are distributed in the central and north-central parts of the area, representing about 26.8%. Resources with bad-clean float coal are widely distributed in the south and north areas, accounting for about 71.0% (Figure 3 and Table 4). Preparation of the raw coal results in coal with fair characteristic occurring only slightly, and a small decrease in the proportion of coal with poor characteristic (Tables 3 and 4). Unusually, the proportion of coal with bad characteristic increases to a small extent (Tables 3 and 4), which may be a consequence of the high-organic-sulfur content, as discussed in our earlier publication.44

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Table 6. Distribution Area (km²), Predicted Reserves (million tonnes), and Proportions (%) of Coals with Different Cleaning Potential Characteristics in the Three Exploration Areasa

| coal quality system classification | scarce | excellent | good | fair | poor | bad |
|----------------------------------|--------|-----------|------|------|------|-----|
| area                             | 2.60   | 109.98    | 119.33 | 76.95 | 103.84 |
| reserve                          | 10.02  | 413.38    | 447.37 | 257.87 | 334.94 |
| proportion                       | 0.68   | 28.24     | 30.57 | 17.62 | 22.89 |
| cleaning grade system classification | scarce  | excellent | good | fair | poor | bad |
| area                             | 228.55 | 41.21     | 41.47 | 59.47 | 41.99 |
| reserve                          | 878.11 | 135.24    | 104.42 | 169.08 | 176.76 |
| proportion                       | 60.00  | 9.24      | 7.13  | 11.55 | 12.08 |
| cleanability system classification | proficient | good | fair | poor | worse | total |
| area                             | 87.06  | 204.08    | 106.86 | 14.70 | 412.70 |
| reserve                          | 273.75 | 731.11    | 409.37 | 49.34 | 1463.57 |
| proportion                       | 18.70  | 49.95     | 27.97 | 3.37  | 100.00 |

“In the Cleaning grade system, the reserve refers to the reserves of the raw coals, which can be treated into different cleaning grade float coals through floatation.

accounting for about 94.7%, are widely distributed. The remaining resources, about 5.3%, are classified as good-clean float coal and are found near the ZK0501 well in the west-central part of this area (Figure 3e and Table 4). After preparation, the proportion of coal with excellent characteristic increases significantly, accompanied by a corresponding decrease in the proportions of coals with good, fair, and poor characteristics (Tables 3 and 4). The cleaning grades of float coal from the No. 9 seam in the Yitang area mainly consist of good, fair, and poor-clean float coal, accounting for about 5.2, 46.5, and 48.0%, respectively (Table 4). Resources having excellent and good cleaning grade float coal are found near the ZX0502 well in the south-central part of the area. Resources with fair-clean float coal are distributed in east and north-east parts; poor-clean float coal occurs in the west and south-west of the area (Figure 3). After preparation of the raw coal, the proportions of coals with fair and poor characteristics increase, while coal with poor characteristic is not produced. Coals with excellent and good characteristics are produced only to a limited extent (Tables 3 and 4). These observations most likely reflect the effect of the organic sulfur content.43

4.3. Cleanability. Equation 1 in the ref 44 was used to calculate the cleanabilities of the coals examined in this study, as explained in earlier papers from our laboratory.45,46 Coals of different cleanabilities in the three exploration areas are also shown in Figure 4. According to these distribution maps, the predicted reserves and proportions of coals with different cleanabilities were calculated and are shown in Table 5.

From Table 5, it can be seen that for the No. 2 coal seam in the Anping area, good and proficient cleanability resources were dominant. The fair cleanability coals were less distributed. Worse and poor cleanability coals were not found at all. Coals from the No. 10 seam in this area classify as fair, good, and proficient cleanability. In this case, fair and good cleanability coals were dominant, as shown in Table 5, while coals of proficient cleanability were less prevalent. Similar to the No. 2 seam, worse and poor cleanability coals were not found in the No. 10 seam either.

Table 5 shows that fair and good cleanability coals dominate in the No. 3 seam in the Xizhuang area, while poor cleanability coals occur in a lower proportion than other cleanability coals. This is a notable contrast to the Anping area, where no coals classified as poor were found. Proficient cleanability coals represent only a tiny proportion of the coal in this seam. As in the Anping area, coal with worse cleanability was not found. For the No. 3 seam in the Xizhuang area, fair and good cleanability coal resources clearly dominate; consequently, poor, and proficient cleanability coals contribute much less. Similar to previous results, coals of worse cleanability were not found.

Fair and good cleanability coal resources dominated for the No. 3 coal seam in the Yitang area, while both proficient cleanability and poor cleanliness coals were less common (Table 5). There were no coals with worse cleanliness. In the No. 10 coal seam, good and proficient cleanability coals were dominant. Coals having poor and worse cleanabilities were not found. This last observation is consistent with the results shown previously, poor cleanability coals either being absent or, at most, a small proportion of the seam, and worse cleanability coals not occurring at all in this area.

4.4. Summary and Discussion. A summary of all distribution areas, predicted reserves, and proportions of coals of different cleaning potentials for the three exploration areas combined is given in Table 6. The total predicted reserve of the coals in the three exploration areas is about 1460 million tonnes, including coals ranging from poor through proficient cleanabilities. No coals classified as worse cleanability were found.

By comparing the reserve proportions (Table 6) of coals with different qualities and cleaning grades in the three areas before and after coal preparation, the proportions of coals with good, fair, poor, and bad characteristics decrease dramatically, whereas the proportion of coal with excellent characteristic increases significantly after preparation. To a large extent, these results provide insight into the geological implications for coal preparation. In the present study, we classified scarce excellent, excellent, and good-quality coal, being characterized by the sulfur contents and ash yields no more than 1.5 and 20.0%, respectively, as high-quality coal. Hence, the proportion of high-quality coal is about 28.9%. At the same time, coal that can be processed into high-quality coal accounts for about 69.2% (Table 6). A comparative analysis of the reserve proportions of coals of different qualities and cleaning grade characteristics in the six coal seams (Tables 3 and 4) shows that most coal that formed in a terrestrial environment can be processed into high-quality coal, whereas only comparatively little of that formed in a paralic environment will yield high-quality coal. The coal seams that formed in different environments have been listed in Table 1.
Based on the previous studies and on the analyses presented in this paper, we propose a cleaning potential gradient ($\Delta P$) based on a comparison of the reserve proportions (Tables 2 and 3) of coals of different qualities and cleaning grades, that is, the post-preparation increment of the proportions of coals with different qualities and cleaning grades. To a large extent, the cleaning potential gradient expresses both the geological and physical meaning of the cleaning potential. The formula for calculating the cleaning potential gradient value is as follows

$$\Delta P (i, \Delta P_i) = \begin{cases} 1^\circ \sum_{i=1}^{\text{VI}} (\chi - x_i), & x_i < \chi \\ 0^\circ \sum_{i=1}^{\text{VI}} (\chi - x_i), & x_i \geq \chi \end{cases}$$

In eq 2, $\Delta P$ is the cleaning potential gradient; $i$, the quality/cleaning grade of raw coal/float coal; $x_i$ the proportion of coal with different qualities; $\chi$, the proportion of coal which can be processed into different cleaning grade float coals; and $(i, \Delta P_i)$, the cleaning potential level. The symbols I, II,..., IV represent the quality and/or the cleaning grade.

The value of $\Delta P$ by itself cannot accurately and specifically reflect the cleaning potential gradient. Using data for the No. 2 and No. 10 seams in the Anping area as specific examples, $\Delta P$ would instead be expressed as "$\Delta P (i, \Delta P_i) = 87.13\%$ (II, 81.01%; III, 6.12%)" and "$\Delta P (i, \Delta P_i) = 2.83\%$ (IV, 2.17%; V, 0.66%)", respectively. These results illustrate in detail the increments in the proportions of coals of different qualities/cleaning grade characteristics. $\Delta P (i, \Delta P_i)$ can reflect the cleaning potential gradient as well as the cleaning potential level. The cleaning potential gradient defined in this way was applied to the six seams in the three research areas. The results are shown in Table 7. For the whole six coal seams, the modes of the quality of raw coal, the cleaning grade of float coal, and the cleanability of coal are fair, excellent, and good, respectively. Their cleaning potential gradient is 59.3% (II) (Table 7).

Based on the modes of the data, both the quality of raw coals and the cleaning grade of float coal of No. 2 (Anping), No. 3 (Xizhuang), and No. 3 (Yitang) seams are better than those of the other seams in the three areas. The cleanability of coals of the Anping No. 2 and No. 10, the Yitang No. 3 and No. 9 seams is superior to those of other seams in the study areas. The proportion of high-quality coal in the raw coal of the Xizhuang No. 3 and No. 3 up seams exceeds that of the other seams in the areas. Nearly 100% of the float coal is high-quality coal from the Anping No. 2, the Xizhuang No. 3 up and No. 3, and the Yitang No. 3 seams. In contrast, the corresponding values for the Anping No. 10 and the Yitang No. 9 seams are no more than 6%. The cleaning potential gradient of No. 2 (Anping), No. 3 up, and No. 3 (Xizhuang), and No. 3 (Yitang) is better than that of other coals in the study areas (Table 7).

Combining these findings with the geological information on six seams, the quality of most raw coals and the cleaning grade of most float coals of seams formed in a terrestrial environment are clearly better than those of coals formed in a paralic environment. With respect to geological or physical aspects, the cleaning potential gradient of coal formed in a terrestrial environment is also better than that of coal formed in a paralic environment. From an economic perspective, the cleanability of coal in the Anping and Yitang exploration areas can be better than that of the Xizhuang area, which can be attributed to the organic sulfur content ($S_{o,d}/S_{d} \geq 70.0\%$) of coal in the Xizhuang area (Table 7).

The limiting value of sulfur content for high-quality coal is that it does not exceed 1.5%. From results for the Anping No. 10 and the Yitang No. 9 seams, we found that it is practically impossible to remove organic sulfur from coal by physical preparation processes such as flotation. This is completely consistent with the generally accepted observation for virtually all coals. In the specific case of the coals studied here, this means that it is difficult to process raw coal having an organic sulfur content more than 1.5% into high-quality prepared coal. Therefore, it makes little sense to process coal of >1.5% organic sulfur, even though such coal may have attractive values of cleanability. Another manifestation of the effect of organic sulfur content is that the cleanability of No. 9 seam in the Yitang area is remarkably better than that of No. 3 up and No. 3 seams in the Xizhuang area, although the cleaning potential gradients suggest the opposite. In this case, the situation is attributed to the high proportion of high-quality coal in raw coal and to the high ratio of organic sulfur to total sulfur. For a raw coal of good quality, it is difficult to further improve its quality through preparation processing. This shows the necessity of considering economic factors when contemplating the processing of raw coal of good quality.

In general, when the cleaning potentials of coal resources are evaluated, it is not only the sulfur contents and ash yields of coals before and after preparation that should be considered. It is also necessary to take into account the geological factors affecting genesis, contents, the modes of occurrence, and the forms of the sulfur and of the mineral matter in coal. These factors include the nature of the original coal-forming plant material, the depositional environment, the water salinity (i.e., whether fresh or marine), the coal-forming...
period, the distance between the provenance region and the area of sedimentation, possible bacterial and/or hydrothermal activity, and the degree of weathering and oxidation,” which are shown in Figure 5. In addition to these factors, moisture and relative humidity can affect the surface properties of low-grade coals and may further affect the cleanliness of coals during processing. Such possible effects of humidity and moisture need consideration and further study.

The detailed discussion of the effects of geological factors on the cleaning potentials of coals was shown in our previously published paper. In the present paper, we focused on the reserves of coals of different cleaning potentials and the changes in the relative proportions of coals of different qualities as a consequence of preparation processing. Based on these parameters, we have proposed the concept of a cleaning potential gradient. The rationality and applicability of the cleaning potential gradient will further examine in future studies, to be published in due course.

5. CONCLUSIONS

The total predicted coal reserve in the three exploration areas is about 1460 million tonnes, containing poor, fair, good, and proficient cleanliness coal resources. Fair and good cleanliness coals dominate, with proficient cleanliness coals also having a significant contribution. The cleanliness of the coals in the Anping and Yitang exploration areas are better than those of Xizhuang area.

The proportion of high-quality coal is about 28.9%. Raw coal, which can be processed into high-quality coal, accounts for about 69.2%. The proportions of coal with good, fair, and poor characteristics decrease dramatically, whereas the proportion of coal with excellent characteristic shows a corresponding significant increase as a result of the preparation of the raw coal.

The cleaning grade of float coal of the resources formed in a terrestrial environment is better than that of coal formed in a paralic environment, whereas the cleanliness, in the economic meaning, of coal depends greatly on the inorganic sulfur contents and also slightly depends on ash yields.

The necessity of processing raw coal of good quality needs to be considered in terms of economics. It does not make economic sense to process coal with an organic sulfur content more than 1.5%, even though it has better cleanliness.

It is important to recognize that that cleanliness reflects only the cleaning potential of coal as it undergoes preparation, that is, the degree of removal of ash and sulfur from float coal relative to the raw coal. Consequently, the cleanliness value cannot reflect or predict the actual quality of the float coal that would be produced. In addition, the equations used in the present work were not established to take into account the degree of removal of potentially hazardous trace elements (as examples, mercury, selenium, or arsenic) during the coal preparation processes. Both of these considerations need to be examined further, so that the evaluation method can be augmented to take them into account. Also, it should be clear that the present work does not consider process economics, that is, whether a coal of a particular cleanliness classification could be cleaned to a desired level of sulfur and ash reduction economically. At last, the geological factors having potential effects on cleaning potentials, except for coal-forming environment and local geological features (folds, faults), need further study. The work in this paper has considered only coals from three general exploration areas in one province. However, we believe that the approaches used in this work are of general applicability in the field of clean coal geology, and we hope that this work will stimulate similar studies by colleagues elsewhere.

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Notes
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