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Sources of rare earth elements REE+Y (REY) in Bayili Coal Mine from Wensu County of Xinjiang, China

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Abstract: By analyses on the trace elements of coals, host-rocks and wall-rocks, this study aims to trace the sources and evaluate the utilization prospects of REE+Y (REY) in coals from Bayili Coal Mine (Wensu, Xinjiang, China). The distribution patterns of REY in the coals are divided into two groups, flat-type and heavy REE-enrichment type (H-type). The REY of the former was mainly from the gneisses of the basement of the coal-bearing basin, and that of the later was partly from hydrothermal solution. The host-rocks show two types of REY patterns, middle REE-enrichment type (M-type) and H-type, which are due to the injection of REY from acid terrestrial water and hydrothermal solution, respectively. Almost all the coal samples are plotted into the promising area on the diagram of percentage of critical elements ($\mathrm{REY}_{\mathrm{def,\ rel}}$) vs ratio of sum of critical elements to the sum of excessive elements (C_{outl}) and half of the coal samples have high contents of Ga closing to the cut-off grade of Ga deposit as by-product, which indicate that the REY and Ga in Bayili Coal Mine are of utilization prospects as by-product.

Key words: source; rare earth elements; distribution pattern; coal; Wensu County (Xinjiang)

1 Introduction

Rare earth elements and yttrium (REY) are widely used as metal catalysts, phosphors, light-emitting diodes, permanent magnets, various components for renewable green energy equipment, and batteries [1]. The importance of REY has been universally recognized in recent years due to relative changes in supply and demand [2]. Just because of the strategic importance of REY to advanced technologies and national security and defense, several legislative proposals to support domestic production of REY have been passed by U.S. Government [3]. Lanthanides (fifteen elements from lanthanum to lutetium) and Y, i.e. REY, together with scandium (Sc), were defined as the REE by the International Union of Pure and Applied Chemistry. The geochemical classifications of REE or REY (REE+Y) are different according to research purposes. SEREDIN and DAI [4] divided the REY in coal into light (LREY: La, Ce, Pr, Nd, and Sm), medium (MREY: Eu, Gd, Tb, Dy, and Y), and heavy (HREY: Ho, Er, Tm, Yb, and Lu) groups. This classification is more convenient than other classifications for description of the REY distribution in coals. According to the relationship between demand and supply of individual REY in recent years, SEREDIN [5] has divided REY into critical (Nd, Eu, Tb, Dy, Y and Er), uncritical (La,

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Pr, Sm and Gd) and excessive (Ce, Ho, Tm, Yb and Lu) groups.

The REE deposits can be broadly divided into two genetic types, primary deposits and secondary deposits [6]. The primary REE deposits are mainly associated with carbonatite–alkaline complexes [7], which cover about 51% of the total rare-earth oxide reserves worldwide and approximately 65% of China's REE reserves [8,9]. The secondary REY (supergene) deposits can be represented by weathered crust elution-deposited (ion-adsorbed) deposit, which is one of typical REY deposits developed in South China [10,11]. The carbonatite deposits usually have high REY contents and large reserves, but are typical sources of only LREY. Though the weathered crust elution-deposited ore deposits are sources of all REY metals, this type of deposits is characterized by low total REY contents and small reserves [10]. Moreover, the resources of these weathered crust elution-deposited ore deposits are being exhausted [12]. As the exponential growth of REY consumption in the 21st century, the rare-earth raw material crisis has become a serious problem that we have to face. Therefore, prospecting for and exploiting new REY alternative resources have become extremely urgent and important.

The REY contents in all the coals are lower than those of UCC (upper continental crust). However, during coal burning process, REY are strongly retained in the solid residue (coal ash) after coal combustion [13], which leads to the REY enrichment in the coal ashes relative to the original coals. Assuming that all the REY are remained in the coal ashes, enrichment can be up to approximately 5 to 10 times for the coals having mineral contents of 20% to 10%, respectively [14]. According to this conversion rate, the total $(REY)_2O_3$ in the coal ash produced by combustion of Chinese average coal will reach 972 μg/g, which is close to or higher than the cut-off grade (800−900 μg/g) suggested by SEREDIN and DAI [4]. It can be seen that the REY-rich coal deposits will be new potential resources of REY metals.

The enrichment of REY in coals is influenced and controlled by many factors [15]. DAI et al [16] summarized the enrichment of trace elements in Chinese coals as five genetic types: (1) source-rock-controlled; (2) Marine-environment-controlled; (3) hydrothermal-fluid-controlled; (4) ground-water-controlled; (5) volcanic-ash-controlled. The sources of the REY in coals provide the basic data for analysis of the accumulation process and genetic mechanism of enrichment. This study aims to trace the sources of REY in the coals from Bayili Coal Mine in Wensu County (Xinjiang, China) based on the REY and other trace elements data.

2 Geological setting

Bayili Coal Mine from Wensu County of Xinjiang, China, is located in the middle part of Kuqa Foreland Depression, which extends in a nearly E−W direction between Tianshan Mountains in the north and the Tarim Plate in the south. This depression is a meso-cenozoic sedimentary basin, where many coal mines are distributed. Bayili Coal Mine is one of these coal mines in Wensu County, Xinjiang, China (Fig. 1).

The basement rocks of the basin, which are exposed in Haerke Mountains in the northern adjacent region of the depression, are composed of Proterozoic gneisses, Carboniferous tuffaceous sandstone and Hercynian granites. The sedimentary sequences in the Bayili Coal Mine include Triassic, Jurassic, Cretaceous, Tertiary and Quaternary strata.

Triassic strata include Ehubulak Group ($T_{1\text{-}2}e$), Kelamayi Formation ($T_{2\text{-}3}k$) and Huangshanjie Formation (T_3h). Ehubulak Group is composed of purple or greyish green conglomerate, pebbly sandstone, coarse sandstone intercalated fine sandstone and muddy siltstone. Kelamayi Formation consists of sandstone, siltstone and black carbonaceous mudstone. Huangshanjie Formation is mainly composed of dark grey or black muddy shale interlayered by sandstone. Triassic strata contact with underlying basin basements in fault or unconformity.

Jurassic strata include lower Jurassic Tariqik Formation (J_1t), Ahe Formation (J_1a) and Yangxia Formation (J_1y), which are the coal-bearing sequences in the region, as well as middle Jurassic Qiakemake Formation (J_2q). The Tariqik Formation is composed of dark grey sandy conglomerate, coarse sandstone, fine sandstone, siltstone and coal seams, with an average thickness of 56.79 m. The Ahe Formation mainly consists of interbedded grayish-white fine conglomerate, coarse sandstone and fine sandstone. The thickness of this formation is about 196 m. The Yangxia Formation, with a

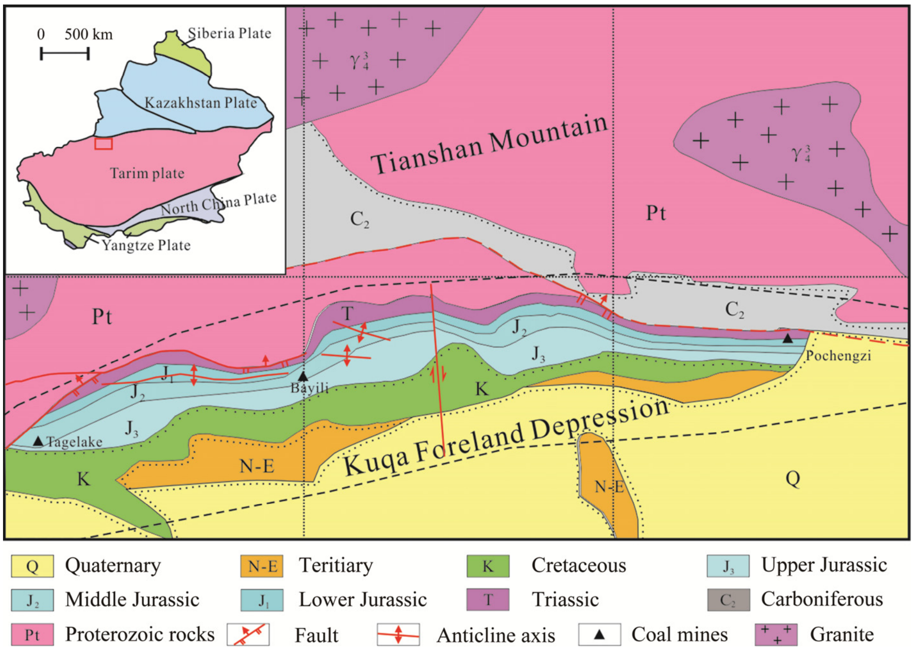

Fig. 1 Location of Bayili Coal Mine, Wensu county, Xinjiang, China

thickness of 380–578 m (average 434 m), is divided into lower, middle and upper parts. The lower portion consists of gray-green siltstone, fine sandstone and gray-brown carbonaceous mudstone, intercalated with lenticular gray-yellow siltstone. The middle part is composed of yellow or grey coarse sandstone, gravel-bearing coarse sandstone, fine sandstone and siltstone. The upper portion is composed of mudstone and muddy siltstone, with a layer of coal seam at the uppermost part. The middle Jurassic Qiakemake Formation is mainly composed of gray-green or gray-yellow coarse sandstone with fine sandstone interlayer, siltstone and carbonaceous mudstone, and gray-white conglomerate and coarse sandstone. The thickness of Qiakemake Formation is approximately 426 m. The Jurassic sequence is underlied by the Triassic strata in conformity, and overlied by different strata from Cretaceous to Quaternary in different places in the coal mine.

3 Samples and analyses

The samples include coals, immediate host-rocks (carbonaceous siltstones and silty mudstones) and wall-rocks of coal-bearing sequence, as well as basement-rocks of the basin, including Carboniferous tuffaceous sandstones, Proterozoic gneisses and Hercynian granites.

The samples for major elements analysis were digested using HNO_3−$HClO_4$−HF−HCl solution. Low carbonaceous and high carbonaceous samples were melted by lithium borate and lithium nitrate, respectively. The detection instruments are inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Agilent 5110, USA) and X-ray fluorescence spectrometer (XRF, PANalytical PW2424, Holland). Three sub-samples were prepared for all samples. One sub-sample was digested with 4-acid solution and analyzed by ICP-AES, to check the grade of S, Ca, Fe, Mn, Cr etc and minor elements, to confirm the applicability of XRF procedures. Another sub-sample, after being fused with lithium metaborate−lithium tetraborate flux and an oxidizing agent (lithium nitrate), was used for major elements analysis by XRF spectrometry. The third pulp sub-sample was used for determining a loss-on-ignition at 1000 °C. All the resulting data were combined to produce a "total". The difference for high carbonaceous samples should be fired before fusion. The relative deviation of precision control was less than 10%, and the relative error of accuracy control was less than 10%.

Two sub-samples for trace and ultra-trace elements analysis were prepared. One sub-sample was digested with HF−HNO_3−$HClO_4$ solution. The residue was leached with dilute hydrochloric acid.

The solution was analyzed by inductively coupled plasma-mass spectrometry (ICP-MS, Agilent 7900, 7700x, USA) for ultra-trace level elements and by inductively coupled plasma-atomic emission spectrometry (ICP-AES, USA, Agilent 5110) for trace level elements. The results were corrected for spectral inter-element interference. Another sub-sample was added to lithium metaborate/ lithium tetraborate flux, mixed well and fused in a furnace at 1025 °C. The melt was then cooled and dissolved in an acid mixture containing nitric, hydrochloric and hydrofluoric acids. This solution was then analyzed by inductively coupled plasma-mass spectrometry. According to the actual situation of the sample and the digestion effect, the comprehensive value was the final test results. For high carbonaceous samples, the difference should be fired before fusion. The relative deviation of precision was less than 5% (XRF) and 10% (ICP), and the relative error of accuracy was less than 5% (XRF) and 10% (ICP). Both the major and trace elements analyses were completed by the ALS Chemex (Guangzhou) Co., Ltd., China.

4 Results

4.1 Major elements

4.1.1 Rocks from coal mine

The analysis results of major elements show that the contents of most major element oxides of coals are much lower than the average contents of Chinese coals (ACCC) [16] except MnO_2, which possibly results from the lower contents of detrital and clay minerals in the coals relative to those in Chinese average coals. The immediate host-rocks (carbonaceous siltstones and silty mudstones) have much higher contents of most major element oxides than ACCC, except for P_2O_5, MnO and Fe_2O_3, which probably reflects the characteristics of the source rocks.

4.1.2 Basement rocks

Almost all types of the basement rocks have similar contents of SiO_2, Al_2O_3, K_2O, Fe_2O_3 and TiO_2. But Proterozoic gneisses and Hercynian granites have higher contents of Na_2O and CaO than Carboniferous tuffaceous sandstone. The contents of MgO and MnO of Proterozoic gneisses are higher than those of granites and tuffaceous sandstones. The contents of P_2O_5 are the highest in gneisses and the lowest in tuffaceous sandstones. Generally, the gneisses are rich in Mg, Mn and P relative to granites and tuffaceous sandstones. The tuffaceous sandstones are poor in P, Na and Ca.

4.2 Distribution patterns of REY

4.2.1 Rocks from coal mine

The REY patterns of coals from Bayili Coal Mine can be divided into two groups. The first group shows flat-type in REY partition patterns and is low in REY contents. The second is characterized by enrichment in HREE (H-type), which is more enriched in REY relative to the former. The two groups show no evident Eu and Ce anomalies (Fig. 2(a)). Almost all the immediate host-rocks that belong to coal-bearing sequence and are adjacent to coal seam, but are not coals (see Fig. 2 [17]) from Bayili Coal Mine have similar REE distribution patterns enriched in MREE with all the $La_N/Sm_N<1$ (0.60−0.92) and the most $Gd_N/Lu_N>1$ (0.95−1.69) for the samples (Fig. 2(b)). The δCe values of the samples are 0.921−1.035, closing to 1 and showing no Ce anomalies. The δEu values are between 0.813 and 0.995, showing weak Eu negative anomalies, which belong to subtype 3 (swell-like without Eu-anomalies) [4]. The wall-rocks, which do not belong to coal-bearing sequence and lie upper or lower coal-bearing sequence (see Fig. 2), can be divided into two groups by REY partition patterns. One group shows flat-type REY patterns without REY fractionation and is low in REY contents. The other is characterized by slight enrichment in MREE and has higher REY content (Fig. 2(c)). The later is close to subtype 3 of M-type according to SEREDIN and DAI [4].

4.2.2 Basement rocks

The basement rocks of the basin, Carboniferous tuffaceous sandstones, Proterozoic gneisses and Hercynian granites, have different REY contents and partition patterns. The tuffaceous sandstones are characterized by enrichment in HREE with $La_N/Lu_N<1$, $La_N/Sm_N<1$ and $Gd_N/Lu_N<1$. The δEu and δCe are 0.56−0.65 and 0.57−0.97, respectively, showing moderate Eu negative anomalies and weak Ce negative anomalies. The contents of REY are moderately high with an average ratio of REY/UCC about 2.3 for all the samples (Fig. 2(d)). The gneisses have flat-type REE partition patterns, without δEu and δCe anomalies and with REY/UCC closing to 1 (Fig. 2(d)). The granites are also characterized by

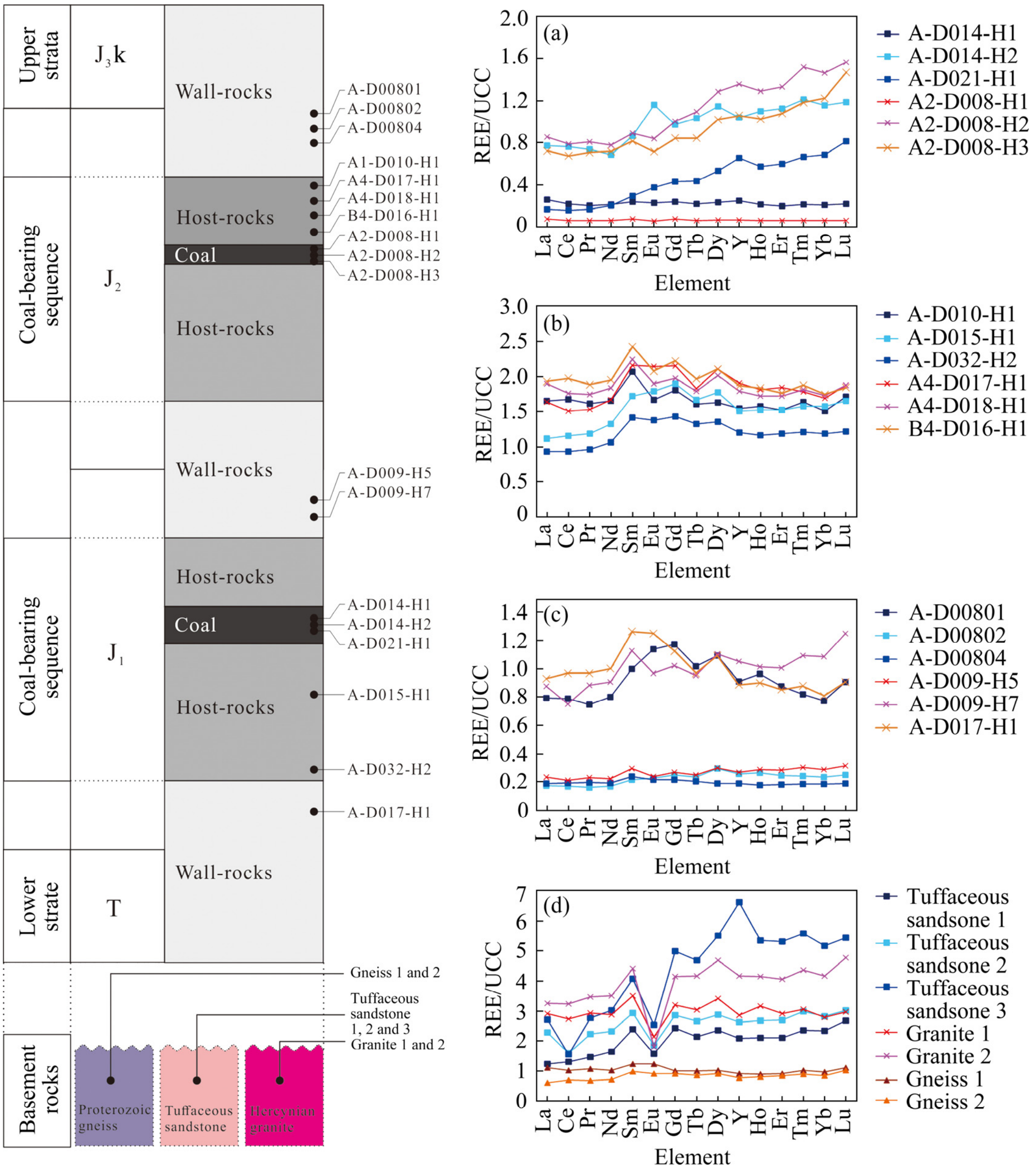

Fig. 2 REY patterns of samples from Bayili Coal Mine (Normalized by upper continental crust [17]): (a) Coals; (b) Host-rocks; (c) Wall-rocks; (d) Basement rocks

flat-type for REE partition patterns similar to those of gneisses, but show strong Eu negative anomalies (δEu=0.424−0.644) and have very high REY contents (the average ratio of REY/UCC is about 3.2) (Fig. 2(d)).

5 Discussion

5.1 Sources of REY in coal-bearing sequence

The REY in the coal-bearing sequence can be from various and multiple sources, including sediment-source rocks, seawater, groundwater, volcanic ashes, hydrothermal solutions, magmatic fluids, and submarine exhalation [16,18]. Actually, the REY from groundwater and hydrothermal solutions could be originally from sediment-source rocks and transported into the basin by the groundwater and hydrothermal solutions. Generally, the sediment-source rocks have great influence on REY contents and enrichment in the coal-bearing sequence. Just as pointed by DAI et al [16], the nature of sediment-source region located on the margin of coal basin is the dominant factor for the background values of trace elements in the coal basin.

However, the leaching, transporting and

depositing of REY by various water (or fluids) could produce overprints of total REY signatures on various sedimentary rocks in the coal-bearing basin. By research on REY occurrence in numerous Chinese coals, DAI et al [16,19,20] found that both terrigenous and hydrothermal influences can affect the distribution of REY in coals. Thus, during tracing the sources of REY in coal-bearing sequences, detailed analysis of REY patterns of coal-bearing sequence and sedimentary source-region rocks is necessary.

The REY partition patterns and some fractionation indexes, such as anomalies of La, Ce, Eu, Gd, and Y, can often be used to identify the sources and accumulation mechanism of REY in coals [3]. In Bayili Coal Mine, the REY partition patterns of coals, host-rocks and wall-rocks are different. The coals show two types of REY patterns: flat-type (poor in REY) and H-type (rich in REY). The host-rocks have a similar REY pattern characterized by M-type enrichment with weak Eu negative anomalies (close to subtype 3). The wall-rocks show two types of REY patterns, flat-type (poor in REY similar to coals) and M-type (rich in MREE and without Eu anomalies).

The REY patterns of all the above rocks can be divided into three categories: (1) flat-type (N-type, can be subdivided into two subtypes): subtype 1 (without or with weak Eu anomalies), including the coals with low REY contents, the wall-rocks with low REY contents and basement gneisses; subtype 2 (with strong Eu negative anomalies and high contents of REY), presented by basement granites; (2) H-type, including tuffaceous sandstones (belonging to subtype 1, with strong Eu negative anomalies) and coals with moderate REY contents (belonging to subtype 2, without Eu anomalies); (3) M-type, without or with weak Eu negative anomalies, including host-rocks and the wall-rocks with moderate REY content (Figs. 2(b) and (d)).

It can be seen from the above analysis that the N-type of REY pattern of the coals and the wall-rocks with low REY content is similar to that of gneisses in basin basement. These coals and wall-rocks probably inherit and remain the REY signatures of the source-region rocks, which indicates that the gneisses are one of the sources of REY in the coal-bearing sequence. The coals with moderate REY contents show a similar REY pattern (H-type) to that of the tuffaceous sandstones in basement, but the Eu anomalies are very different. The host-rocks and the wall-rocks with moderate REY contents show M-type of REY without or with weak Eu negative anomalies, which are different from the REY patterns of basement rocks. The significant difference between coals and basement rocks in REY distribution patterns indicates that the REY in coals comes from other sources besides basement rocks.

5.2 Terrestrial waters and REY sources in coal-bearing sequence

It can be seen from the above discussion that some other sources of REY have contributed to the coal-bearing sequence. Two marked characteristics of the REY patterns in the coal-bearing sequence from Bayili Coal Mine are: (1) the REY contents of the coals with H-type REY partition are higher than those of the coals with flat-type partition; (2) M-type of REY distribution is quite common in coal-bearing sequence, including the immediate host-rocks and wall-rocks.

M-type of REY distribution is rather typical for the coals that have reacted with acid natural waters circulated in the coal basins [5]. Terrestrial water can influence the REE contents and partition patterns of the rocks by water−rock interactions. Because the compositions of terrestrial waters vary substantially compared to that of seawater, the REE signatures of various terrestrial waters overprinted on the rocks might be different. Studies have demonstrated that the acid water shows enrichment in MREE and alkaline water shows enrichment in HREE [21−23]. According to this, it is suggested that the M-type of REY distribution in the host-rocks and wall-rocks from Bayili Coal Mine resulted from acid natural waters, probably the circulated acid terrestrial waters. Because the M-type distribution is not only shown in the immediate host-rocks but also in the wall-rocks, the waters (fluids) flow is characterized by regional circulation. Just as pointed out by JOHANNESSON et al [22] that all of the acid waters exhibit the shale-normalized REE patterns being generally enriched in MREE over both LREE and HREE, the acid terrestrial waters drained into the coal basin could be enriched in MREE after they flowed through the basement rocks. When circulated inside the coal basin, the MREE-enriched water should impart the REE signatures to the wall-rocks and host-rocks of the coals by water−rock interaction, which has been demonstrated by previous studies [24]. Because of the impermeable feature, the coals do not show enrichment in MREE for the absence of significant water−rock interaction, although the coals are rich in humic matter which is easier to absorb MREY than to absorb LREY and HREY [25].

5.3 Hydrothermal fluids and REY sources in coal-bearing sequence

The H-type REY distribution in the coals is especially frequent [4,23,24]. One of the results can be explained by the injection of materials from mafic rocks which are enriched in HREE normalized to UCC. However, no mafic rocks including mafic dykes and tuffs were formed during or post the development of the coal-bearing basin in the studied region. The Al_2O_3/TiO_2 mass fraction ratio is a useful indicator in inferring the rock types in the sediment-source region for coal deposits [20,24]. The sediments derived from mafic, intermediate, and felsic igneous rocks have the Al_2O_3/TiO_2 ratios of 3–8, 8–21, and 21–70, respectively [26]. The Al_2O_3/TiO_2 mass fraction ratios of the coals, immediate host-rocks and wall-rocks from Bayili Coal Mine suggest that these rocks were from terrigenous rocks with felsic–intermediate compositions (Fig. 3).

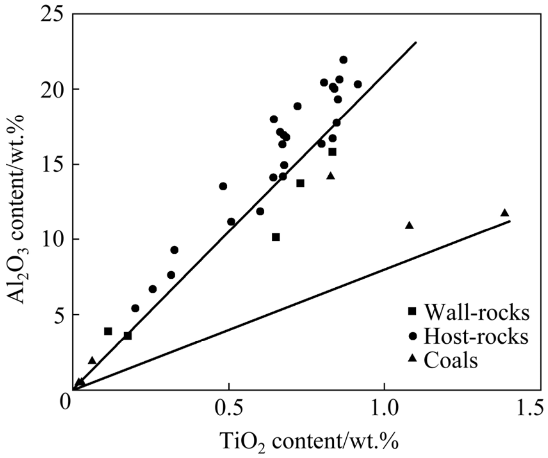

Fig. 3 Plot of mass fractions of Al_2O_3 versus TiO_2 for rocks from Bayili Coal Mine

Therefore, there are some other factors besides the sediment source rocks being responsible for the HREE enrichment in the coals. A number of studies have proved that the influences of waters (fluids), including marine waters, alkaline terrestrial waters, some low-temperature alkaline hydrothermal solutions, and high-temperature (>500 °C) volcanogenic fluids, can explain the geneses of the H-type REE distribution in coals [23,27]. The tectonic background and evolution of studied region demonstrate that the marine water was absent during and post the development of the coal-bearing basin. Therefore, marine water is not the cause of the HREE-enrichment of the rocks. The H-type REY distribution in the coals cannot be explained by the influence of high-temperature volcanogenic fluid, because the volcanic activity was absent during and post the development of the coal basin. Consequently, alkaline terrestrial waters and low-temperature alkaline hydrothermal solutions are probably the factors resulting in heavy HREE enrichment in the coals.

The terrestrial waters have been discussed above. The M-type REY distribution of the wall-rocks and host-rocks demonstrates that the groundwater is of acid but not of alkaline character. Thus, the most likely factor leading to the coals enriched in HREE is the hydrothermal solution. A number of studies have proved that many different coals in the world are characterized by HREE enrichment, which is just the influence of hydrothermal fluid/solution on the coal [15,16,24,28,29].

It is probably argued that the REY in coals may be influenced by coal-forming environment. However, it can be seen from Fig. 2 that from bottom to top, the coals have not shown systematical variations in REY contents and patterns, and the host-rocks have the same situation. Therefore, it is suggested that the enrichment and distribution of REY in coals are not affected significantly by coal-forming environment, and mainly controlled by other factors, such as sediment-source regions [30]. Moreover, SEM-EDS analyses show that the REY in the coals in Bayili Coal Mine mostly occurs inside clay mineral kaolinite and REY-bearing detrital mineral xenotime, which also indicates that the sediment-source rocks are the principal controlling factors of REY in the coals.

From discussion above, it is suggested that the REY in Bayili coals mainly was originated from basement rocks of the basin, and partly from acid terrestrial water and hydrothermal solution.

5.4 Potential utilization prospects of REY and other trace elements

5.4.1 Utilization prospects of REY in Bayili Coal Mine

REY recovery as a by-product from coal deposits is considered as a promising way for obtaining these critical metals [5]. A number of studies have evaluated and discussed the utilization prospects of the REY in coals [4,12,14,16,20,31,32]. The average total REY contents of world coals, USA coals and Chinese coals are 68.5, 62.1 and 137.9 μg/g, respectively [33−35], all of which are lower than that of upper continental crust (UCC, 168.4 μg/g) [17]. Appraising of industrial utilization of REY in coals as by-product is generally based on the sum REY oxides (REO) contents in the coal ashes produced by the combustion of the coals. The average content of REO in world coal ashes is about 404 μg/g [33]. SEREDIN and DAI [4] suggested that the cut-off grade of REY mineral resource as by-product could be taken as 800−900 μg/g for coal seams with thicknesses of >5 m.

The calculated average REO content in coals from Bayili Coal Mine is 99.8 μg/g. However, the REY can be enriched in coal ashes by 5 to 10 times relative to the feed coals having mineral matter contents of 20% to 10%, respectively [14]. This is because the REE are strongly retained in the solid residues (ashes) after coals combustion [13] and the coal ashes are only a small mass fraction of the burned coals. According to this, if the mineral matter content is over 15%, the REO content in the ash produced by the combustion of the coal from Bayili Coal Mine would be nearly 800 μg/g. Study by BLISSETT et al [36] has shown that it is possible to enrich REY in coal ashes with 505 μg/g REO to approach that required for economic extraction by a multistage processing route.

Certainly, the mode of occurrence of the REY in the coals is a very important factor to evaluate the utilization prospects of REY as a by-product. The occurrence of the REY in the coals controls the behavior of the REY during coal combustion. Although a number of studies have demonstrated that the distribution of REY in the coals is predominantly controlled by mineral matter, which is favorable to keep the REY in the coal ashes after the combustion of the coals. However, the organic-hosted REE have also been suggested, especially for HREE [37]. Fortunately, the REY in the coals in Bayili Coal Mine mainly occur inside clay mineral kaolinite and REY-bearing detrital mineral xenotime (Fig. 4).

By considering the REY content in the coals and the relationship between demand and supply of individual REY, SEREDIN and DAI [4] proposed a comprehensive evaluation method to appraise the prospect of coal, which has been mentioned above. According to the plot of outlook coefficient (C_{outl}) vs percentage of critical elements in total REY ($\text{REY}_{\text{def, rel}}$), almost all the samples from Bayili Coal Mine belong to the second type ($30\%\le\text{REY}_{\text{def,rel}}\le 51\%$ and $0.7\le C_{\text{outl}}\le 1.9$) (Fig. 5), which can be regarded as promising REY raw materials for economic development [4].

5.4.2 Evaluation on other trace elements

Besides REY, many other elements in the coals have also attracted high attention as by-product. For example, after evaluation on the promising of REY in U.S. domestic coals [3], other elements including Li, Be, Ti, V, Mn, Co, Ga, Ge, Se, Zr, Nb, Ru, Rh, Pd, In, Sn, Sb, Te, Ba, Hf, Ta, Re, Os, Ir, Pt and W, were selected for evaluation as recovery of critical elements [38]. The element Ga, which is used widely in alkaline aluminum batteries [3], deserves attention and has the prospect of comprehensive utilization in the Bayili Coal Mine. Ga contents in Chinese coals and world coals are 6.55 μg/g [16] and 5.8 μg/g [33], respectively. The industrial grade of Ga content in coals is 30 μg/g [16]. The Ga content in the coals from Bayili Coal Mine is anomaly high. Half of the coal samples have Ga contents (23.7−29.7 μg/g) close to industrial grade as by-product. But it is regret that the mode of occurrence of the Ga in the coals was not determined in this study. The carrier minerals of Ga in coals are mainly boehmite, kaolinite, strontium phosmobite, bauxite and so on. And the Ga generally exists inside clay minerals and kaolinite in the form of microscopic inclusions or analogues matter [39]. But Ga was not found inside these minerals by SEM-EDS. Therefore, the mode of occurrence of Ga in the Bayili coals remains research. However, it is still believed that Ga has a good comprehensive utilization prospect in the coals from Bayili Coal Mine.

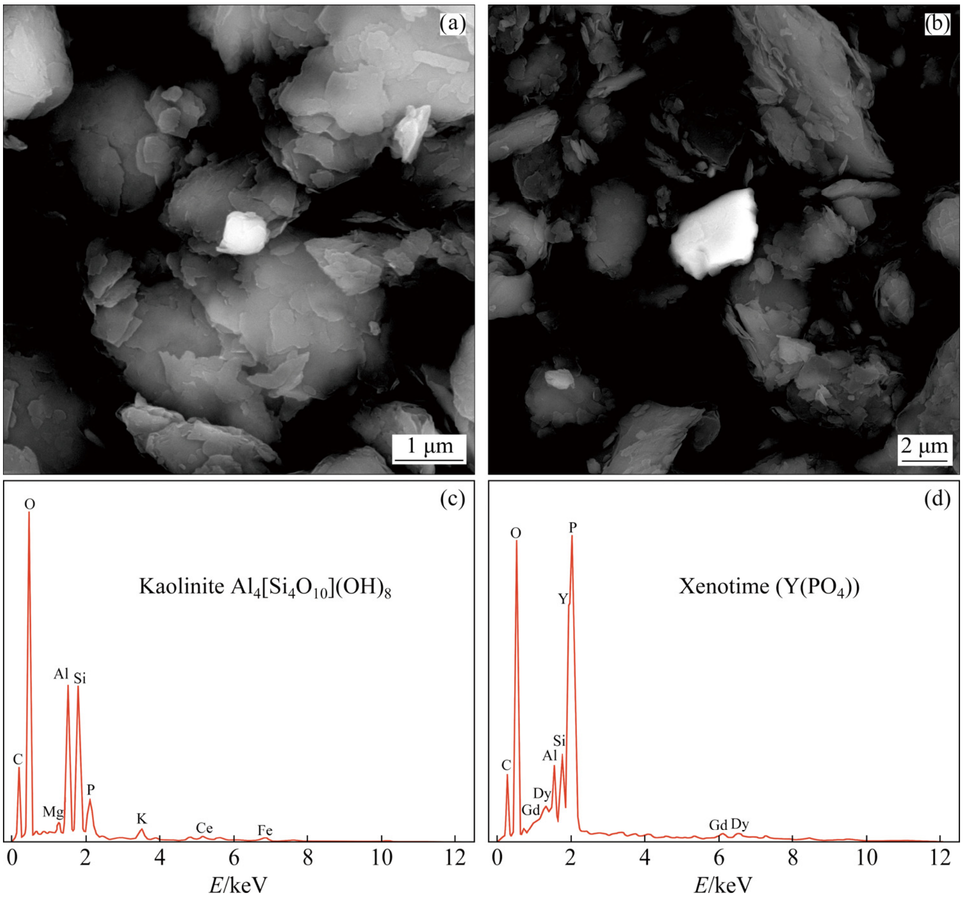

Fig. 4 Back-scattered electron images (a, b) and EDS spectra (c, d) of kaolinite (a, c) and xenotime (b, d)

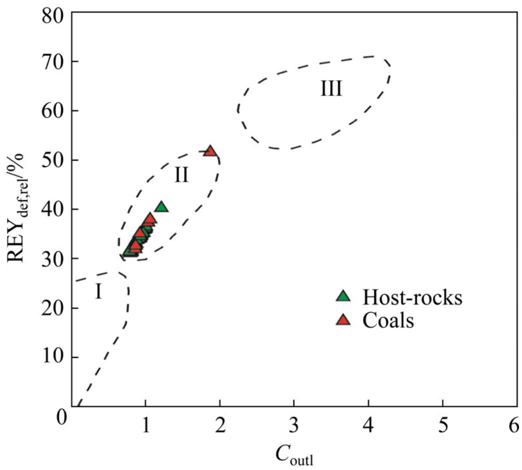

Fig. 5 $REY_{def,rel}$−C_{outl} plot for samples from Bayili Coal Mine: I−Unpromising; II−Promising; III−Highly promising; $REY_{def,rel}$−Percentage of critical elements (Nd, Eu, Tb, Dy, Y and Er) in total REY; C_{outl}−Ratio of sum of critical elements to the sum of excessive elements (Ce, Ho, Tm, Yb and Lu)

6 Conclusions

(1) The accumulation of the REY in coal-bearing sequence from Bayili Coal Mine in Wensu County, Xinjiang, China, has undergone multi-stage geological processes, which leads to various distribution patterns of REY in the coals, immediate host-rocks and wall-rocks.

(2) The REY showing flat-type pattern in the coals was mainly originated from the gneisses in the basin basement. The REY of H-type pattern in the coals was derived partly from hydrothermal solution, which elevated the REY contents and changed the REY distribution pattern inherited from source-rocks.

(3) The M-type REY distribution, presented by the host-rocks and part of wall-rocks, was formed by the influence of acid terrestrial water on the rocks.

(4) The REY and Ga are of good utilization promising as by-product in Bayili Coal Mine. According to the diagram of $REY_{def, rel}$ versus C_{outl}, almost all the samples from Bayili Coal Mine belong to promising scope for the economic development. A part of Ga contents of the coals are close to or exceed the cut-off grade of Ga deposit as

by-product, which indicates that the Ga in Bayili Coal Mine is economically significant.

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新疆温宿巴依里煤矿稀土和钇(REY)的物质来源

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摘　要：通过对新疆温宿县巴依里煤矿中煤、主岩和围岩中微量元素的分析，探讨新疆温宿巴依里煤矿中稀土等元素的来源及其作为煤矿伴生资源的利用前景。巴依里煤矿煤中的稀土元素配分模式可分为平坦型和重稀土富集型(H 型)两类。前者 REY 主要来源于含煤盆地基底的片麻岩；后者部分来源于热液。含煤岩系的主岩中稀土元素分布模式可分为中稀土富集型(M 型)和重稀土富集型(H 型)两类，分别与 REY 部分来源于酸性陆地水和热液有关。在煤矿 REY 应用前景评价判别图，即关键元素百分比($\mathrm{REY}_{\mathrm{def,\ rel}}$)−关键元素总量与过量元素总量比($C_{\mathrm{outl}}$)图解中，几乎所有的样品都落在有前景成矿区域。有一半的煤样具有较高的 Ga 含量，接近作为煤伴生资源的边界品位。这表明，巴依里煤矿中 REY 和 Ga 作为煤矿伴生资源具有很好的利用前景。

关键词：物质来源；稀土元素；配分型式；煤；温宿县(新疆)

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