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Composition and Trace Element Content of Coal in Taiwan

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ABSTRACT

To investigate the trace element contents of local coal, four coal samples were collected from operating mines in NW Taiwan. Detailed petrographic and chemical characterization analyses were then conducted. Analytical results indicate that (1) the samples were high volatile bituminous coal in rank with ash content ranging from 4.2 to 14.4% and with moisture content ranging from 2.7 to 4.6%; (2) the macerals were mostly composed of vitrinite with vitrinite reflectance less than 0.8%; (3) the sample of Wukeng mine has the highest Fe_2O_3 (29.5%), Tl (54.8 ppm), Zn (140 ppm), and As (697 ppm) contents in ash and Hg (2.3 ppm) in the coal. If used properly, these coals should not present health hazards.

(Key words: Trace element, Coal ash, Petrographic analysis)

1. INTRODUCTION

Coal seams usually originate from peat deposited in swamps, especially a stable, continually subsiding swamp in a warm and humid climate. Besides the major elements C, H, O, N, S, trace elements (< 1 wt %) may also reflect the depositional environment of peat. Furthermore, a better knowledge of coal quality parameters may help to minimize some of the health problems caused by coal use. Information about the concentration and distribution of potentially toxic elements in coal may assist people to avoid those areas of coal deposit having high concentration of these elements. The purpose of this study is to evaluate the depositional environments and public health concerns of four operating coalmines in Taiwan, by analyzing the coal composition and trace element contents.

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2. LITERATURE REVIEW

Goldschmidt (1935) was the first to study the abundances of trace elements in coal ash. Swaine (1975) discussed the concentration, origin and enrichment of trace elements in coal. Gluskoter et al. (1981) described the affinity of trace elements according to their association with organic or inorganic materials in coal. Finkelman (1981) pointed out that in a low rank coal such as lignite and sub-bituminous coal, trace elements such as Na, Mg, Ca, Sr, and Ba usually associated with organic constituents in coal. Finkelman (1982) then studied the modes of occurrence of trace elements in detail.

Pareek and Bardhan (1985) had studied the association of trace elements with macerals and found that Cu, Ni, Co, V, Ga, and B usually associated with vitrinite, although Cu and Ni can originate from both organic and inorganic sources. Martinez-Tarazona et al. (1992) believed that most of the trace elements in bituminous coal were concentrated in detritus and diagenetic minerals. Lu et al. (1995) investigated the distribution of trace elements of coal in China, Spears and Zheng (1999) studied the origin of elements in UK coal, whereas Helle et al. (2000) completed the chemical characterization of coals from Chile. Their results indicate a similar organic/inorganic association trend.

Chou (1984) studied the geochemistry of coal and overlying strata in the Illinois Basin, U.S.A. He concluded that high-sulfur coal is also enriched in Mo, B, U, Fe, Tl, and Hg relative to low-sulfur coal. The excess amounts of S, Mo, B, and U in high-sulfur coal were probably derived from seawater that flooded the swamp and stopped peat deposition, because concentrations of these elements in seawater are much higher than those in fresh water. On the other hand, concentrations of Fe, Tl, and Hg are extremely low in seawater. Therefore, it is suggested that Fe, Tl, and Hg were derived from a terrigenous source by weathering and were transported to the swamp by rivers. Furthermore, chalcophile elements (Mo, Fe, Tl, and Hg) were incorporated in pyrite during the early diagenesis of peat in a sulfur-rich and reducing environment. B and U were associated predominantly with the organic matter.

Some of the trace elements were found to be a good indicator of their depositional environment. Bouska (1981) pointed out that Th/U > 7 in terrestrial sediments whereas it is < 7 in marine sediments. Furthermore, the higher Th/U ratio indicates a more oxidized environment. Taylor and McLennan (1985) had studied the Th/U in Post-Archean shale and adjusted the terrestrial-marine threshold to 4.8. Gayer et al. (1999) also concluded the lower Th/U ratio was found in a more reductive, marine influenced coal seam.

In addition, Chao et al. (1994) pointed out the SiO_2 and Al_2O_3 contents can be used as indicators of terrestrial-prone depositional environments, whereas the CaO, MgO and Fe_2O_3 contents can be used as indicators of marine-prone depositional environments, because of their weathering-resist properties. They also proposed a $(CaO + MgO + Fe_2O_3) / (SiO_2 + Al_2O_3)$ ratio higher or lower than 0.22 indicating a strong or weak reductive depositional environment for humic coals, respectively. Tang et al. (1996) further discussed how the ratios of Sr/Ba and B/Ga could be used as indicators of a depositional environment. According to them, Sr/Ba ratio 0.1~0.6, 0.7~1.2, 1.3~1.6 and B/Ga ratio < 4, 4~10, > 10 implied terrestrial, littoral to brackish water, and marine depositional environments, respectively.

As for public health concerns, Finkelman et al. (1999) studied the health impacts of domestic coal use in China. They found that certain local diseases in SW China could be attributed to As, Hg, F, Se poisoning by trace element emissions from residential coal burning. Information on the modes of occurrence of these toxic elements and the textural relations of the minerals and macerals may help predict the behavior of the potentially toxic components during coal combustion.

3. LOCAL COAL GEOLOGY

Ho (1983) studied and mapped in detail nearly all of the major coalfields in northern Taiwan. Tsai (1988) evaluated the paragenetic relationship between coalification and tectonic movement by studying the orientation of the reflectance indicatrix of vitrinite. Hsiao and Hu (1990) combined various geologic and geophysical plus well-logging data and made a complete Tertiary basin analysis of western Taiwan. Their investigation includes stratigraphic correlation, sedimentary study, tectonic evolution, and reservoir analyses. In addition, Tsai and Sun (1993) conducted a study on coal petrology and hydrocarbon generation in Hsinchu-Miaoli area, NW Taiwan. They concluded that the variation of coal rank reflected the depositional environment, burial metamorphism and tectonic activities.

The Shihti Formation is the most important coal-bearing formation in Taiwan. It consists of bluish-gray to light brown sandstone and dark gray micaceous shale. Seven mineable coal seams are included with their thicknesses mostly less than one meter thick each. The Miocene formations were deformed due to the Penglai Orogeny starting from the Plio-Pleistocene. The geologic structures in the study area include folds and faults more or less along a NE-SW direction. Most of the folds are asymmetric anticlines with steeper NW limbs whereas most of the faults are imbricate thrust faults with SE-dipping fault planes.

As for local sedimentary studies, Chou (1976) finished a sedimentologic and paleogeographic study of the Shihti Formation in western Taiwan. In addition, Yu and Teng (1996, 1999) and Yu et al. (1999) studied the facies characteristics and depositional environment as well as sea-level changes in the Miocene strata of northern Taiwan. According to them, the Shihti Formation was deposited in a tide-influenced coastal plain and a low-energy wave-influenced shelf environment, probably embracing delta plains, estuaries, swamps, lagoons, beaches, and shallow neritic environments.

4. SAMPLING AND ANALYTIC METHODS

Grab coal samples were collected from four operating mines in NW Taiwan, the Lifeng, Yufeng, Anshuen, and Wukeng mines. All of the samples belong to the middle Miocene Shihti Formation and are located in the Western Foothill Belt of Taiwan (Fig. 1). According to local mining information, Wukeng mine, Anshuen mine, Yufeng mine and Lifeng mine were operating on coals from the uppermost, main, lower, and lowest coal seams in the Shihti Formation. Detailed petrography and chemical characterization analyses were then conducted. Sample collection and preparation and analytical methods including Proximate, Ultimate, atomic absorption spectroscopy, X-ray fluorescence, specific-ion electrode, neutron activation analysis,

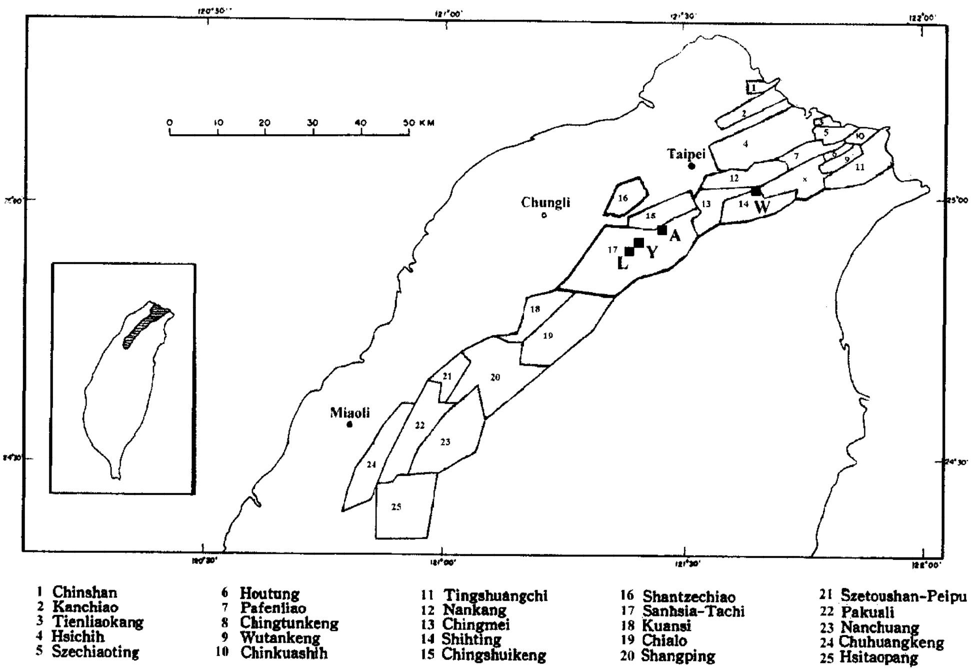

Fig. 1. The location and sampling sites of coalfields in the Western Foothill Belt of Taiwan; 1~25 coalfields, A: Anshuen mine, L: Lifeng mine, Y: Yufeng mine, W: Wukeng mine.

and spectra-photometric were all conducted according to ASTM procedures and U.S. Geological Survey (USGS) guidelines (Fig. 2).

5. ANALYTICAL RESULTS

5.1 Proximate and Ultimate Analysis

According to USGS, the results of Proximate (Industrial) analysis and Ultimate (Elemental) analysis are listed in Table 1.

5.2 Maceral Composition and Vitrinite Reflectance

Maceral composition and vitrinite reflectance were further analyzed and listed in Table 2. According to the data in sections 5.1 and 5.2, the samples were high volatile bituminous coal in rank with ash yields ranging from 4.2 to 14.4% and moisture content ranging from 2.7 to 4.6%. Furthermore, the macerals were mostly composed of vitrinite. The pyrite (1.79%) and

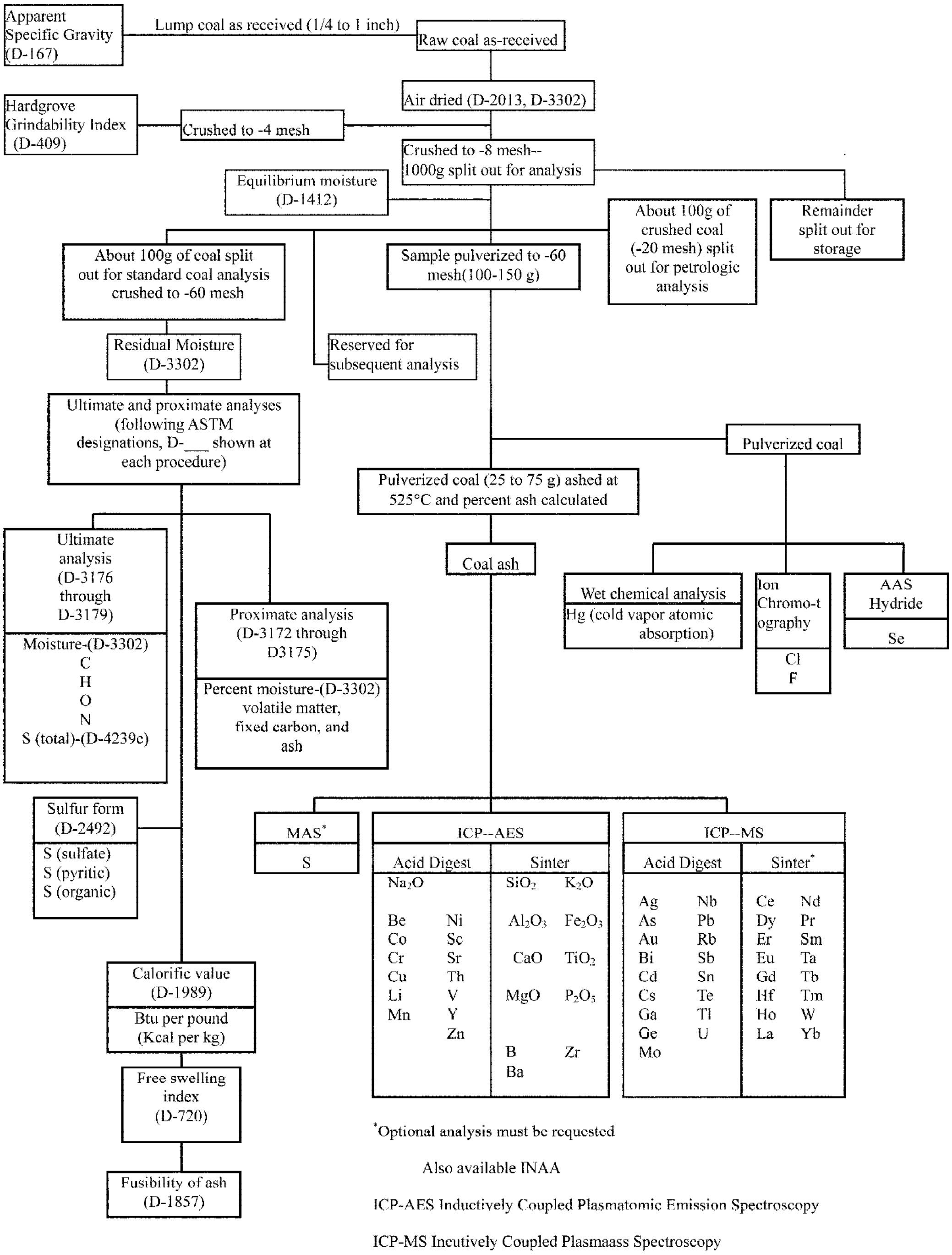

Fig. 2. Flow chart of the analytic methods used by the U.S. Geological Survey at the time the coal samples were analyzed (2001).

Table 1. Proximate and Ultimate analysis results of samples; Ssul, Spy, and Sorg represent sulfate S, pyritic S, and organic S contents, respectively.

	Moisture(%)	Ash(%)	Volatile matter(%)	Fixed Carbon(%)
Anshuen	2.75	5.91	40.44	53.65
Yufeng	2.72	4.18	43.27	52.55
Lifeng	2.69	14.36	37.03	48.61
Wukeng	4.61	10.05	45.04	44.91

	C(%)	H(%)	N(%)	O(%)	S(%)	Ssul(%)	Spy(%)	Sorg(%)
Anshuen	78.18	5.26	1.88	7.94	0.83	0.08	0.16	0.59
Yufeng	79.18	5.66	1.69	8.53	0.76	0.07	0.14	0.55
Lifeng	70.64	4.95	1.74	7.55	0.76	0.04	0.19	0.53
Wukeng	70.27	5.21	1.71	9.95	2.81	0.37	1.79	0.65

Table 2. Maceral composition and vitrinite reflectance of samples.

	Vitrinite(%)	Exinite(%)	Inertinite(%)	Mineral Matter(%)	Ro(%)
Anshuen	95.00	1.75	0.00	3.25	0.81
Yufeng	88.50	6.63	0.62	4.25	0.71
Lifeng	92.75	4.50	0.00	2.75	0.78
Wukeng	85.50	4.00	0.00	10.50	0.42

total sulfur content (2.81%) of the Wukeng coal is much higher than the other three coal samples, which can be attributed to the influence of marine transgression close to the final stage of depositional cyclothem, because it was mined from the uppermost coal seams of the Shihti Formation, as previously mentioned.

5.3 Trace Element Analysis

The analytical results of trace element contents are listed in Table 3. The enrichment factors were also calculated by comparing to their average crust contents from Horne (1978).

Table 3. Trace element contents of the four coals and their EF (enrichment factors) values compared to crust contents (after Horne, 1978); #: %, others: ppm.

items	Na_2O#	Al_2O_3#	CaO#	Fe_2O_3#	K_2O#	MgO#	P_2O_5#	SiO_2#	TiO_2#	Hg	Be	Co
Anshuen	1.10	18.30	1.30	9.90	1.80	0.93	0.32	52.30	1.30	0.21	14.80	90.50
Yufeng	0.59	25.10	4.90	11.30	1.30	0.90	0.74	41.30	1.70	0.07	8.40	44.20
Lifeng	1.00	23.20	0.50	5.60	3.40	1.40	0.12	46.30	0.83	0.08	10.20	29.70
Wukeng	0.26	18.90	0.98	29.50	2.30	1.00	0.06	37.10	0.75	2.30	14.40	36.50
crust	3.91	15.61	5.17	7.02	3.19	3.56	0.30	60.18	1.06	0.50	6.00	40.00
Anshuen(EF)	0.28	1.17	0.25	1.41	0.56	0.26	1.07	0.87	1.23	0.42	2.47	2.26
Yufeng(EF)	0.15	1.61	0.95	1.61	0.41	0.25	2.47	0.69	1.60	0.14	1.40	1.11
Lifeng(EF)	0.26	1.49	0.10	0.80	1.07	0.39	0.40	0.77	0.78	0.16	1.70	0.74
Wukeng(EF)	0.07	1.21	0.19	4.20	0.72	0.28	0.20	0.62	0.71	4.60	2.40	0.91

items	Cr	Cu	Li	Mn	Ni	Sc	Sr	Th	V	Y	Zn	B
Anshuen	168.00	101.00	88.20	403.00	232.00	31.80	787.00	21.00	245.00	63.60	82.50	929.00
Yufeng	171.00	147.00	136.00	732.00	105.00	35.30	2210.00	37.00	333.00	66.80	35.90	1350.00
Lifeng	135.00	119.00	212.00	155.00	90.20	27.40	594.00	25.50	313.00	39.60	116.00	310.00
Wukeng	157.00	104.00	152.00	202.00	138.00	23.10	747.00	16.00	217.00	49.20	140.00	1120.00
crust	200.00	70.00	65.00	1000.00	100.00	5.00	150.00	11.50	150.00	28.10	80.00	10.00
Anshuen(EF)	0.84	1.44	1.36	0.40	2.32	6.36	5.25	1.83	1.63	2.26	1.03	92.90
Yufeng(EF)	0.86	2.10	2.09	0.73	1.05	7.06	14.73	3.22	2.22	2.38	0.45	135.00
Lifeng(EF)	0.68	1.70	3.26	0.16	0.90	5.48	3.96	2.22	2.09	1.41	1.45	31.00
Wukeng(EF)	0.79	1.49	2.34	0.20	1.38	4.62	4.98	1.39	1.45	1.75	1.75	112.00

Table 3. Continued.

items	Ba	Zr	Ag	As	Au	Bi	Cd	Cs	Ga	Ge	Mo	Nb
Anshuen	613.00	292.00	<1	377.00	<10	0.64	0.17	7.00	40.70	81.20	13.80	33.20
Yufeng	1520.00	357.00	<1	47.30	<10	1.30	0.11	6.80	34.70	19.10	28.90	23.00
Lifeng	636.00	197.00	<1	50.20	<10	1.00	0.46	25.20	35.20	34.20	9.70	15.20
Wukeng	643.00	182.00	<1	697.00	<10	0.97	0.34	15.50	31.80	41.80	16.20	11.10
crust	430.00	220.00	0.02	5.00	0.001	0.20	0.18	3.20	15.00	7.00	2.30	29.00
Anshuen(EF)	1.43	1.33	—	75.40	—	3.20	0.94	2.19	2.71	11.60	6.00	1.14
Yufeng(EF)	3.53	1.62	—	9.46	—	6.50	0.61	2.13	2.31	2.73	12.57	0.79
Lifeng(EF)	1.48	0.90	—	10.04	—	5.00	2.56	7.88	2.35	4.89	4.22	0.52
Wukeng(EF)	1.50	0.83	—	139.40	—	4.85	1.89	4.84	2.12	5.97	7.04	0.38

items	Pb	Rb	Sb	Sn	Te	Tl	U
Anshuen	48.50	79.10	9.40	6.70	0.33	9.10	7.20
Yufeng	55.30	59.20	7.90	10.70	0.65	6.00	13.50
Lifeng	57.20	196.00	15.50	8.30	0.40	2.30	11.50
Wukeng	52.50	122.00	10.40	7.70	0.40	54.80	11.60
crust	16.00	280.00	—	40.00	—	0.30	4.00
Anshuen(EF)	3.03	0.28	—	0.17	—	30.33	1.80
Yufeng(EF)	3.46	0.21	—	0.27	—	20.00	3.38
Lifeng(EF)	3.58	0.70	—	0.21	—	7.67	2.88
Wukeng(EF)	3.28	0.44	—	0.19	—	182.67	2.90

The trace element contents analyzed were not too striking except for the sample from the Wukeng mine, which (in ash) has the highest Fe_2O_3 (29.5%), Tl (54.8 ppm), Zn (140 ppm), and As (697 ppm) contents and Hg (2.3 ppm on a coal basis). In addition this sample has relatively high U (11.6 ppm), Be (14.4 ppm), Cs (15.5 ppm), Rb (122 ppm) and B (1120 ppm) contents. It is also noticed that the enrichment factors of B, As, and Tl in Wukeng coal are all over 100. In addition, some of the elemental ratios are noticed here:

	Th/U	Sr/Ba	B/Ga	$(CaO+MgO+Fe_2O_3) / (SiO_2+Al_2O_3)$
Anshuen	2.80	1.28	22.83	0.17
Yufeng	2.74	1.45	38.90	0.26
Lifeng	2.22	0.93	8.81	0.11
Wukeng	1.38	1.16	35.22	0.56

Comparing with the discussions from Chou (1984), Chao et al. (1994) and Tang et al. (1997), although they are somewhat inconsistent, the elemental ratios still imply a reductive, littoral to brackish swamp environment during deposition. The inconsistency of elemental ratio can be attributed to differences in plant species, geologic time and local tectonic activities. In addition, the Wukeng coal and Yufeng coal exhibit high B, Mo, and U contents as well as high ratios in both B/Ga and $(CaO + MgO + Fe_2O_3) / (SiO_2 + Al_2O_3)$, which indicate more marine influence during deposition. Furthermore, as previously mentioned, the enrichment of Fe_2O_3, Tl and Hg in the high-sulfur Wukeng coal might be derived from a terrigenous source by weathering, and transported to the swamp by rivers. As for the high As and Zn contents in Wukeng coal, it can be interpreted as incorporation in pyrite during peatification.

After examining studies of local depositional environments done by Chou (1976), Yu and Teng (1996, 1999) and Yu et.al. (1999), the coals from the Lifeng, Yufeng, and Anshuen mines are concluded to be deposited in a lagoon or swamp whereas the coal in the Wukeng mine is believed to have formed in a delta.

6. DISCUSSION AND CONCLUSION

The concentrations of toxic trace elements in most of the samples analyzed were found to be less than the levels in most U.S. and China coals (Finkelman et al., 1999), which has been shown not to be dangerous to human health. Thus, proper use of the coals studied should not result in significant health concerns regarding exposure to potentially toxic trace elements.

The analytic results indicate a reductive, littoral to brackish swamp environment during deposition. The high pyrite content in Wukeng is associated with the enrichment of B, As and Tl, with enrichment factors over 100 by comparing with average trace element contents in crust. The depositional environment of the coals from the Lifeng, Yufeng, and Anshuen mines is concluded to be a lagoon or swamp, whereas the depositional environment of the coal from the Wukeng mine is believed to be a delta.

Better knowledge of coal quality parameters may help minimize some of the health problems caused by coal use. Information on the concentration and distribution of toxic elements in coal may help people avoid those areas of a coal deposit having high concentration of toxic elements. Further study is needed to understand the modes of occurrence of elements during the deposition and coalification stage in the study area.

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