CHAPTER 4
RESULTS AND INTERPRETATION

4.1. Proximate and ultimate analyses

4.1.1 Results and interpretation

4.1.1.1 Proximate analysis

Proximate analysis is the analysis of coal expressed in terms of moisture, ash, volatile matter, and fixed carbon (Table 4.1). It provides a general appraisal of coal characteristics.

Ash content (air-dried)

Ash represents the inorganic, non-combustible residue that remains when coal is burned. It is derived from the various components of the total mineral matter, including discrete crystalline minerals and water soluble and inorganic elements.

Ash content from I zone coal is 5.65 percent. In J zone coal, ash ranges from 11.85 to 40.25 percent and averages 19.83 percent. Ash in K zone coal ranges from 9.46 to 24.67 percent and averages 13.94 percent. Q zone coal ash is from 14.84 to 47.67 percent and averages 29.68 percent.

Moisture content (air-dried basis)

In low rank coal, moisture occurs as bulk or free water on the exterior of particles, in large pores, and within capillaries. It is weakly bonded to coal surfaces. Moisture is a critical coal quality parameter and has indirect influence on a variety of other properties. Specific energy is also very sensitive to moisture content. Mae Moh coal is a relatively high moisture coal. This is in line with its low rank. Moisture content values typically range between 5.49 and 16.42 percent on an air-dried basis. Moisture content and trends are similar within I, J, K, and Q zones coal. Moisture content of I zone coal is 11.24 percent.

In J zone coal it ranges from 8.81 to 16.42 percent and averages 12.66 percent. K zone coal has a moisture content of 8.39 to 10.5 percent and an average of 9.44 percent. In Q zone coal, the moisture content ranges from 5.49 to 14.36 percent and averages 9.16 percent.

Volatile matter

Volatile matter is a measure of the thermal decomposition products formed during heating. It is mostly derived from the breakdown of organic components of the coal. Volatile matter is strongly related to coal rank.

Volatile matter from I zone coal is 48.99 percent, from J zone coal from 20.71 to 54.71 percent with an average of 46.75 percent, from K zone coal from 22.58 to 44.0 percent with an average of 38.57 percent, and from Q zone coal it ranges from 24.15 to 53.73 percent and averages 37.51 percent.

Fixed carbon

Fixed carbon represents the combustible portion of the coal after removal of moisture and volatile matter. It is the result after determination of ash and volatile matter content and is not necessarily the true combustible carbon percentage of coal. Fixed carbon of I zone coal is 34.12 percent. In J zone coal it ranges from 6.42 to 31.06 percent and averages 20.76 percent. K zone coal has from 27.33 to 58.33 percent fixed carbon and an average of 38.06 percent. Fixed carbon in Q zone coal ranges from 13.28 to 36.40 percent and averages 23.66 percent.

4.1.1.2 Ultimate analysis

Ultimate analysis involves determination of the proportions of carbon, hydrogen, nitrogen, and sulfur in coal (Table 4.2), in which carbon and hydrogen occur in combination with each other as complex organic compounds. Carbon is also present in carbonate minerals and hydrogen may also occur as water. Nitrogen occurs within organic coal and forms from plant and animal protein. Sulfur may occur in a variety of forms, such as organic sulfur that is chemically bonded to organic substances, pyritic sulfur, and as sulfate sulfur from oxidation of sulfides. The highest sulfur content occurs in J zone coal, having a range between 2.97 and 10.13 percent and an average of 6.40 percent on an air-dried basis. Coal from zones I, K, and Q averages 1.05, 2.25, and 5.68 percent on an air-dried basis, respectively.

The proximate and ultimate analyses showed that moisture content has a negative correlation with ash but a positive correlation with volatile matter. The correlation between hydrogen and carbon with ash is negative but sulfur has a positive correlation. The correlation between volatile matter and ash and fixed carbon and ash was not significant. The volatile matter had a positive correlation with hydrogen and indicated that hydrogen is in form of water. The decrease of moisture content from upper to lower sequences indicated a common coalification, whereas the increase of fixed carbon indicated the high rank coalification at depth.

Table 4.1 Proximate analyses of coal samples, air-dried basis

Sample location	Sample no.	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)	Ash and moisture free(%)	
						Volatile matter (%)	Fixed carbon (%)
C-1 pit	C1J1	10.47	28.40	54.71	6.42	89.50	10.50
	C1J2	13.05	40.25	20.71	25.99	44.35	55.65
	C1J3A	16.42	12.08	44.44	27.06	62.15	37.85
	C1J3B	8.81	22.91	44.55	23.73	65.25	34.75
	C1J4	11.39	19.87	54.22	14.52	78.88	21.12
	C1J5A	10.20	15.70	43.04	31.06	58.08	41.92
	C1J5B	12.69	18.55	50.01	18.75	72.73	27.27
	C1J5C	13.92	15.20	51.30	19.59	72.36	27.67
	C1J6A	14.54	13.53	51.94	20.01	72.19	27.81
	C1J6B	15.15	11.85	52.58	20.42	72.03	27.97
NE pit	NEK1	9.51	9.46	44.00	37.03	54.30	45.70
	NEK2	9.58	9.51	22.58	58.33	27.91	72.09
	NEK3	8.74	13.68	39.76	37.82	51.25	48.75
	NEK4	9.50	10.46	40.68	39.36	50.82	49.18
	NEQ1	14.36	25.09	24.15	36.40	39.88	60.12
	NEQ2	5.49	47.67	25.77	21.07	55.02	44.98
	NEQ3	6.23	43.59	30.82	19.36	61.42	38.58
	NEQ4	7.03	39.46	29.57	23.94	55.26	44.74
SW pit	SWI	11.24	5.65	48.99	34.12	58.94	41.06
NW pit	NWK1	10.04	9.54	42.20	38.22	52.47	47.53
	NWK2	9.22	24.67	38.78	27.33	58.66	41.34
	NWK3	10.50	12.40	40.15	36.95	52.07	47.93
	NWK4	8.39	21.83	40.37	29.41	57.85	42.15
	NWQ1	11.03	25.95	47.74	15.28	75.75	24.25
	NWQ2	8.69	14.84	40.96	35.51	53.56	46.44
	NWQ3	9.70	18.56	47.35	24.40	66.00	34.00
	NWQ4	10.71	22.28	53.73	13.28	80.18	19.82
Average		10.61	20.48	41.67	27.24	60.70	39.30
C-1 pit		12.66	19.83	46.75	20.76	68.75	28.48
NE pit		8.81	24.87	32.17	34.16	49.48	50.52
NW pit		9.79	18.76	43.91	27.55	69.44	43.06
I zone		11.24	5.65	48.99	34.12	58.94	41.06
J zone		12.66	19.83	46.75	20.76	68.75	28.48
K zone		9.44	13.94	38.57	38.06	50.67	49.33
Q zone		9.16	29.68	37.51	23.66	60.89	39.12

Table 4.2 Ultimate analyses of the coal samples (air dried basis)

Sample location	Sample no.	Ash (%)	C (%)	H (%)	N (%)	S (%)
C1 PIT	C1J1	28.40	32.36	3.13	1.25	10.13
	C1J2	40.25	7.31	1.55	0.74	2.97
	C1J3A	12.08	52.99	4.37	2.33	6.19
	C1J3B	22.91	37.63	3.36	2.42	7.94
	C1J4	19.87	41.00	3.47	2.14	7.67
	C1J5A	15.70	47.40	3.49	1.90	7.74
	C1J5B	18.55	42.21	3.60	1.75	8.35
	C1J5C	15.20	26.50	2.86	2.52	3.94
	C1J6A	13.53	35.78	3.58	2.08	5.58
	C1J6B	11.85	47.73	4.24	3.34	3.50
NE PIT	NEK1	9.46	58.46	4.45	3.26	1.82
	NEK2	9.51	56.06	4.16	3.04	2.11
	NEK3	13.68	62.34	4.38	3.34	1.07
	NEK4	10.46	53.27	8.25	2.66	4.50
	NEQ1	25.09	45.18	3.51	2.15	4.67
	NEQ2	47.67	26.32	2.62	1.33	6.32
	NEQ3	43.59	27.06	2.72	1.40	8.89
	NEQ4	39.46	29.87	2.89	1.48	5.60
NW PIT	NWK1	9.54	36.35	3.16	2.14	2.09
	NWK2	24.67	34.61	3.41	2.94	2.76
	NWK3	12.40	53.97	8.56	3.65	1.01
	NWK4	21.83	47.59	4.02	5.75	2.63
	NWQ1	25.95	34.87	3.42	3.23	4.47
	NWQ2	14.84	42.76	4.07	3.85	2.07
	NWQ3	18.56	28.93	3.07	2.19	7.59
	NWQ4	22.28	33.24	3.63	2.77	5.82
SW PIT	SWI	5.65	46.29	4.42	3.48	1.05
Average		20.48	40.30	3.87	2.56	7.20
C1 PIT		19.83	37.09	3.36	2.05	6.40
NE PIT		24.86	44.82	4.12	2.33	4.40
NW PIT		18.76	39.04	4.17	3.32	3.56
I zone		5.65	46.29	4.42	3.48	1.05
J zone		19.83	37.09	3.36	2.05	6.40
K zone		13.94	50.33	5.05	3.35	2.25
Q zone		29.68	33.53	3.24	2.30	5.68

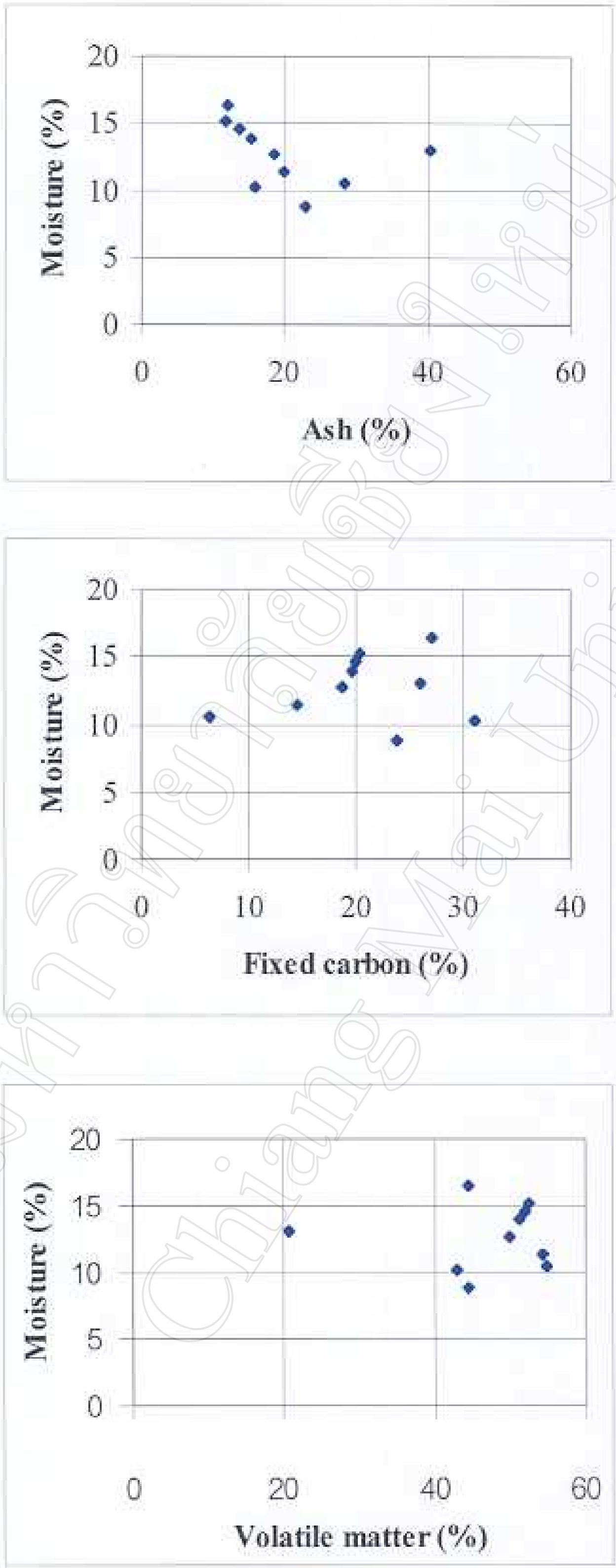

Figure 4.1 Diagram of coal samples from C-1 Pit plotted between Moisture/Ash, Moisture/Fixed Carbon and Moisture/Volatile matter (Air dried basis)

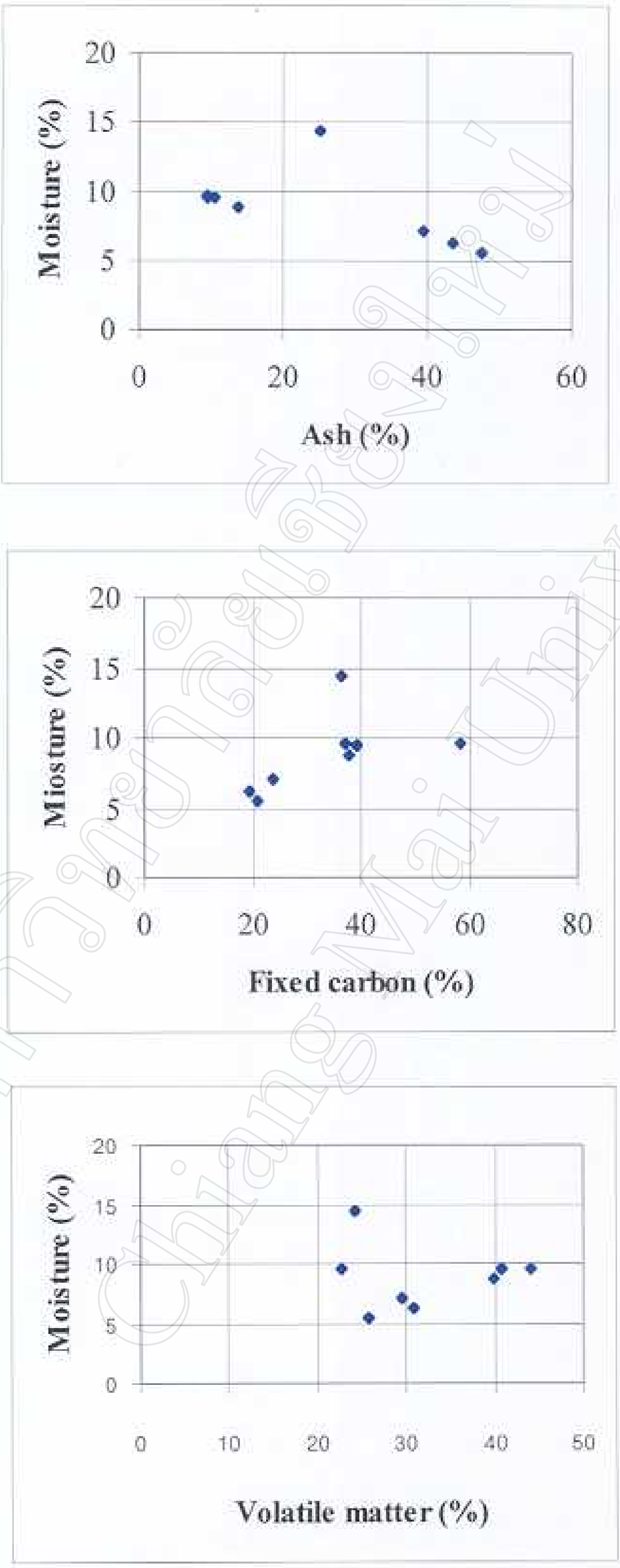

Figure 4.2 Diagram of coal samples from NE Pit plotted between Moisture/Ash, Moisture/Fixed Carbon and Moisture/Volatile matter (Air dried basis)

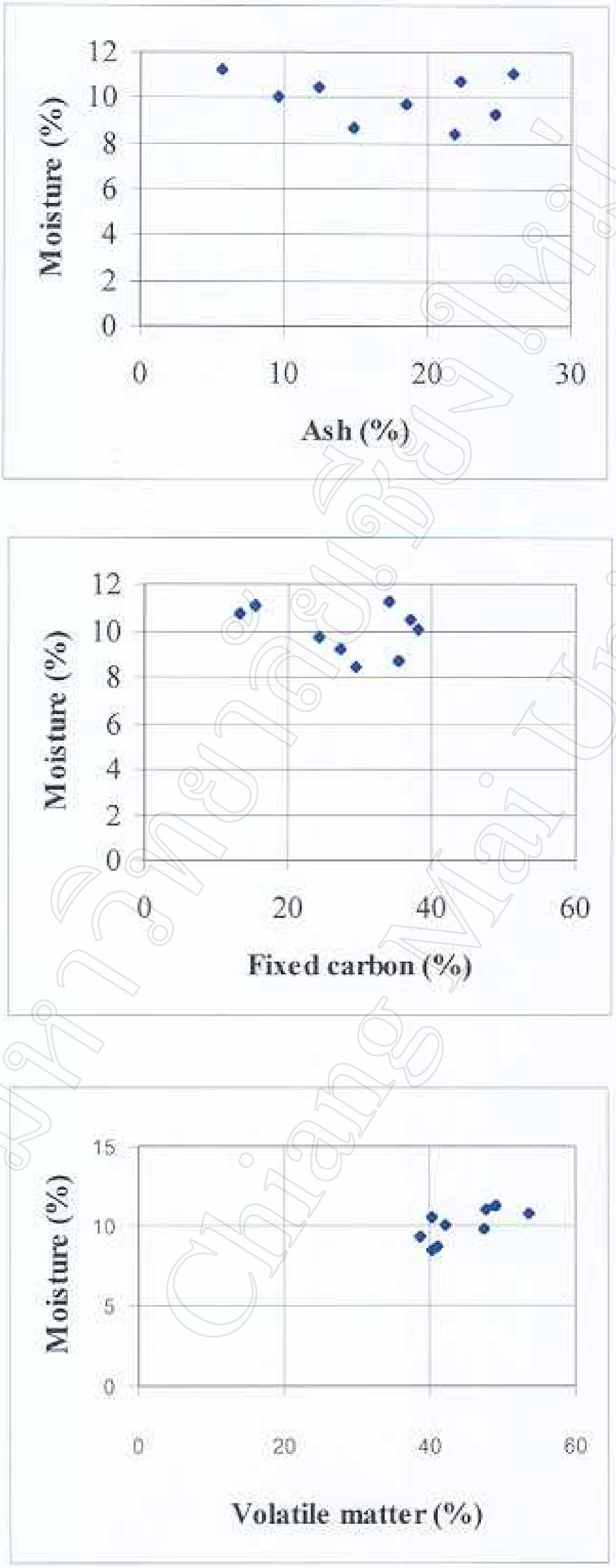

Figure 4.3 Diagram of coal samples from NW Pit plotted between Moisture/Ash, Moisture/Fixed Carbon and Moisture/Volatile matter (Air dried basis)

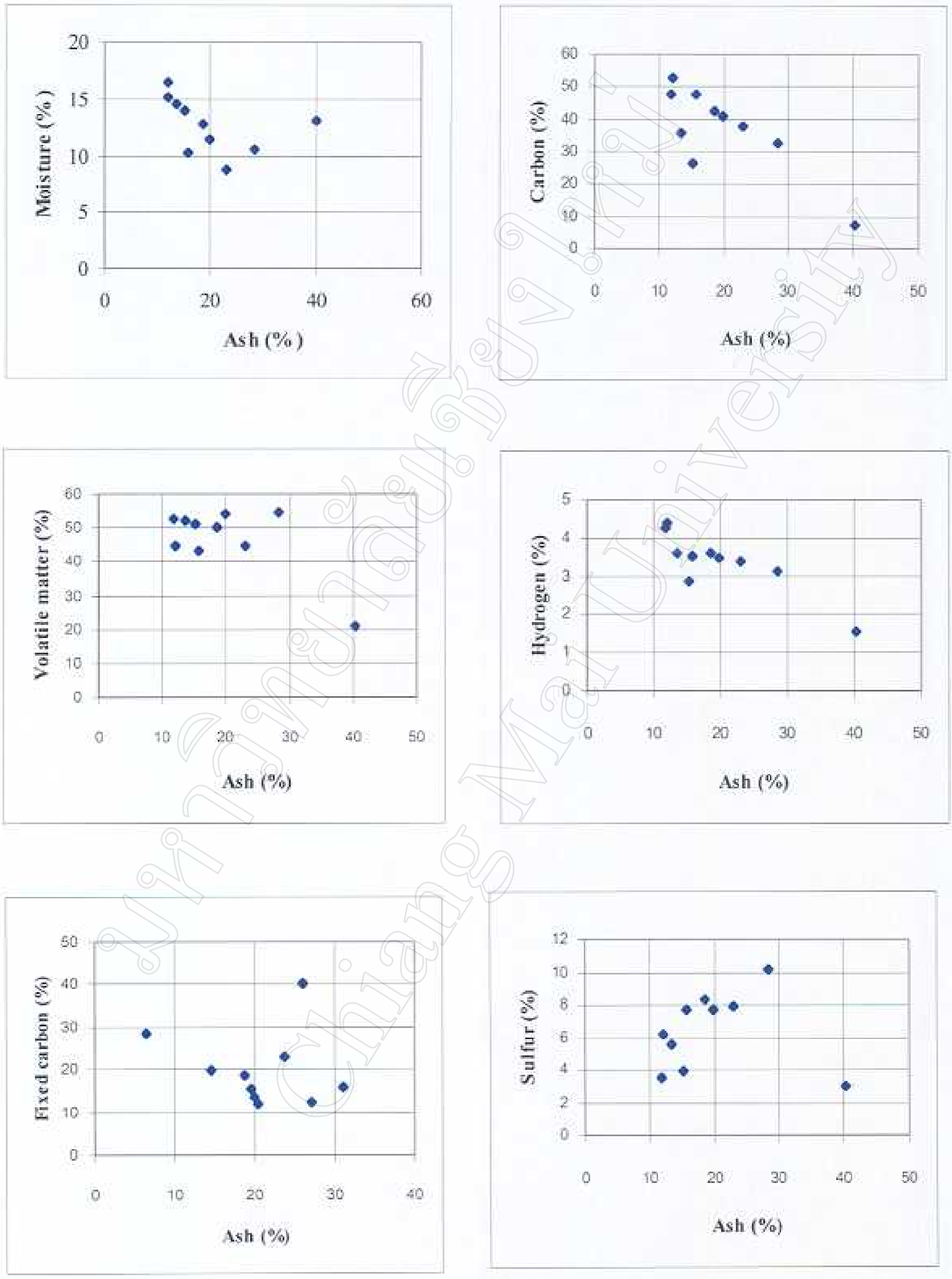

Figure 4.4 Diagram of coal samples from C-1 Pit plotted between moisture/ash, Volatile matter/ash, fixed carbon/ash, hydrogen/ash and sulfur/ash

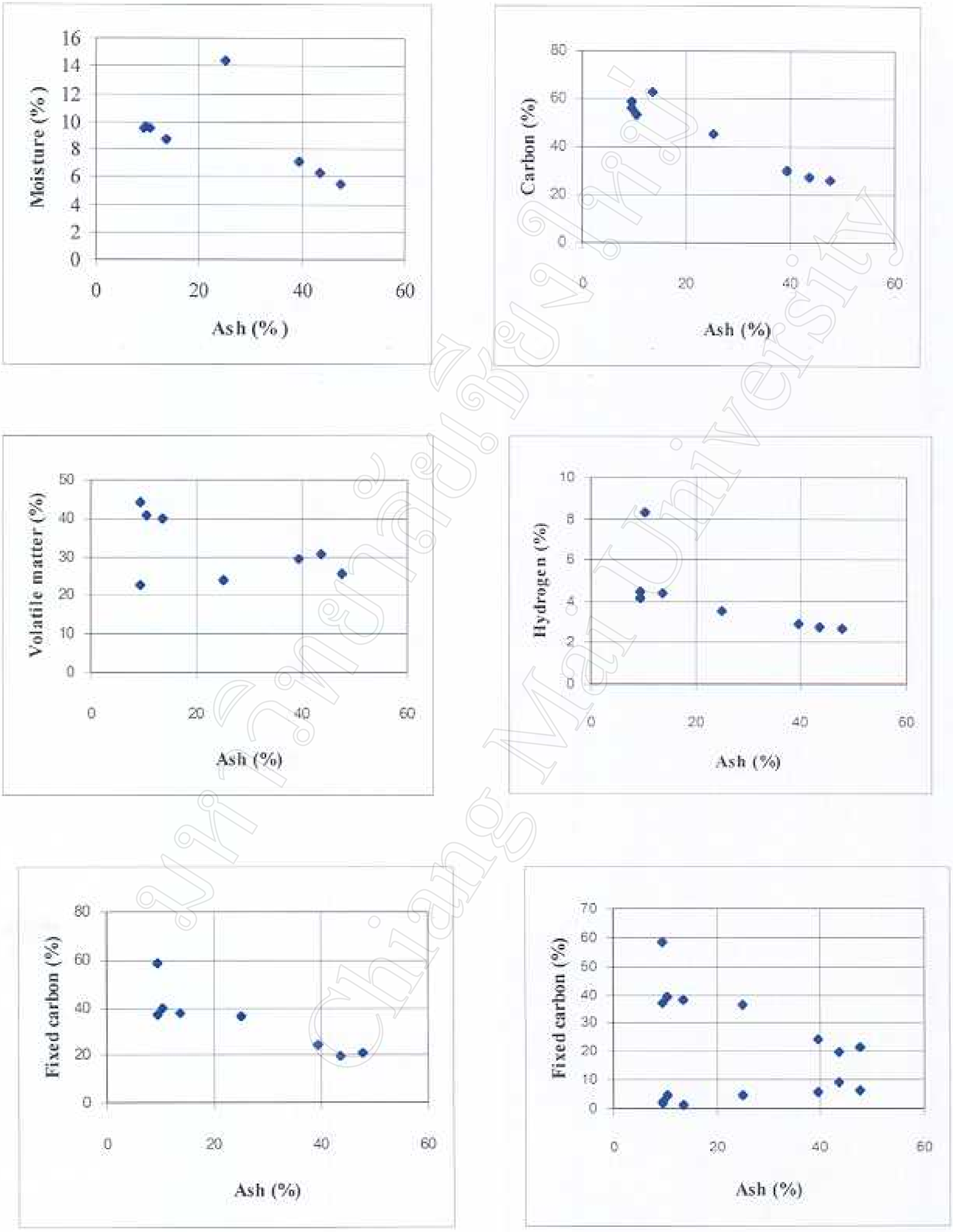

Figure 4.5 Diagram of coal samples from northeast pit plotted between moisture/ash, volatile matter/ash, fixed carbon/ash, carbon/ash, hydrogen/ash and sulfur/ash

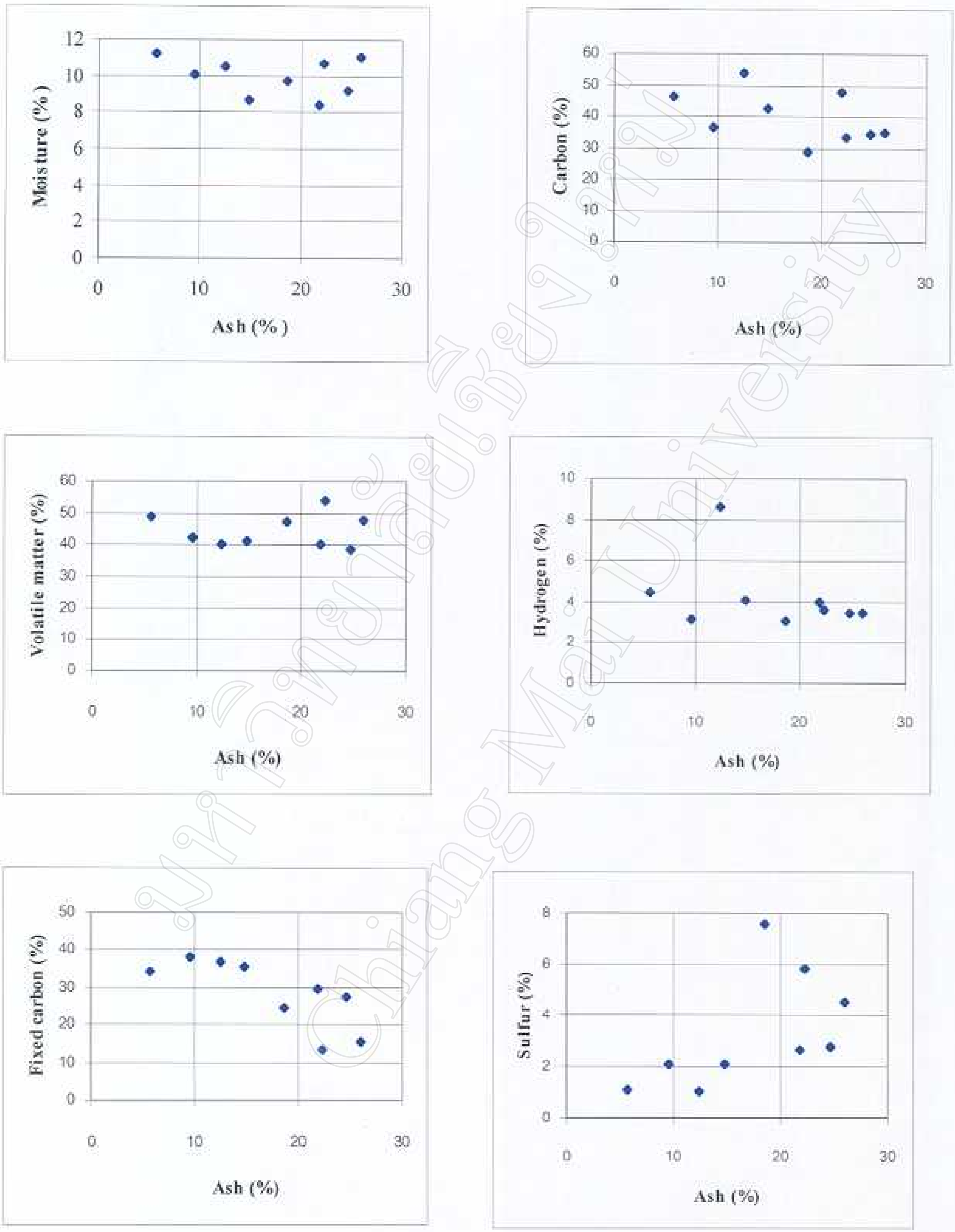

Figure 4.6 Diagram of coal samples from NW Pit plotted between moisture/ash, Volatile matter/ash, fixed carbon/ash, carbon/ash, hydrogen/ash an Sulfur/ash

4.2 X-ray diffraction

4.2.1 Result, mineralogy, and interpretation

X-ray diffraction diagrams show qualitative diffraction peaks of samples. These peaks illustrate the known ranges of minerals in samples. Tables 4.2.1.1, 4.2.1.2, and 4.2.1.3 show the qualitative and semi-quantitative values obtained from x-ray diffraction diagrams. The qualitative analyses of clay mineral groups represent only kaolinite, illite, and chlorite. Kaolinite has values from 0.96 percent to 18.07 percent, illite values range from 0.46 percent to 5.17 percent, and chlorite values range from 0.17 percent to 1.39 percent.

The quantitative distribution of minerals in analyzed samples is distinctive for both the northeast and northwest pits. The minerals in these pits is as follows:

1.In the underburden below the Q zone in the northwest pit, calcite, quartz and siderite are the dominant minerals, their percentages being 33.03, 30.83, and 27.52, respectively. Kaolinite makes up 6.61 percent of the minerals, illite 1.10 percent, and pyrite occurs as only a trace amount of 0.91 percent. In this underburden in the northeast pit, calcite makes up 82.82 percent of the minerals, quartz 12.03 percent, siderite 2.16 percent, kaolinite 1.63 percent, and pyrite 1.36 percent.

2.In the interburden between the K and Q zones in the northwest pit, quartz is dominant and makes up 71.5 percent of the minerals, calcite 17.4 percent, kaolinite 6.36 percent, and illite 4.72 percent. Calcite in this interburden in the northeast pit is the dominant mineral, having a percentage of 61.4 percent. Quartz makes up 26.1 percent of the minerals, pyrite 6.3 percent, kaolinite 3.67 percent, siderite 1.26 percent, and illite 1.24 percent.

3.In the overburden between the J and K zones in the C-1 pit, the minerals are 88.1 percent calcite, 11.2 percent quartz, 0.53 percent pyrite, and 0.18 percent siderite. Various factors of weathering and environmental conditions are favorable for the formation and occurrence of particular minerals. The distribution of these minerals within rocks are related to the nature of the source rock, intensity of weathering, diagenetic factors, and the original chemical conditions within a basin.

Quartz

Quartz is a relatively abundant mineral in most coal. Quartz is considered primary as a syngenetic mineral and is not commonly identified as an epigenetic phase (Renton, 1982). Quartz grains that vary from rounded to subangular are primarily detrital (Davis and others, 1984), being either water-washed or wind blown into a swamp during peat accumulation (Ward, 1989).

Two possible origins of quartz are suggested. First, in a depositional environment dominated by fluvial and lacustrine processes, quartz grains would be largely water-washed detritus periodically transported into a swamp during peat accumulation; being wind blown detritus would be rare. The second origin could be chemical, by direct precipitation from solution, ether chemically or biogenically mediated. Recrystalization to quartz would occur during diagenesis.

Preservation of biogenically derived or directly precipitated silica would require specialized circumstances. Reduced mobility of aqueous silica in the wetland may be related to a weakly alkaline environment. The high calcium oxide content of the Mae Moh coal and preservation of shell fragments within many of the intra-seam partings indicate a neutral to weakly alkaline depositional environment with limited activity by humic acids, a common feature of calcium oxide-rich coal (Teichmuller and Teichmuller, 1982).

Preservation of biogenically precipitated silica may take place through overloading of the silica cycle by inorganic acids, failure of the cycling system through cessation of metabolic activity, and/or by restricted removal of silica-rich pore water during peatification and coalification (Upchurch and others, 1983).

Carbonate minerals

The carbonate minerals identified by x-ray diffraction in the samples from the C-1, northeast, and northwest pits occur in some of the partings and are mostly calcite and siderite. Calcite also is the principle carbonate mineral in non-coal samples and its occurrence is related to the Triassic limestone along the eastern flank of the Mae Moh basin. Several of the partings contain shell fragments that have been interpreted as non-marine (Corsiri and Crouch, 1985).

The presistent calcite, along with the high concentration of calcium dissolved in pore waters and attached to functional groups in organic molecules (Ward, 1991), suggests that the depositional basin waters were neutral to weakly alkaline surface waters, rich in dissolved carbonate. Runoff into the depositional environment, especially from the carbonate rocks that flank the Mae Moh basin, would create alkaline conditions favoring biogenic precipitation of calcite by fresh water gastropods and algae (Sawyer and others, 1988). The preservation of shell fragments throughout the mine strata indicates long term alkaline conditions and limited dissolution by humic acids (Tiechmuller and Tiechmuller, 1982)

In coal, siderite probably forms during the early stages of coalification, whereas calcite and dolomite, which occur primarily in cleats and fractures, forms in later diagenetic stages after the coal has undergone most of its advance in rank (Ward, 1989). Calcite, the most abundant carbonate mineral identified in coal, can be deposited in both fresh water and marine environments.

Clay minerals

Clay minerals are probably the most common inorganic phase present in all types of coal. Renton (1982) has shown that clay minerals constitute, on average, 60 to 70 percent of the mineral assemblage in low temperature ash. Of the various types that can be present, kaolinite and illite are the most common, followed by mixed layer clays and chlorite. The processes that result in the inclusion of clay minerals into any coal include detrital, both water and airborne detritus, alteration of the previously deposited detrital minerals, and direct precipitation in swamp water or in pore spaces within peat (Ward, 1989; Ward and Christie, 1994). Kaolinite is the most common clay mineral that occurs syngenetically (Renton, 1982).

The formation of kaolinite could result from weathered rhyolite, which is derived from the Prae-Lampang mountains. Kaolinite favors acidic conditions with good drainage and low cation (Na^+, K^+,Ca^{2+},Mg^{2+}) activities (Garrels and Christ, 1965; Curtis, 1983; Rimmer and Davis, 1986), whereas high concentrations of total dissolved solids favor the formation of illite (Renton, 1982; Rimmer and Davis, 1986). Andrejenko and others (1983) also identified kaolinite, along with minor illite and montmorillonite, as the dominant clay mineral in fresh water influenced wetlands, whereas illite and montmorillonite are more common in wetlands influenced by marine waters.

Since clays appear to be of detrital origin, they provide little information about the depositional environment. It may be possible that some of the kaolinite is authigenic, particularly in coal when few other clay minerals are present. The high proportion of kaolinite would suggest that the depositional environment at this time may have been acidic and low in total dissolved solids. This favors the formation of authigenic kaolinite and restricts the development of other minerals

Sulfide minerals

Pyrite and marcasite are the dominant sulfide minerals in coal. They occur almost as frequently as carbonate minerals. The presence of abundant syngenetic pyrite in coal is indicative of a marine environment or a transgressive sequence where the coal is overlain by marine rocks. Both minerals suggest that the availability of sulfide ions during deposition or early diagenesis may be the controlling factor for pyrite formation.

The presence of pyrite in almost all samples suggests that near-neutral pit conditions existed in the peat throughout the depositional period. The direct relation of pyrite to organic material provides good evidence that its precipitation was bacterially mediated, the organic material providing an energy source for bacteria sulfate reduction and a neutral pit supporting a high degree of bacterial activity.

The mineralogy of coal and interbedded rocks indicates a continual supply of both iron and sulfur to the depositional area. The iron necessary for the formation of pyrite was likely derived from weathering of the surrounding highlands. Gastropods in the sedimentary sequence indicate that the depositional environment was dominated by fresh water, yet sulfur content in some coal samples exceeded 10 percent. This suggests marine volcanic activity or hydrothermal intrusion during peat accumulation or shortly thereafter. While some of sulfur may have come from the degradation of plant debris, as has been suggested for low sulfur, fresh water coal (Casagrande and others, 1977), another source may be from weathering of a gypsiferous horizon external to the coal basin. A third possibility is that the sulfur may be of volcanic origin, but too old to be the Pleistocene basalt, as found in the southern portion of the Mae Moh basin which is overlain by

Pleistocene basalt. However, numerous Tertiary intrusions and extrusions have been identified in northern Thailand (Barr and MacDonald, 1981).

Sulfates

A wide variety of sulfate minerals have been identified in coal and associated rocks. The most common calcium sulfate minerals identified are gypsum, $CaSO_4.2H_2O$, bassanite, $CaSO_4.1/2H_2O$, and anhydrite, $CaSO_4$ (Renton, 1982).

The scattered euhedral crystals identified most commonly in the rocks associated with the coal likely developed in response to periodic wetting and drying of elevated flood plain or overbank deposits. Evaporation in this exposed sediment would result in hypersaline pore water and gypsum precipitation when the sediment was soft enough to allow uninhibited crystal development. Gypsum has also been identified in coal horizons. Although this occurrence is somewhat less, it would suggest that periodic drying, or at least an increase in water salinity, occurred throughout the depositional environment.

Table 4.3 Qualitative and semi-quantitative data of x-ray diffraction traces in the C-1 pit

Minerals identified	Relative abundance (%)											
	RB	T	J1/J2	J2/J3A	J3A/J3B	J3B/J4	J4/J5A	J5A/J5B	J5B/J5C	J5C/J6A	J6A/J6B	J6B/K
Calcite	3.88	28.78	93.31	91.78	87.04	96.61	72.85	94.43	86.59	72.09	39.87	88.13
Quartz	80.91	62.78	2.38	6.22	6.09	2.18	20.82	3.65	11.06	23.36	53.16	11.16
Gypsum	6.33	0.66	1.98	1.36	4.47	0.8	1.45	1.42	0.96	1.49	4.98	-
Pyrite	0.15	0.1	0.75	0.64	0.27	-	-	0.5	0.43	0.3	1.99	0.53
Illite	1.1	1.49	-	-	-	-	1.42	-	-	-	-	-
Siderite	-	-	-	-	-	0.24	-	-	-	0.27	-	0.18
Kaolinite	7.63	5.79	-	-	-	-	3.46	-	0.96	2.49	-	-
Chlorite	-	-	0.25	-	-	0.17	-	-	-	-	-	-
Dolomite	-	0.4	1.33	-	2.13	-	-	-	-	-	-	-

Table 4.4 Qualitative and semi-quantitative data of x-ray diffraction traces in the northwest pit

Minerals identified	Relative abundance (%)									
	RB	T	K1/K2	K2/K3	K3/K4	IB(K/Q)	Q1/Q2	Q2/Q3	Q3/Q4	UB
Calcite	-	-	68.21	74.72	79.84	17.39	-	1.09	-	33.03
Quartz	94.62	90.33	23.02	13.28	10.3	71.53	87.45	86.02	87.16	30.83
Gypsum	-	-	-	-	2.87	-	-	-	-	-
Pyrite	-	-	-	-	1.7	-	-	-	-	0.91
Illite	0.69	1.55	-	-	-	4.72	1.71	0.54	1.06	1.1
Siderite	1.86	-	1.02	7.43	-	-	-	3.56	-	27.52
Kaolinite	2.83	8.12	7.75	4.57	-	6.36	10.84	8.79	11.78	6.61
Chlorite	-	-	-	-	-	-	-	-	-	-
Dolomite	-	-	-	-	5.29	-	-	-	-	-

Table 4.5 Qualitative and semi-quantitative data of x-ray diffraction traces in the northeast pit

Minerals identified	Relative abundance (%)							
	K1/K2	K2/K3	K3/K4	IB(K/Q)	Q1/Q2	Q2/Q3	Q3/Q4	UB
Calcite	42.31	1.21	42.43	61.41	1.63	-	-	82.82
Quartz	48.08	83.88	39.36	26.12	79.01	92.78	86.98	12.03
Gypsum	-	-	1.08	-	-	-	-	-
Pyrite	1.19	-	1.47	6.3	0.16	-	-	1.36
Illite	-	5.17	-	1.24	0.46	-	1.04	-
Siderite	4.1	-	14.27	1.26	0.67	0.68	4.32	2.16
Kaolinite	4.32	9.05	-	3.67	18.07	6.54	7.66	1.63
Chlorite	-	-	1.39	-	-	-	-	-
Dolomite	-	0.69	-	-	-	-	-	-

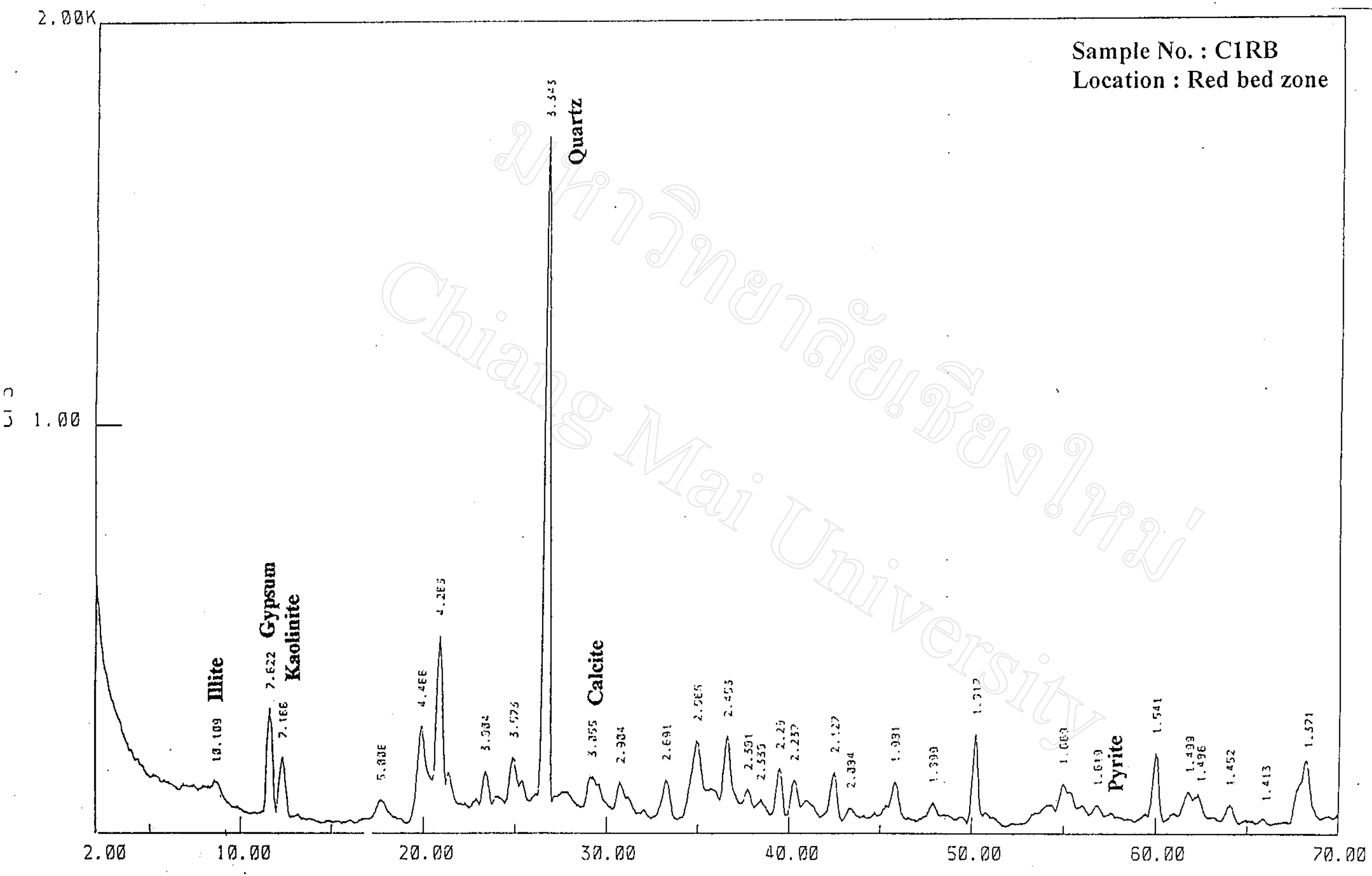

Figure 4.7 XRD patterns of clay mineral from C1RB (red bed) sample

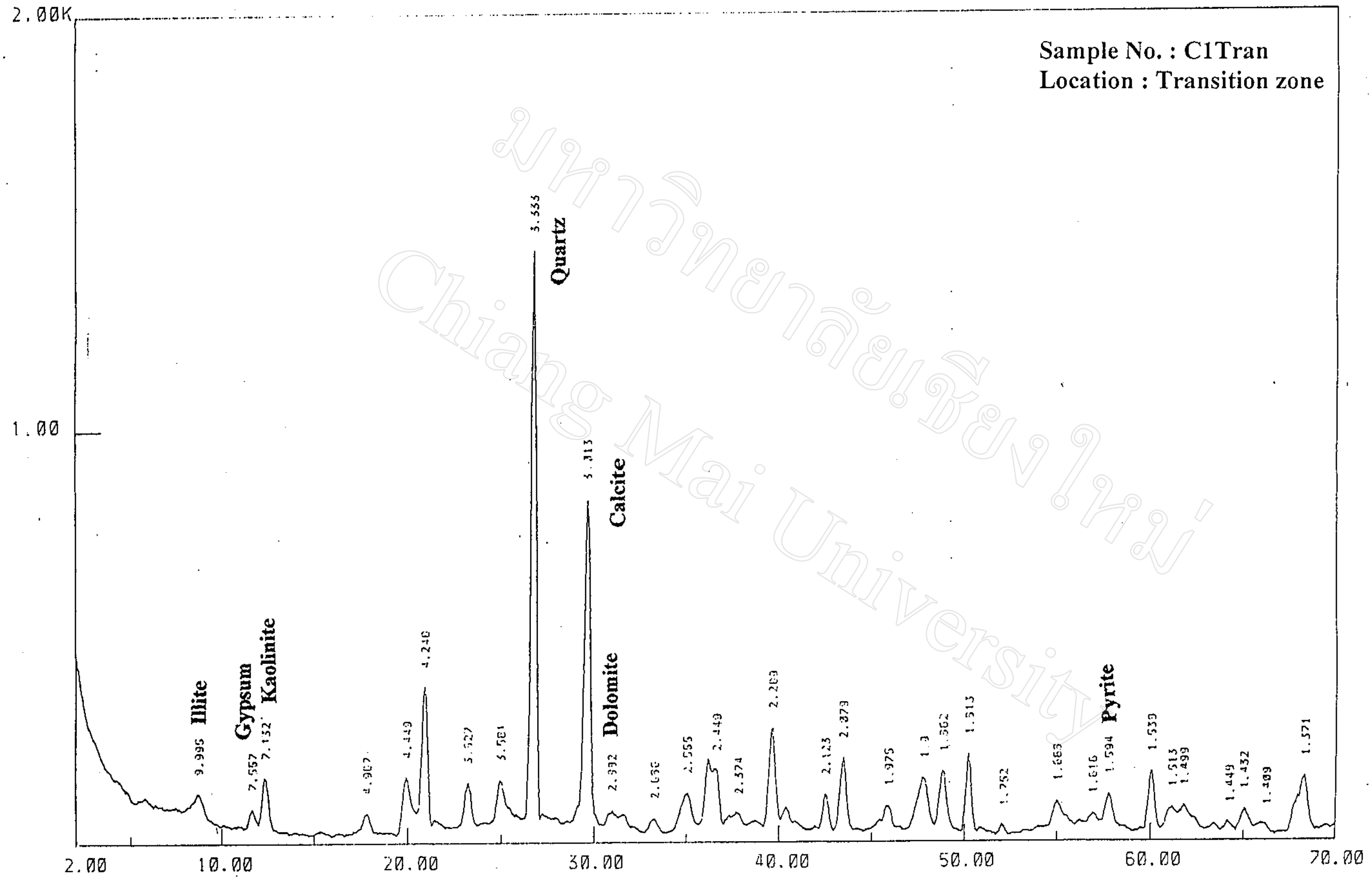

Figure 4.8 XRD patterns of clay mineral from C1Tran sample

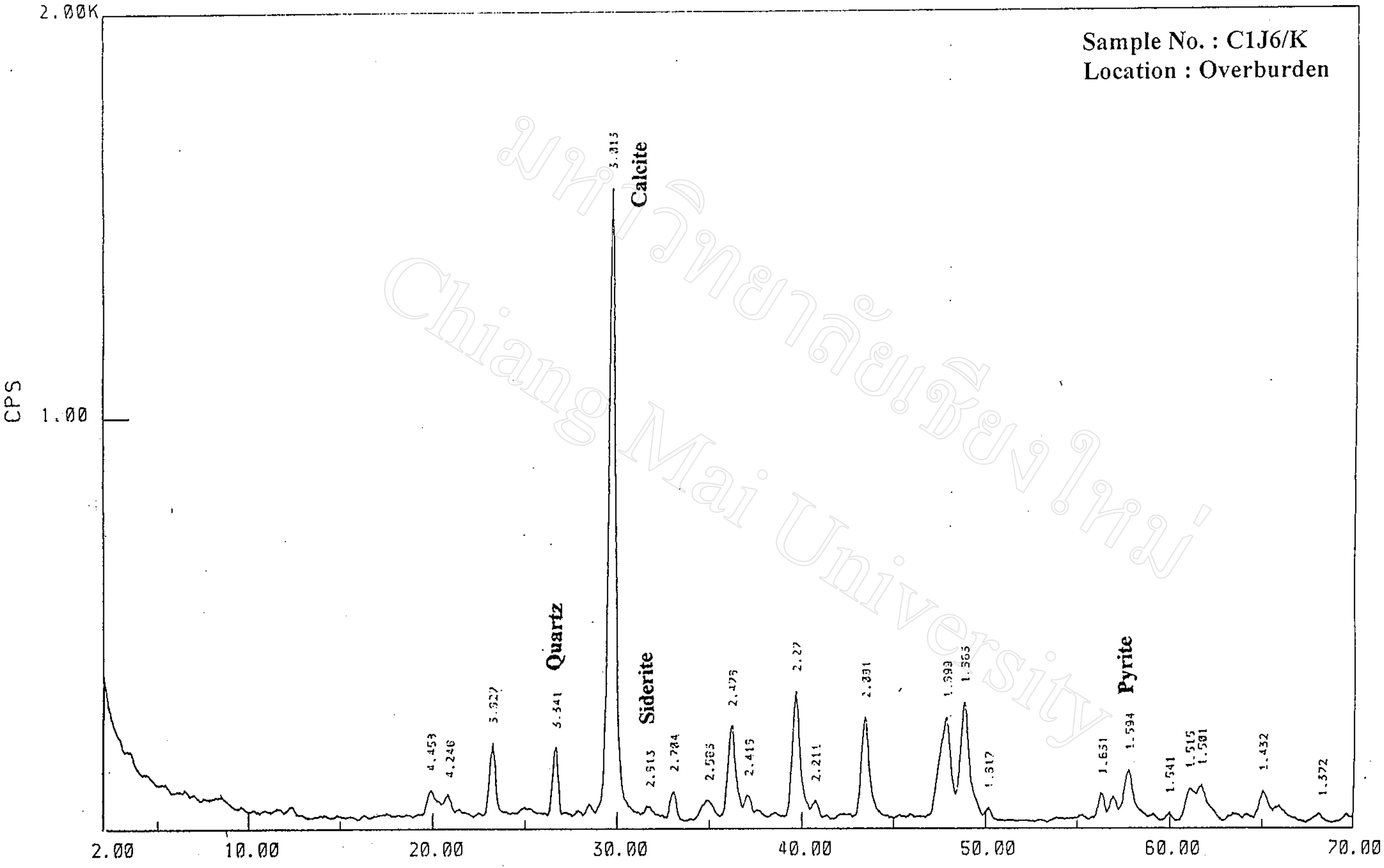

Figure 4.9 XRD patterns of clay mineral from C1J6/K (overburden) sample

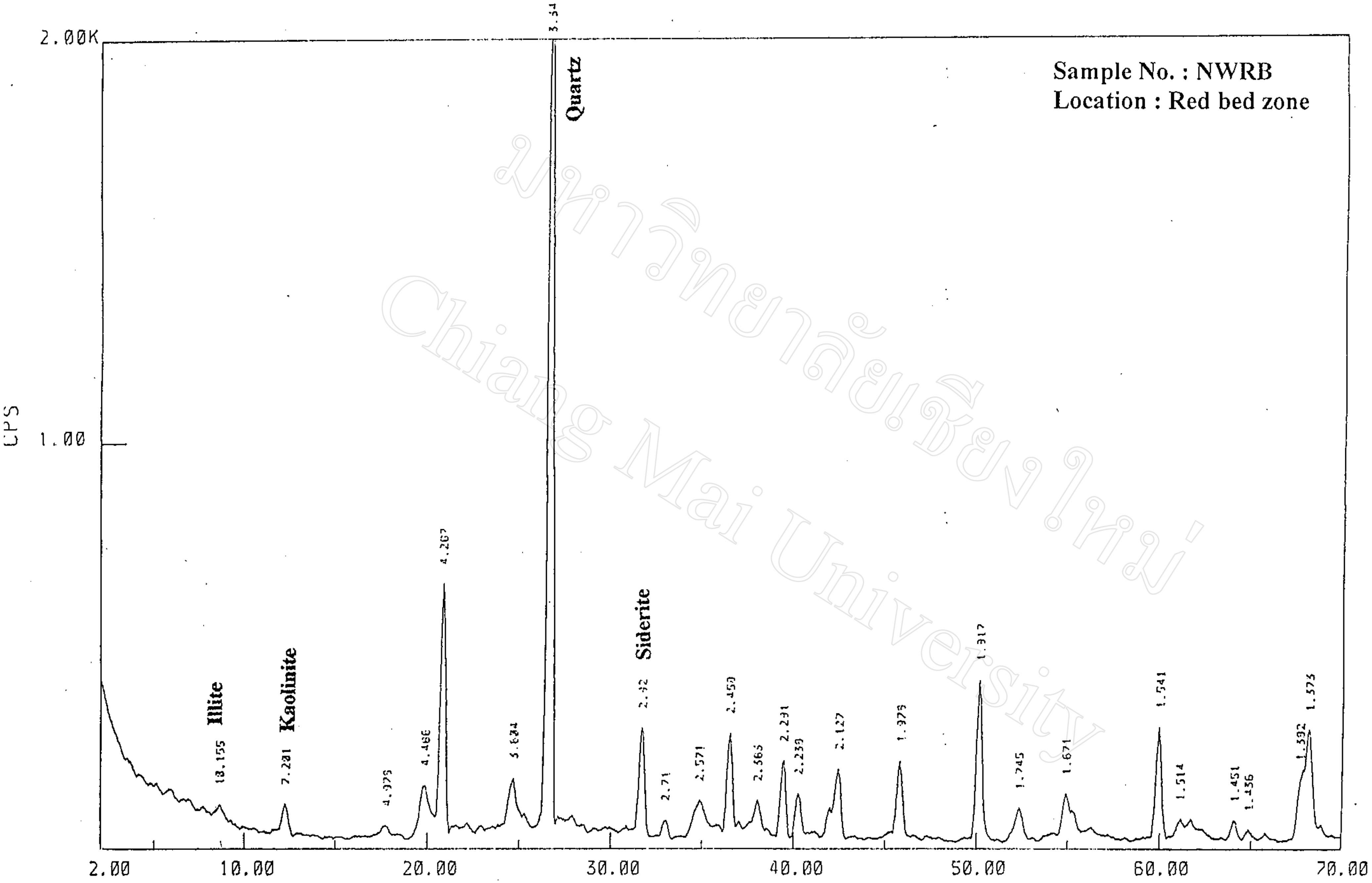

Figure 4.10 XRD patterns of clay mineral from NWRB (red bed) sample

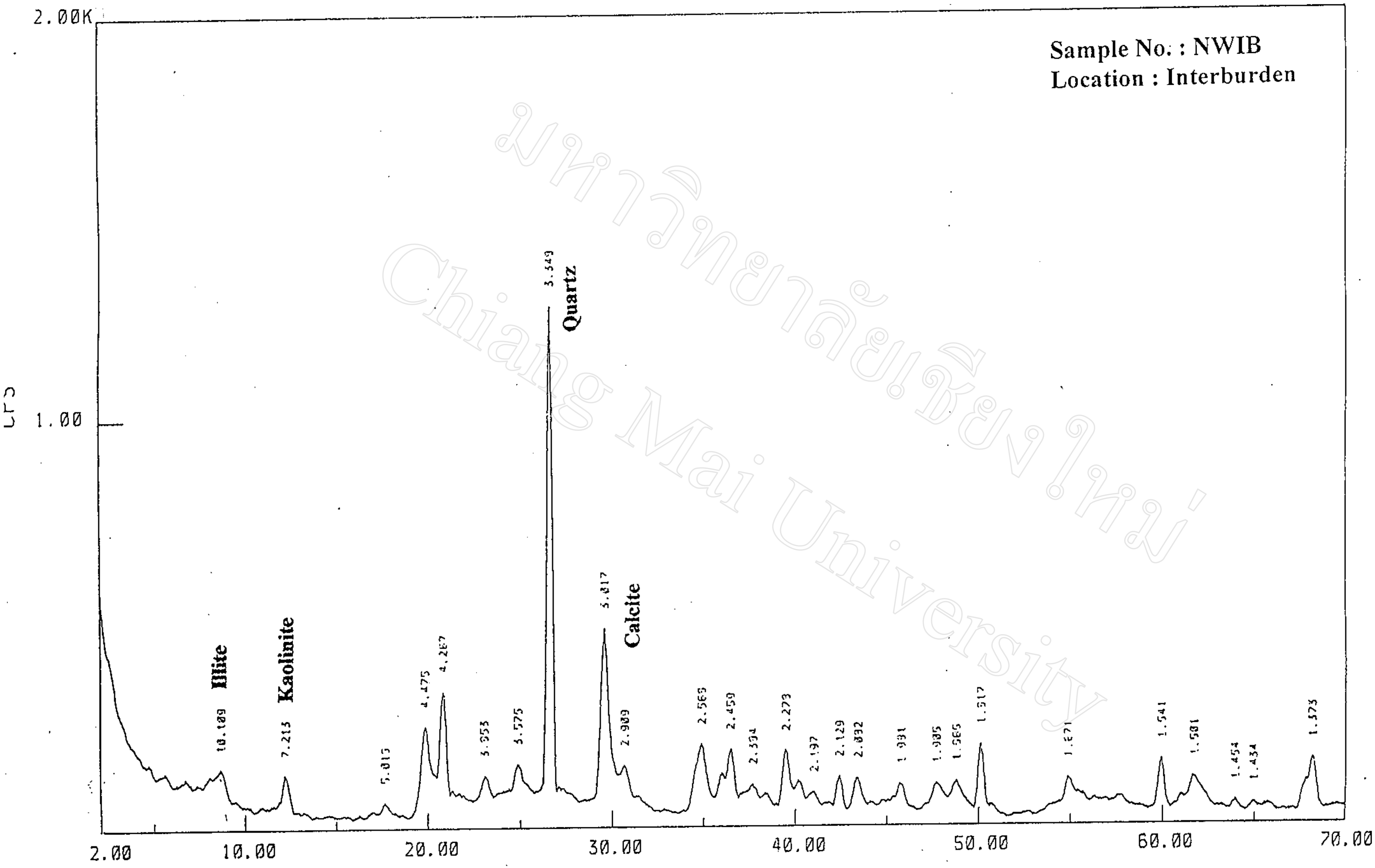

Figure 4.11 XRD patterns of clay mineral from NWIB (interburden) sample

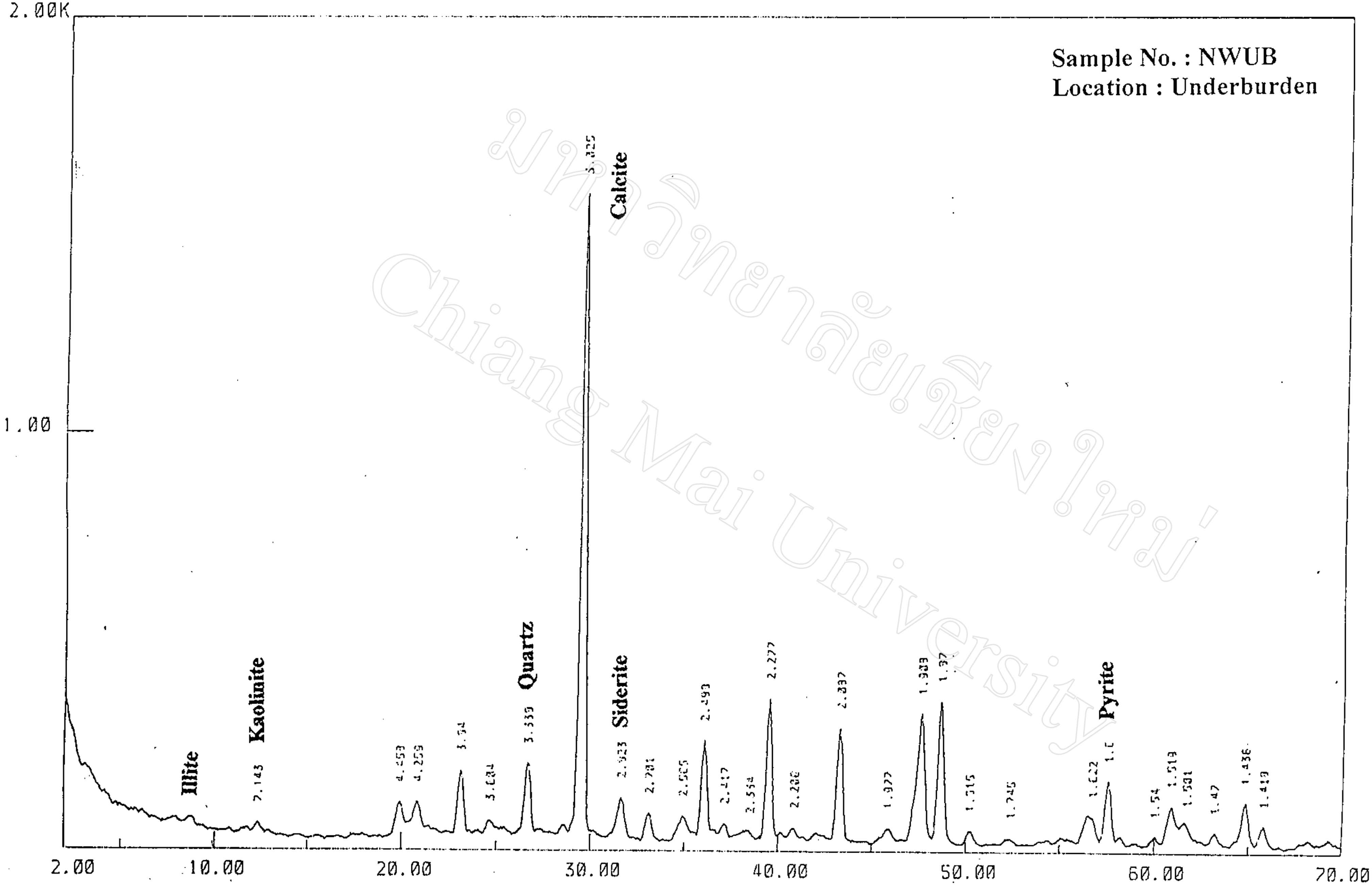

Figure 4.12 XRD patterns of clay mineral from NWUB/Q4 (underburden) sample

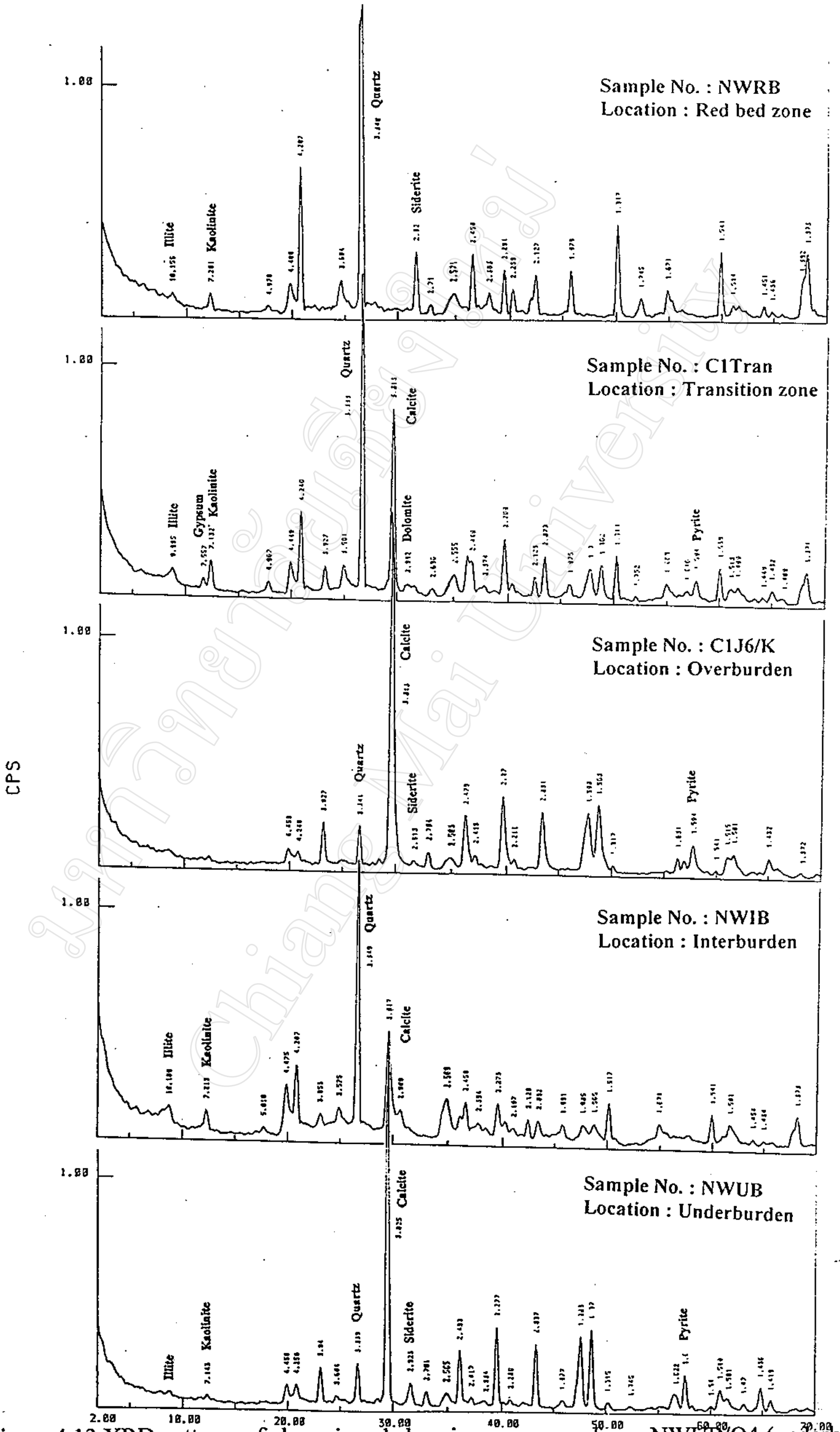

Figure 4.13 XRD patterns of clay mineral showing sequences from NWUB/Q4 (underburden) sample- NWRB (red bed) sample

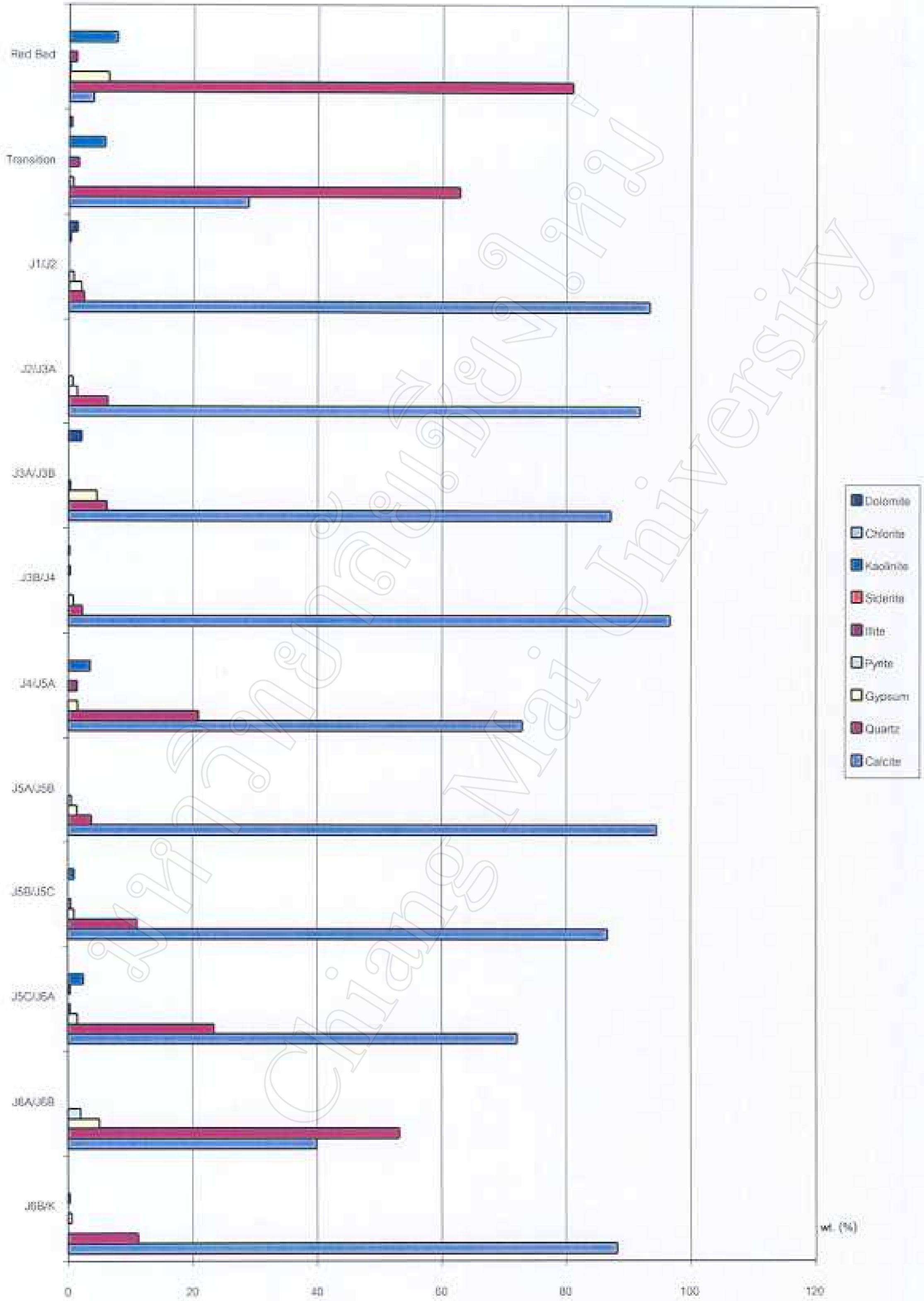

Figure 4.14 Diagram showing vertical variation of minerals in J (C-1 Pit)

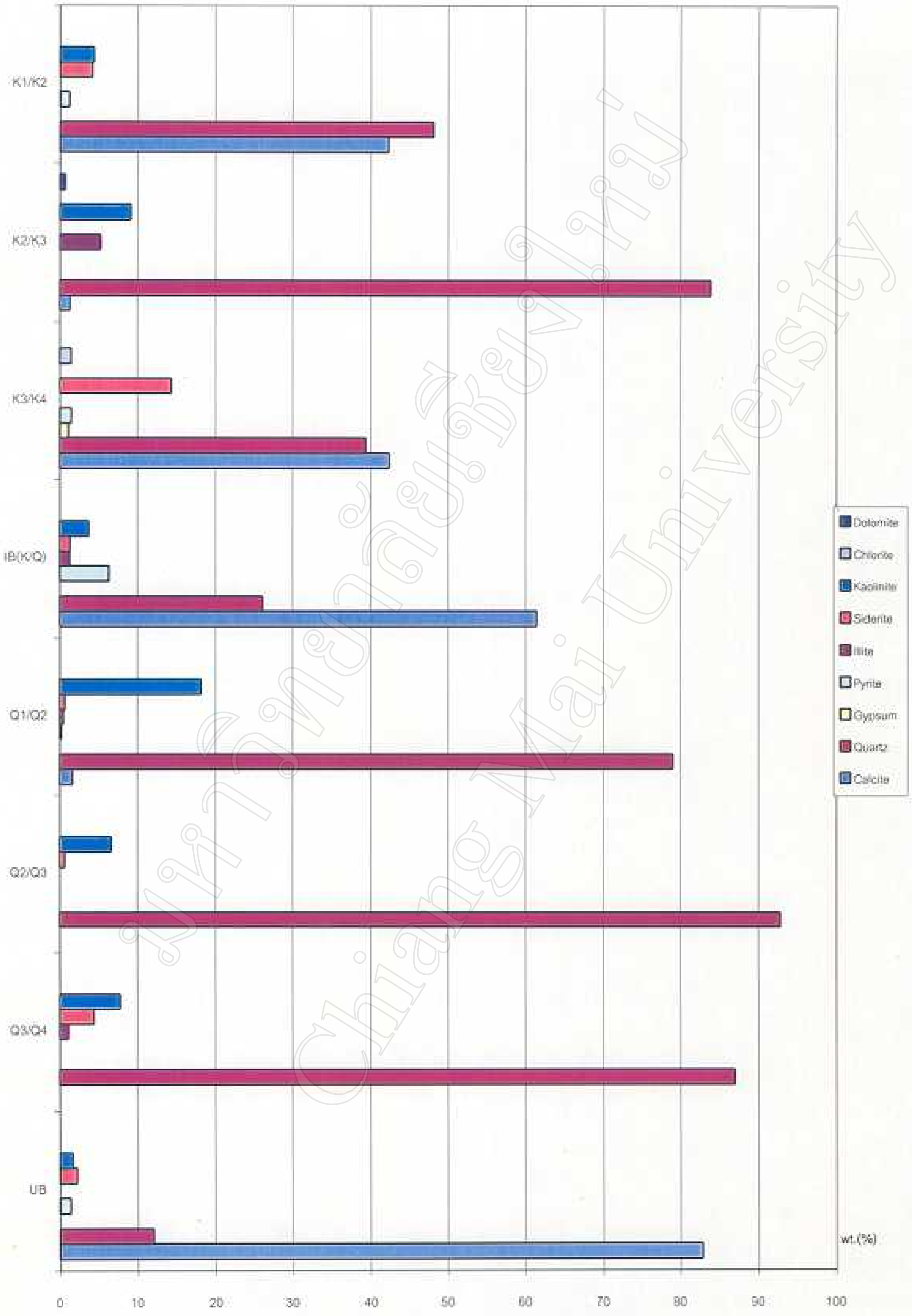

Figure 4.15Diagram showing vertical variation of minerals
K,Q zone, NE Pit

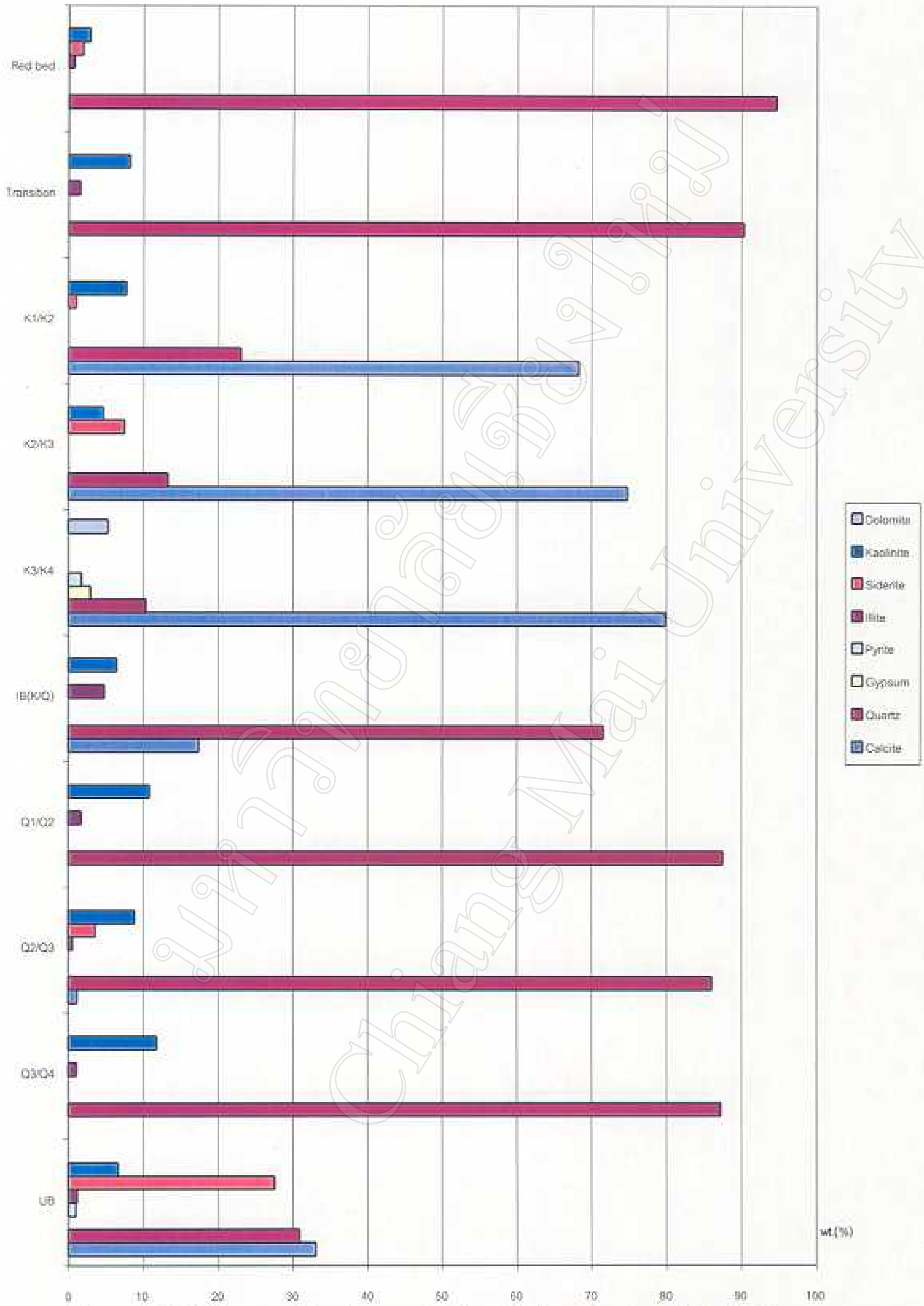

Figure 4.16 Diagram showing vertical variation of minerals in K,Q (NW Pit)

4.3 X-ray fluorescence

4.3.1 Result and interpretation

4.3.1.1 J zone, C-1 pit

The silica dioxide content in 21 samples from the J zone of the C-1 pit averages 20.15 percent and ranges from 7.94 to 36.76 percent. This silica dioxide content is high in the J2 and J4/J5A zones and in the lower portion of the seam, below the J5B/J5C zone.

The aluminum oxide concentration ranges from 2.8 to 20.2 percent and averages 6.1 percent. There is a wide distribution about the mean. This aluminum oxide content is highest in coal and, like silica dioxide, is concentrated in the J2 and J4/J5A zones and in the lower portion of the seam, below the J5B/5C zone.

The calcium oxide content ranges from 3.6 to 50.9 percent. Its average concentration is 28.14 percent. The high content is in partings in the J1/J2, J2/J3A, J3B/J4, and J5A/J5B zones.

The magnesium oxide occurrence ranges from 0.47 to 10.24 percent and averages 2.76 percent. The high magnesium oxide content occurs in the lower portion of the J coal seam.

The iron oxide concentration ranges from 1.44 to 30.44 percent and averages 11.8 percent. Iron oxide content is high in the J coal seam but there is a slight decrease in concentration from the top of the seam to the bottom of the seam.

The potassium oxide content averages 1.40 percent and ranges from 0.58 to 2.44 percent. Like silica dioxide and aluminum oxide, the lower portion of the J zone has a high potassium oxide content.

The sulfur trioxide occurrence ranges from 0.73 to 29.2 percent and averages 8.49 percent. High values occur in the J coal seam.

4.3.1.2 K and Q zones, northeast pit

The silica dioxide concentration ranges from 10.8 to 68.64 percent and average 42.15 percent. High values are found in the upper and lower portion of the K seams.

The aluminum concentration varies from 4.97 to 26.64 percent and averages at 16.17 percent. Like silica dioxide high values occur in the upper and lower portion of the K seams.

The average calcium oxide content is 9.13 percent. It ranges from 0.08 to 31.03 percent. This content is strongly biased by five high-content samples that are mostly from partings. Apart for eight samples, the vertical distribution of calcium oxide is relatively even.

The magnesium oxide concentration varies from 0.53 to 6.11 percent and averages 1.84 percent. The highest concentration is in the K1 seam.

The iron oxide content ranges from 2.37 to 37.56 percent and averages 11.99 percent. The highest concentration occurs in the K4 zone.

The occurrence of potassium oxide ranges from 0.89 to 3.29 percent and averages 2.14 percent.

The sulfur trioxide concentration ranges from 0.07 to 25.78 percent. Its average is 2.50 percent and the highest concentration is in the K1 seam.

4.3.1.3 K and Q zones, northwest pit

The silica dioxide content of samples from the K and Q zones ranges from 8.11 to 62.32 percent and averages 40.75 percent. High concentrations occur in the upper and lower portions of these zones.

The aluminum oxide concentration averages 17.42 percent and ranges from 5.32 to 28.8 percent. Like silica dioxide, high concentrations occur in the upper and lower portions of these zones.

The calcium oxide content ranges from 0.2 to 35.8 percent. Its average concentration is 10.25 percent and the high content is in the upper portions of the zone and in the underburden zone.

The magnesium oxide concentration varies from a trace to 7.23 percent and has an average of 2.22 percent. High concentrations occur in the I and K3 zones.

The average iron oxide concentration is 7.89 percent and the concentration ranges from 1.8 to 21.09 percent. An underburden parting sample has the highest content. However, the vertical concentration does not very significantly.

The potassium oxide content varies from 0.71 to 3.20 percent and averages of 2.12 percent.

The sulfur trioxide concentration ranges from 0.01 to 42.67 percent and averages of 5.21 percent. The highest concentration occurs in the upper portion of the zone, in the I seam.

The observed correlation fits well with mineralogical trends and the vertical change in element concentration. Silica dioxide occurs alone in quartz or with aluminum in kaolinite and with potassium in illite. In the J-1 zone in the C-1 pit, the concentration of silica, aluminum, and potassium is in line with the proportion of quartz, kaolinite, and illite. In the K zone in the northeast pit, silica, aluminum, and potassium concentrations are also slightly more abundant. In the Q zone in the northeast and northwest pits, the lower portion of the zone contains the highest proportion of silica, aluminum, and potassium. This reflects the increased proportion of quartz and clay.

Calcium occurs primarily in calcite and gypsum and likely also in organic combination. Calcite is the dominant mineral phase in partings and high ash samples, corresponding to Ratanasthien (1997) report of calcic diatoms in these beds. Iron and sulfur occur together primarily as pyrite but likely also occur separately associated with organic material. The positive correlation of iron and sulfur in the K and Q zones supports the presence of pyrite. The presence of abundant syngenetic pyrite in coal in indicative of a marine environment or of a transgressive sequence where the coal is overlain by marine rocks. Both environments suggest that the availability of sulfate ions during deposition or early diagenesis may be the controlling factor for pyrite formation.

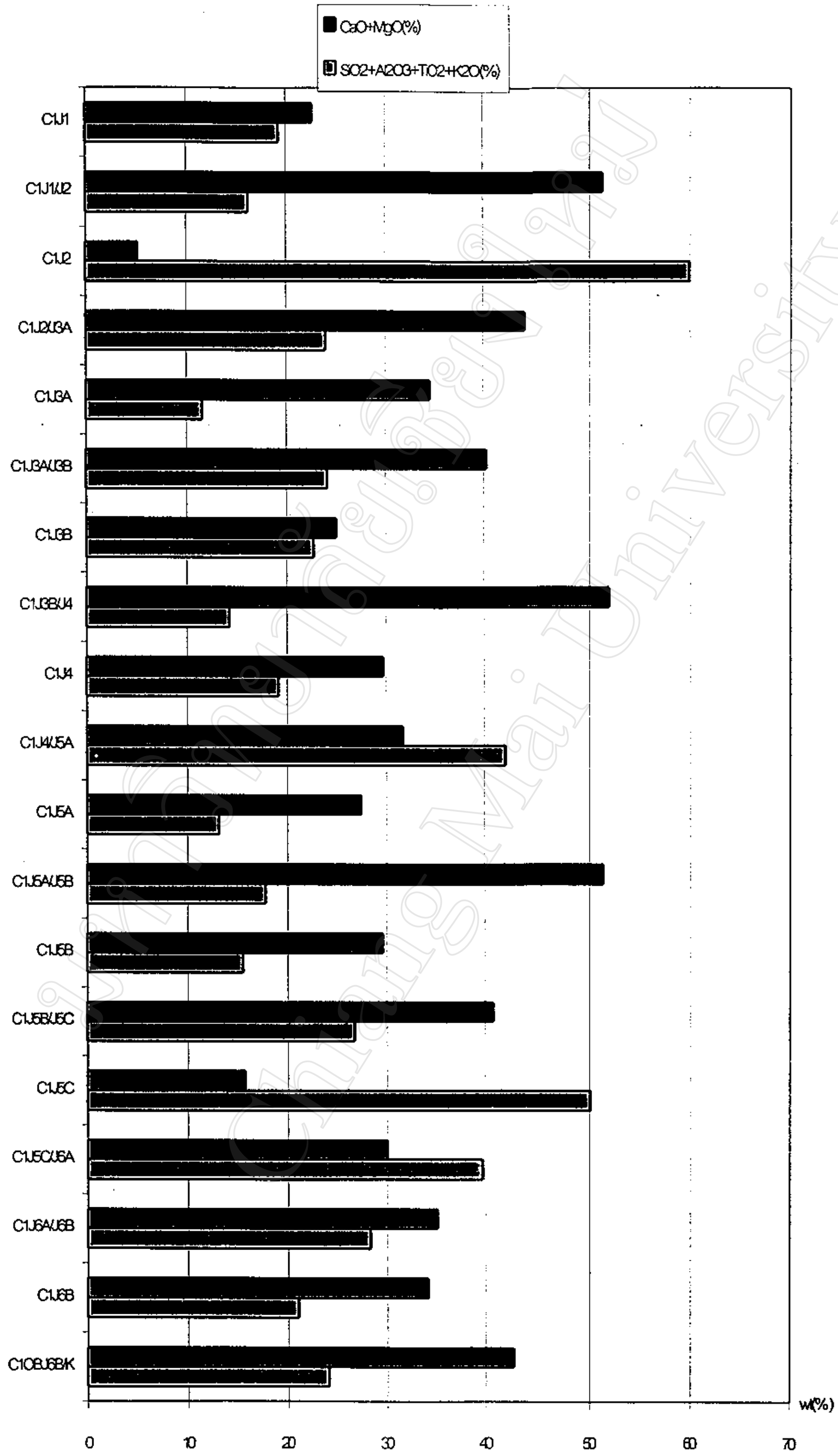

Figure 4.17 Diagram showing vertical variation of major elements in J zone, C-1 Pit

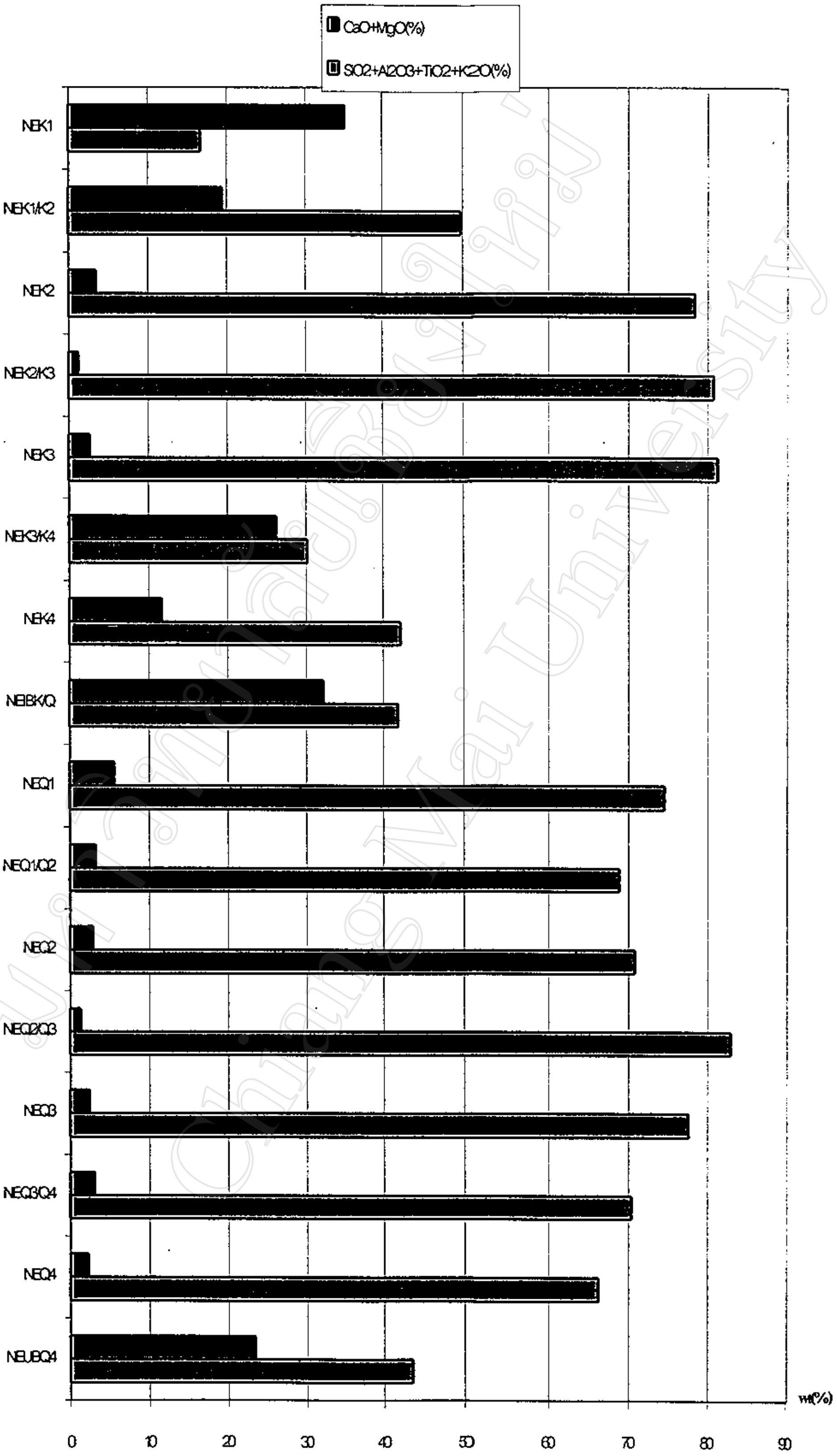

Figure 4.18 Diagram showing vertical variation of major elements in K, Q zone, NE Pit

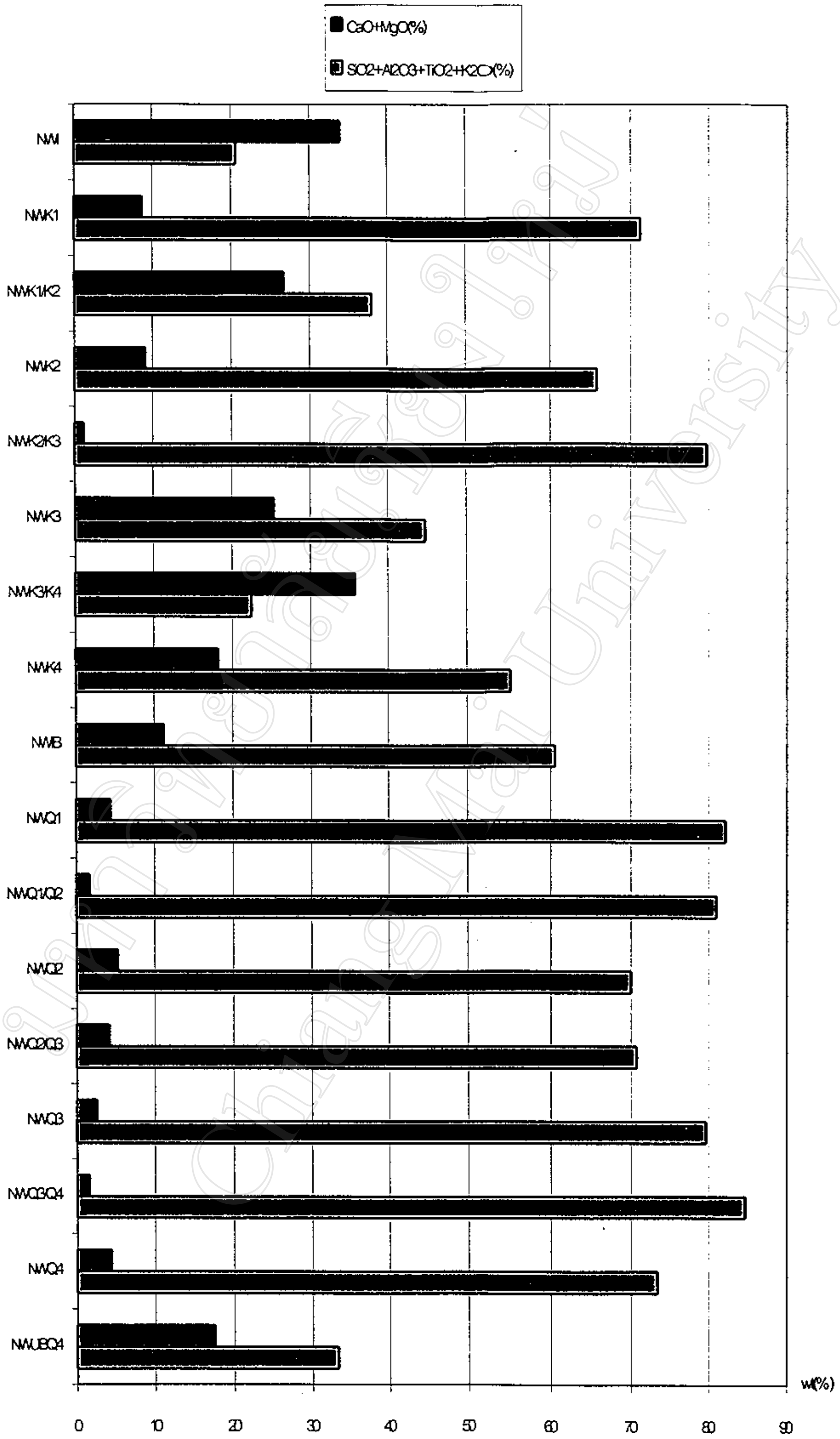

Figure 4.19 Diagram showing vertical variation of major elements in K, Q zone, NW
Pit

4.4 Induced couple plasma analysis

4.4.1 Result and interpretation

The minor elements in coal are generally present in amounts less than 1000 parts per million. They constitute elements considered to be of environmental concern, such as barium, strontium, cobalt, chromium, nickel, vanadium, and zinc, and trace elements considered to be of no or only minor environmental concern, such as zircon and rare earth elements.

4.4.1.1 Elements of environmental significance

Barium

Barium has been reported in both organic and inorganic associations. In low rank coal there is good evidence for organic association where the barium is attached to carboxyl groups (Finkelman, 1981; Miller and Given, 1986; Lyons and others, 1989; Mukherjee and others, 1993). Mineral associations include barite (Gluskoter and others, 1977; Finkelman, 1981; Powell and others, 1990), carbonates (Hower and Bland, 1989; Hower and others, 1991; Spears and Martinez-Tarazona, 1993), feldspar (Finkelman, 1981), clay minerals (Palmer and Filbey, 1984; Querol and others, 1992) and phosphates (Spears and Martinez-Tarazona, 1993).

The average barium concentration in samples from the J zone in the C-1 pit is generally higher than the average crustal abundance of 250 parts per million. The average barium content in the pit coal is 803 parts per million and this content ranges from 274 to 2267 parts per million. There is some enrichment in samples from the J-5B and J-5C seams and the highest barium concentration occurs in the J-5C seam, where it is 2267 parts per million.

In the K zone in the northeast and northwest pits the average barium concentration is more than twice the average crustal abundance. Barium content in four samples from the K zone in the northeast pit ranges from 826.3 to 1919 parts per million and averages 1248 parts per million. Barium content in four samples from the K zone in the northwest pit ranges from 485.8 to 1517 parts per million and averages 789 parts per million.

In the Q zone the barium content is only slightly greater than its average crustal abundance. In this zone, barium concentration ranges from 11.87 to 1138 parts per million and averages 682 parts per million in four samples from the northeast pit and ranges from 268.4 to 1517.2 parts per million and averages 580.2 parts per million in four samples from the northwest pit.

Strontium

Relative to the earth's crust, Strontium is enriched in the J zone in the C-1 pit. The highest concentration of strontium occurs in the J5B seam at 1800 parts per million. The vertical distribution of strontium is variable in the zone, being higher in samples from the middle and lower portions of the zone. In the K zone in the northeast and northwest pits, strontium is concentrated in the lower and upper portions of the zone. The highest concentration occurs in the K-3 seam in the northwest pit. The correlation of strontium with ash, silica, aluminum, and potassium is poor to weakly negative. In the J zone in the C-1 pit strontium is not correlated with calcium. However, it is positively correlated with calcium in the K and Q zones in the northwest pit.

The positive correlation of strontium with calcium suggests a combined association. Strontium is known to substitute for calcium in calcite (Deer and others, 1964). Although not identified by x-ray diffraction, small concentrations of strontium could be present in the minerals strontianite or celestine.

Cobalt

Swaine (1990) indicate that cobalt can occur in both organic and inorganic association. The cobalt-bearing mineral linnaeite, $(Co, Ni)_3S_4$, has been identified in coal by a number of authors (Goldschmidt, 1935; Finkelman, 1981) and correlation data for many coal samples indicate a cobalt-sulfide association (Van der Flier-Keller and Fyfe, 1987; Querol and others, 1992). A clay mineral association has also been suggested (Finkelman 1981; Van der Flier-Keller and Fyfe, 1987).

The average cobalt content in samples from the C-1, northeast, and northwest pits in the Mae Moh mine is highest in the J zone and least in the Q zone. The average cobalt concentration in coal samples from the J and K zones is slightly higher than the worldwide average of 29 parts per million. The average from and the Q zone is slightly less than the worldwide average.

In the J zone in the C-1 pit, the cobalt concentration in 10 samples ranges from 18.67 to 43.1 parts per million and averages 28.3 parts per million. The highest concentrations occur in samples in the upper portion of the zone where the ash content is also high.

The cobalt content in samples from the K zone in the northeast pit ranges from 16.69 to 38.96 parts per million, with an average of 25.52 parts per million. Samples from the lower portion of the zone have slightly higher cobalt content. The lowest concentration occurs in the K-2 seam in the northeast pit. In the K zone in the northwest pit cobalt in four samples ranges from 16.37 to 62.17 parts per million, with an average 30.59 parts per million.

The cobalt content of four samples from the Q zone in the northeast pit ranges from 15.69 to 39.71 parts per million, with an average of 23.07 parts per million. Cobalt content is highest in samples from the upper portion of the zone. In the Q zone in the northwest pit, the cobalt content of all samples ranges from 14.88 to 38.83 parts per million and averages 22.3 parts per million. Samples with the highest cobalt concentration occur in the Q-2 seam in the northwest pit.

Chromium

An inorganic clay mineral association for chromium was suggested by Finkelman (1993). Van der Flier-Keller and Fyfe (1987) suggested that chromium is also likely to be associated with heavy minerals.

In C-1 and northeast pits, chromium concentration is highest in samples from the J zone and least in samples from the Q zone. The average chromium content in samples is generally higher than average crustal content of 185 parts per million.

Chromium concentration in 10 samples from the J zone in the C-1 pit ranges from 83 to 1196 parts per million and averages 264 parts per million.

Chromium concentration in four samples from the K zone in the northeast pit ranges from 103 to 236 and averages 143 parts per million. The four samples from the K zone in the northwest pit have chromium contents that range from 72.1 to 3374 parts per million, with an average of 946 parts per million. In the northeast pit K zone, the highest chromium concentrations occur in samples from the lower portion of the zone, whereas in the northwest pit K zone, the chromium content is highest in samples from the K-3 seam.

In the Q zone's northeast pit, chromium content in four samples ranges from 81.2 to 132 parts per million, with an average of 192 parts per million. Four samples from the Q zone's northwest pit have an average chromium content of 100 parts per million, with a range from 71.7 to 161 parts per million. In both pits high chromium concentrations occur in samples from the Q-2 seam.

Nickel

Gluskoter and others (1977) suggested that nickel is distributed between sulfide minerals and the organic materials in coal in Illinois. Fractionation experiments by Miller and Given (1986) on samples from North Dakota lignite indicated that nickel was partially to largely complexed with organic matter. Finkelman (1993) indicated the probable mode of occurrence for nickel is unclear and that it can occur with organic material, sulfides, or clay minerals.

The average nickel concentration in coal samples from the Mae Moh mine is less than the average crustal abundance of 105 parts per million. The average nickel concentration is highest in the J zone and approximately equal in samples from the Q and K zones. Nickel in J zone samples in the C-1 pit range from 32.0 to 233.2 parts per million and average 64.6 parts per million. The highest nickel concentrations occur in samples from the J-1 seam in the C-1 pit.

Nickel content in K zone samples in the northeast pit ranges from 22.3 to 70.8 parts per million and averages 43.5 parts per million. In K zone samples in the northwest pit, nickel content varies from 17.4 to 665 parts per million and averages 189 parts per million.

Q zone samples in the northeast pit have nickel contents that range from 14.14 to 38.15 parts per million and which average 24.7 parts per million. Samples from this same zone in the northwest pit have nickel contents that vary from 15.37 to 44.4 parts per million and average 25.4 parts per million. Nickel content in the northeast pit is generally high in the upper portion of the Q zone.

In low ash samples the correlation of nickel with ash was positive. This indicates a mineral occurrence and the positive correlation with iron and sulfur suggests the association is likely with iron sulfide. The positive correlation with silica, aluminum, and potassium suggests a possible clay mineral affiliation, though a sulfide association is more likely.

Vanadium

The organic/inorganic association of vanadium in coal is extremely variable. The predominantly organic association for vanadium was indicated by Ruch and others (1974), Gluskoter (1975), Ward (1980), Karner and others (1986), and Lyons and others (1988). The primarily inorganic association for vanadium was indicated by Goodarzi (1987, 1988) and Van der Flier-Keller and Fyfe (1987). The mineral constituents which most often contain trace proportions of vanadium are carbonate and clay minerals (Kuhn, 1980; Valkovic, 1983; Harvey and Ruch, 1986; Finkelman, 1993).

The average vanadium concentration in Mae Moh coal is generally slightly higher than the average crustal abundance of 230 parts per million. Vanadium content is highest in the J zone and least in the Q zone.

In the C-1 pit J zone, vanadium concentration ranges from 934 to 642 parts per million and averages 218 parts per million. Samples from the upper portion of this zone have the highest vanadium content.

Northeast pit K zone samples have vanadium contents that range from 140 to 198 parts per million and average 163 parts per million. K zone samples in the northwest pit have vandium concentrations that range from 81.3 to 151 parts per million and average 121 parts per million. Higher concentrations occur in the upper portion of the K zone in the northeast and northwest pits. Low vanadium concentration occurs in the K-3 seam in the northwest pit.

Vanadium content in the Q zone of the northeast pit ranges from 160 to 191 parts per million and averages 171 parts per million. Northwest pit Q zone samples have vanadium contents that range from 162 to 340 parts per million and average of 242 parts per million. The Q-2 seam in both of these pits contains higher vanadium contents.

Strong positive correlation of vanadium with silica, aluminum, and potassium suggests that vanadium is primarily associated with clay minerals. The negative correlation with calcium indicates that there is no carbonate association.

Zinc

Both organic and inorganic associations for zinc have been suggested. The primary zinc-bearing minerals in coal include sulfides and carbonates. Zinc is also often associated with clay minerals and/or hydrous oxides of iron and manganese where zinc is adsorbed onto clay or oxide surfaces.

The average zinc concentration in samples from the J zone in the C-1 pit is generally higher than zinc's average crustal abundance. This J zone average is 93.87 parts per million and is based on a range from 32.15 to 155 parts per million. Zinc content in northeast pit K zone samples ranges from 131 to 186 parts per million and averages 152.4 parts per million. Northwest pit K zone samples have zinc contents that range from 20.4 to 134 parts per million and average 94.7 parts per million. Zinc concentration ranges from 172 to 327 parts per million and averages 237 parts per million in northeast pit Q zone samples. The range of zinc concentration in the Q zone in the northwest pit is from 147 to 214 parts per million and averages 178 parts per million.

4.4.1.2 Trace elements of no environmental significance

The elements in this group include zircon and some rare earth elements. Relative to the earth's crust, zircon is enriched in the Q zone in the northwest pit. The highest concentration of zircon occurs in the J5A seam on the C-1 pit, where it is 254 parts per million.

Vertical distribution of zircon is variable. In the J zone in the C-1 pit, the concentration of zircon is higher in samples from the middle and lower portions of the zone.

In the K zone in the northeast and northwest pits, zircon is concentrated in the lower and upper portion of the zone. The highest concentration of zircon occurs in the K-1 seam in the northeast pit.

The concentration of zircon is highest in the upper portion of the Q zone in both the northeast and northwest.

The zircon is most commonly identified with detrital sediments rich in quartz, as indicated by a high silica dioxide content, and with the inorganic fraction in low rank coal (Miller and Given, 1987). Zircon is also positively correlated with ash, silica, aluminum, and potassium, indicating a strong affinity for these mineral fractions. This affinity is likely with the clay minerals.

The distribution of lanthanum, cerium, and yttrium is generally high compared to their upper crustal abundance, which is 16, 33, and 20 parts per million, respectively

(Taylor and McLennan, 1985). The highest concentrations of lanthanum, cerium, and yttrium occur in the I seam in the northwest pit and in the Q-4 seam in the northeast pit, where their concentrations are 370, 43.3, 85.56 parts per million, respectively. These elements show a strong correlation with each other.

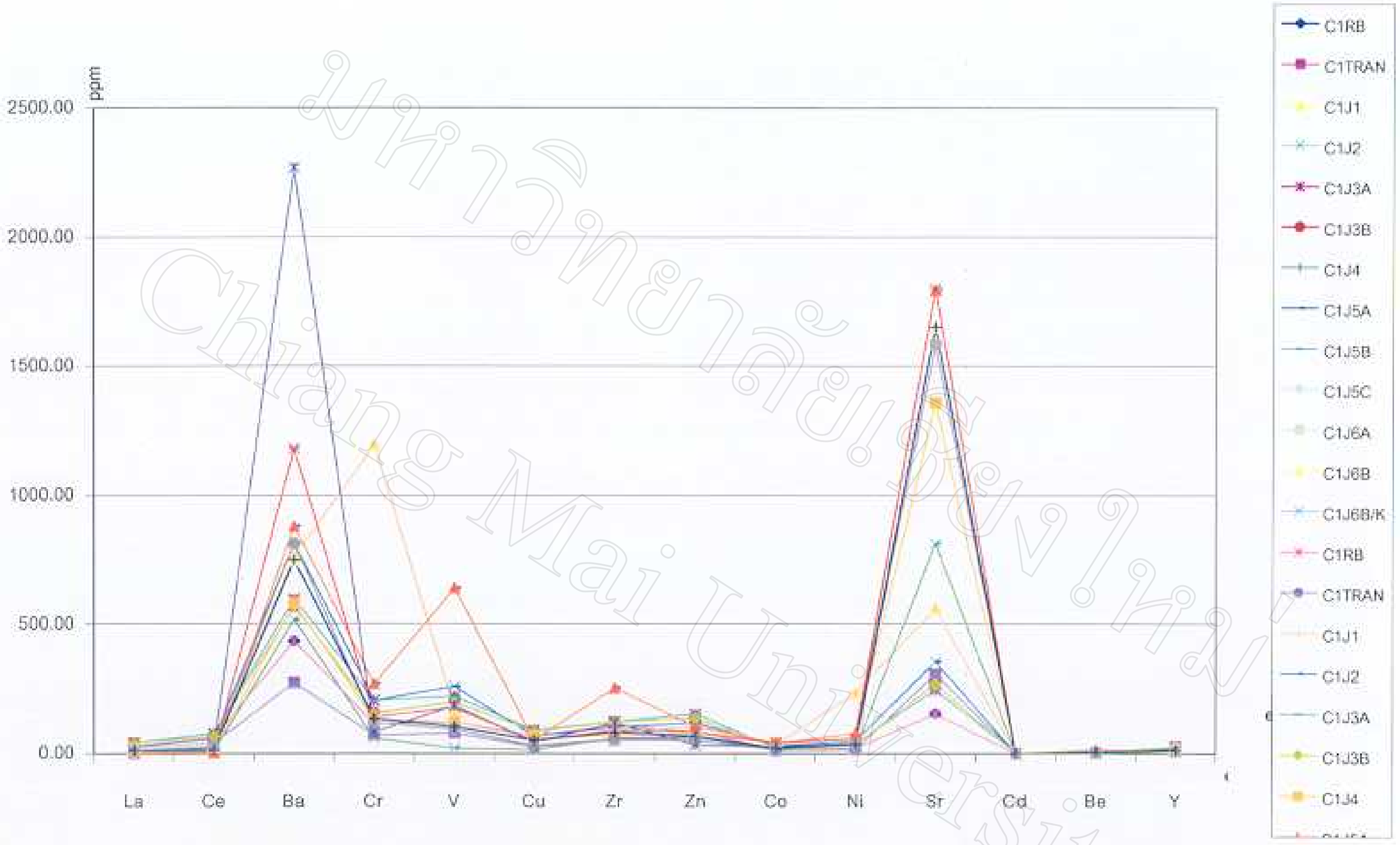

Figure 4.20 Variation plot of trace elements in C-1 Pit

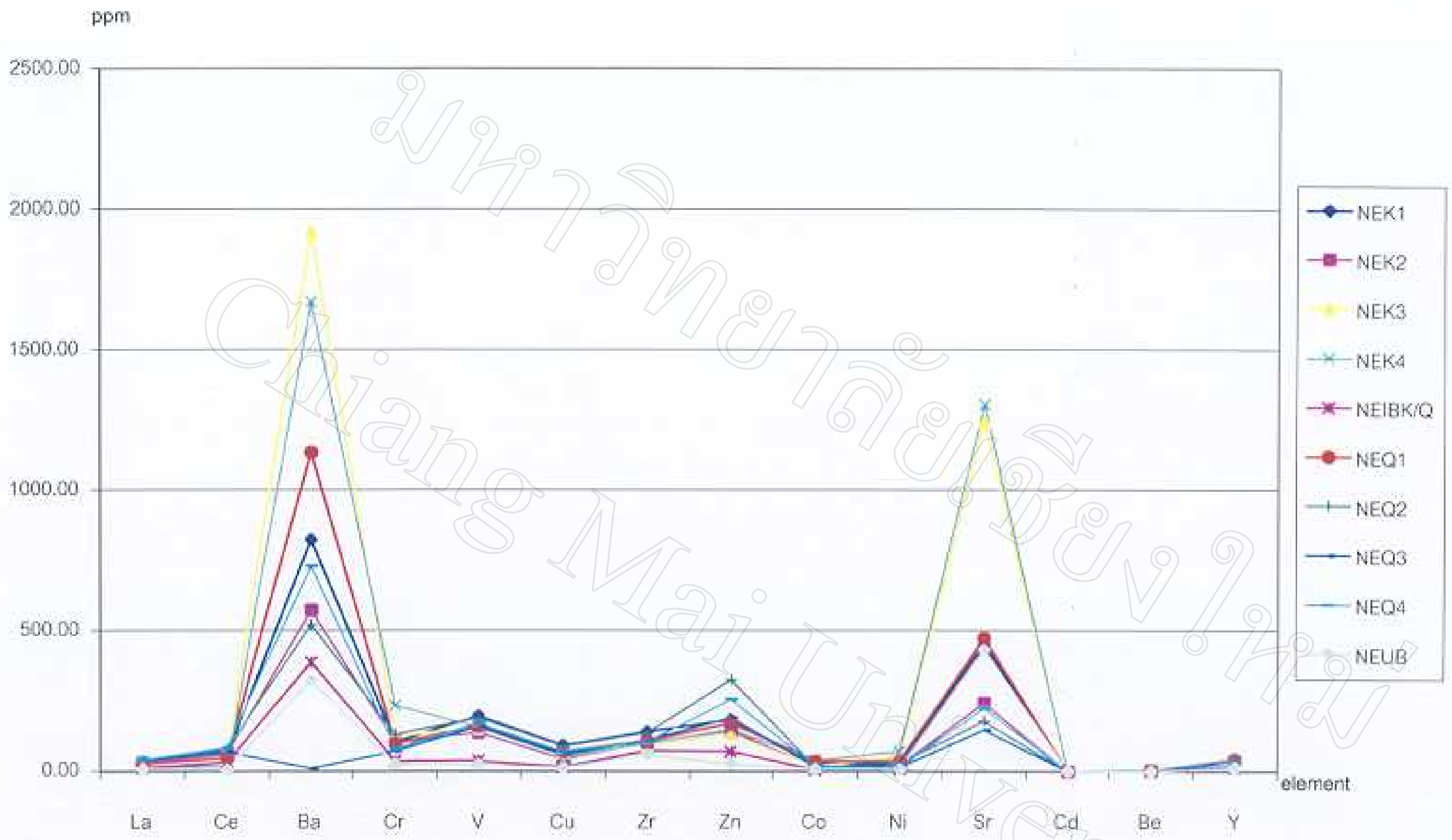

Figure 4.21 Variation plot of trace element in NE Pit

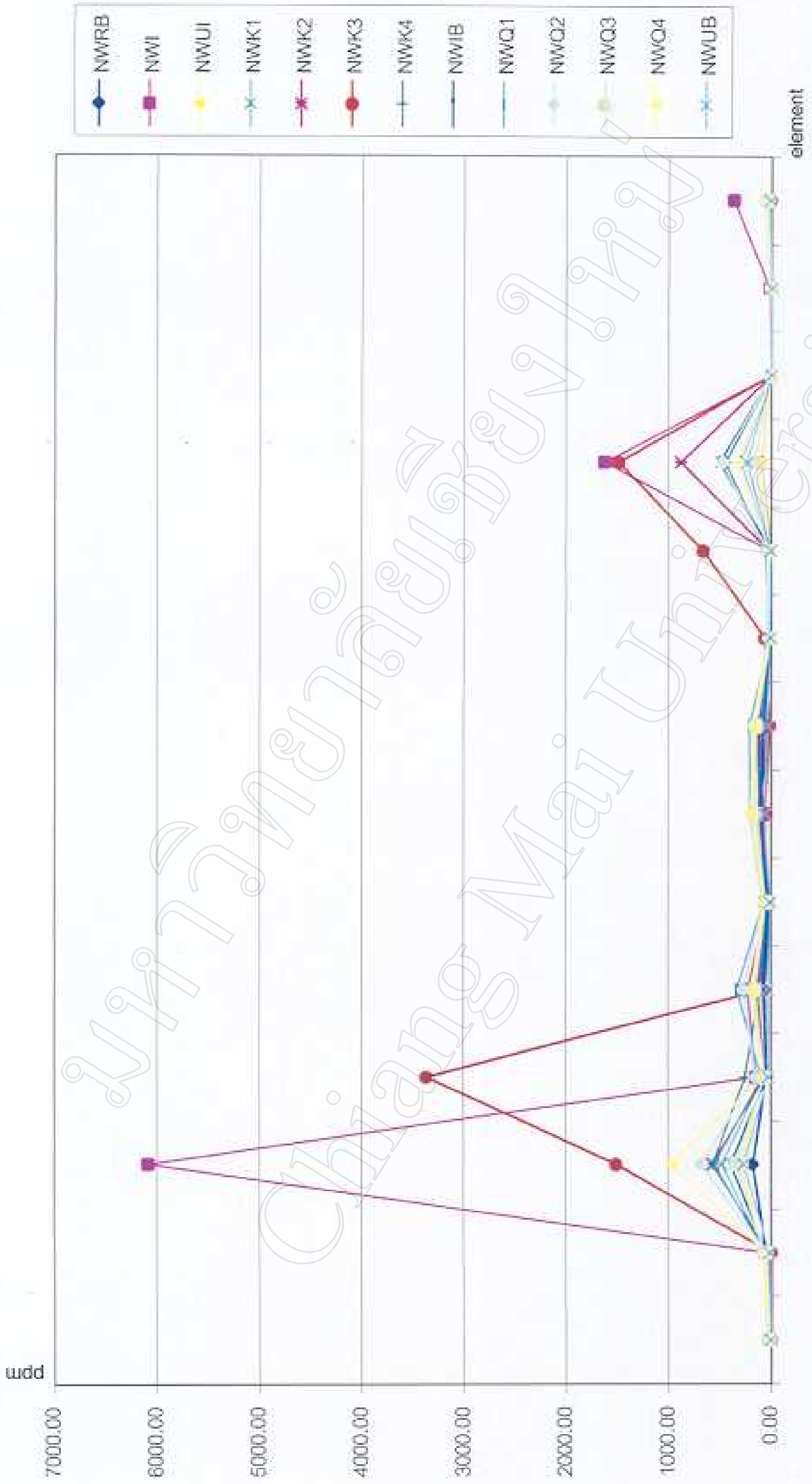

Figure 4.22 Variation plot of trace elements in NW Pit

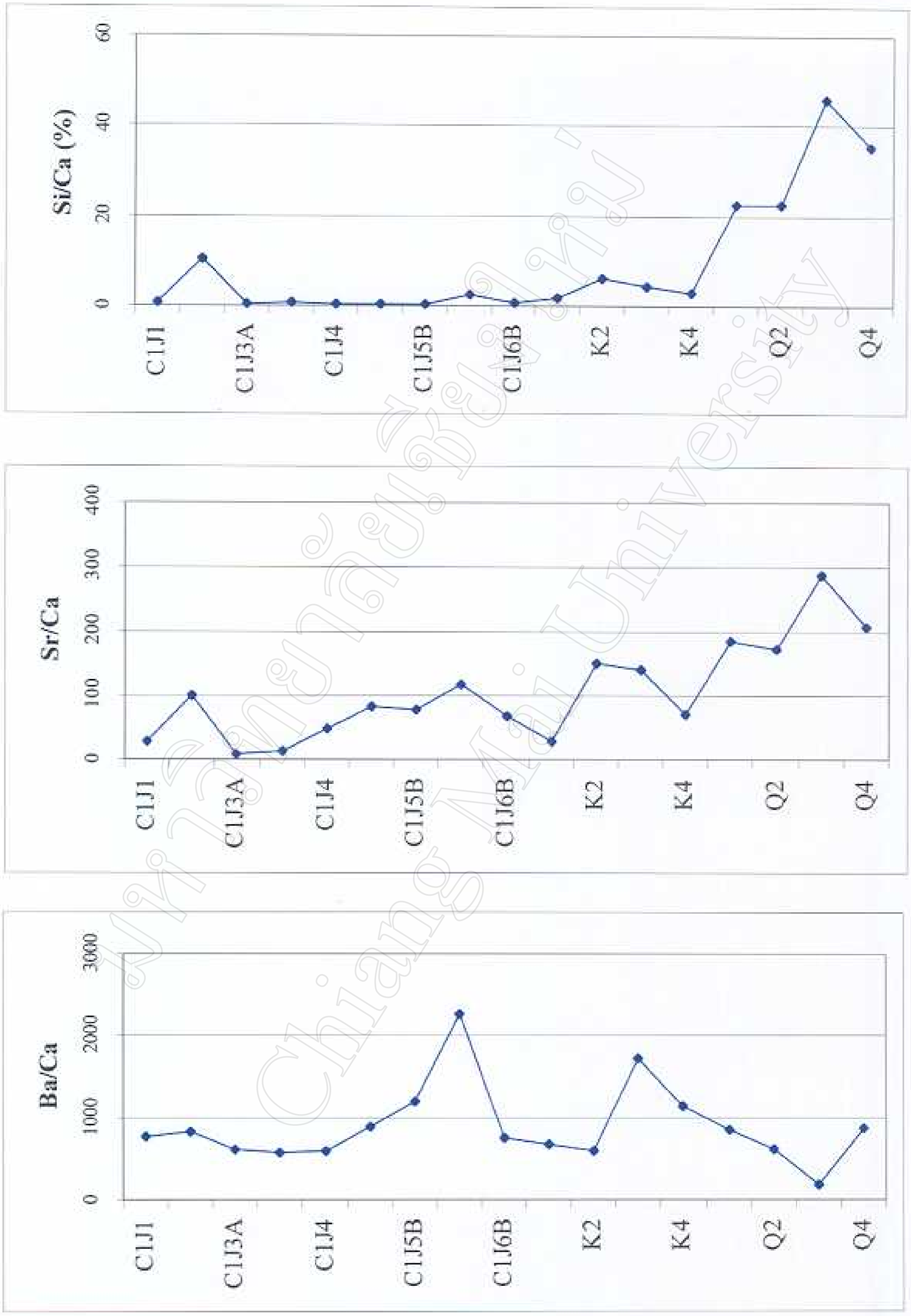

Figure 4.23 Showing the variation plot between Ba/Ca, Sr/Ca, Si/Ca ratio of the Mae Moh coal field

Figure 4.24 Showing the variation plot of Co, Cr and V concentrations of the Mae Moh coal field

4.5 Coal petrography

4.5.1 Result and interpretation

Q zone

Major macerals are the huminite group densinite, gelinite, and textinite macerals. These macerals comprise about 80 percent of the total macerals in the zone. Second in abundance are the liptinite group macerals alginite and liptodetrinite.

The presence of fusinite in Q zone coal indicates that water during deposition was shallow and that at other times conditions were dry. Indications of burning are present throughout the coal seams. Since alginites are rare in the Q zone, depositional sites were not waterlogged during the peat accumulation. Highly oxidized condition of water in the basin led to the formation of liptodetrinite bands by the destruction of all organic materials in the liptinite group.

K zone

Major macerals are huminite group textinite, gelinite, and densinite. Second in abundance is alginite of the liptinite group. Other macerals are sporinite, cutinite, and liptodetrinite. The inertinite maceral group forms a minor constituent and is mostly fusinite, which indicates an arid to semi-arid condition of the basin. Framboidal pyrite is common as an authigenic mineral.

The cutinite-rich and sporinite-rich coal and tree trunk remains, or textinite, in the basin indicate that the depositional area was a forest swamp. The water in the lacustrine depositional area was essentially freshwater. This is indicated by the dominance of thin-walled alginite and the present of sporinite.

J zone

Main macerals are gelinite, textinite, and densinite of the huminite group. Second in abundance are various kinds of alginite, cutinite, and sporinite of the liptinite group. Inertinite group macerals occur as fusinite in variable amounts. Some J coal seams are rich in fusinite. This indicates that natural fires or strong oxidation of plant materials occurred before deposition. The dominant authigenic mineral is framboidal pyrite.

The association of alginite and cutinite in coal throughout the J zone indicates that water level during deposition was intermediate to shallow. The variation of alginite types, especially the presence alginite such as *Reinschia*, *Pila* algae, and *Botryococcus* sp. could also indicate a change in water condition. The richness of framboidal pyrite resulted from the presence of *Desulfoviobrio desulfuricans* bacteria. This may indicate that water in the Mae Moh basin during this time became brackish and was at a high level. The presence of fusinite indicates that there was at times shallow water and dry periods that likely led to natural fires before the deposition.

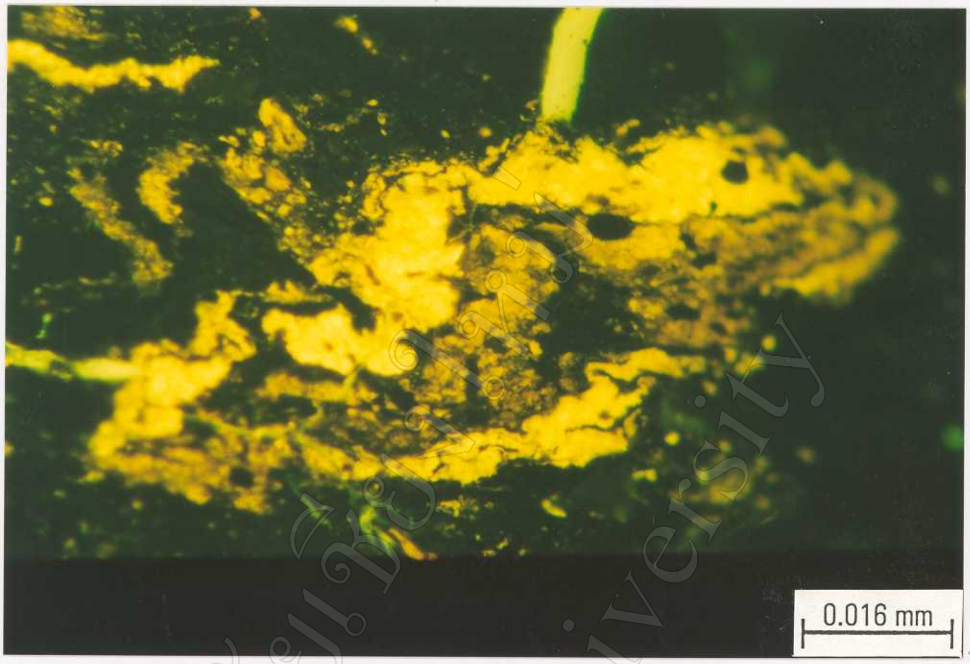

Figure 4.25 Photomicrograph showing sporinite and liptodetrinite in J-1 coal seam under oil immersion, fluorescenced, 50x

Figure 4.26 Photomicrograph showing piece of inertinite (scherotinite filling with exudatinite), in exudatinite background in J-5A coal seam under oil immersion, fluorescenced, 50x

Figure 4.27 Photomicrograph showing framboidal pyrite and liptodetrinite in densinite in J-6B coal seam under oil immersion, fluorescenced, 50x

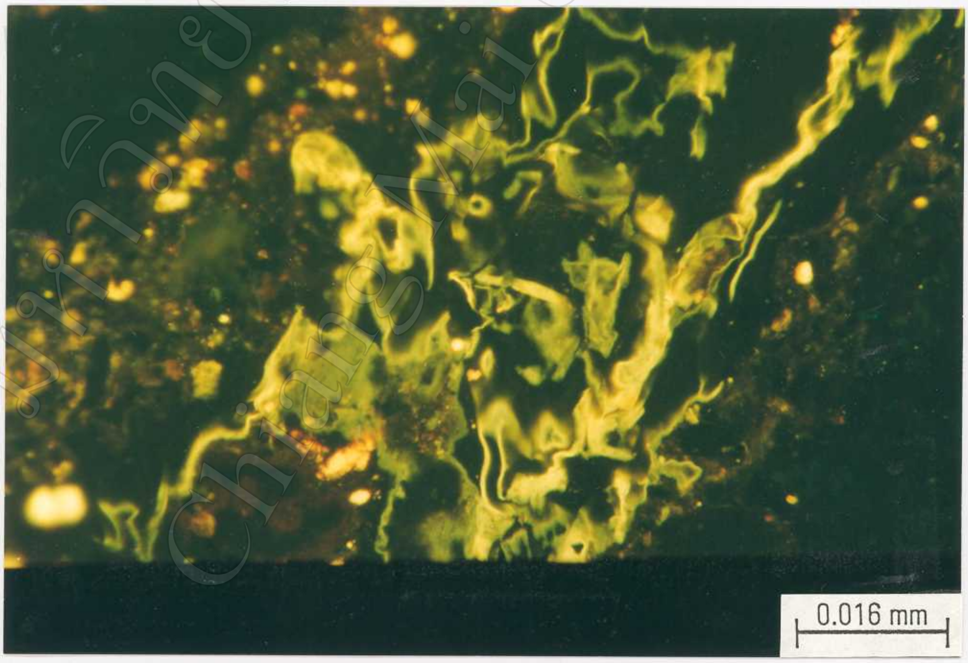

Figure 4.28 Photomicrograph showing alginite, cutinite, sporinite and liptodetrinite in J-6B coal seam under oil immersion, fluorescenced, 50X

Figure 4.29 Photomicrograpg showing colonies of alginite (Botryococcus type I) in J-6B coal seam under oil immersion, fluorescenced, 50X

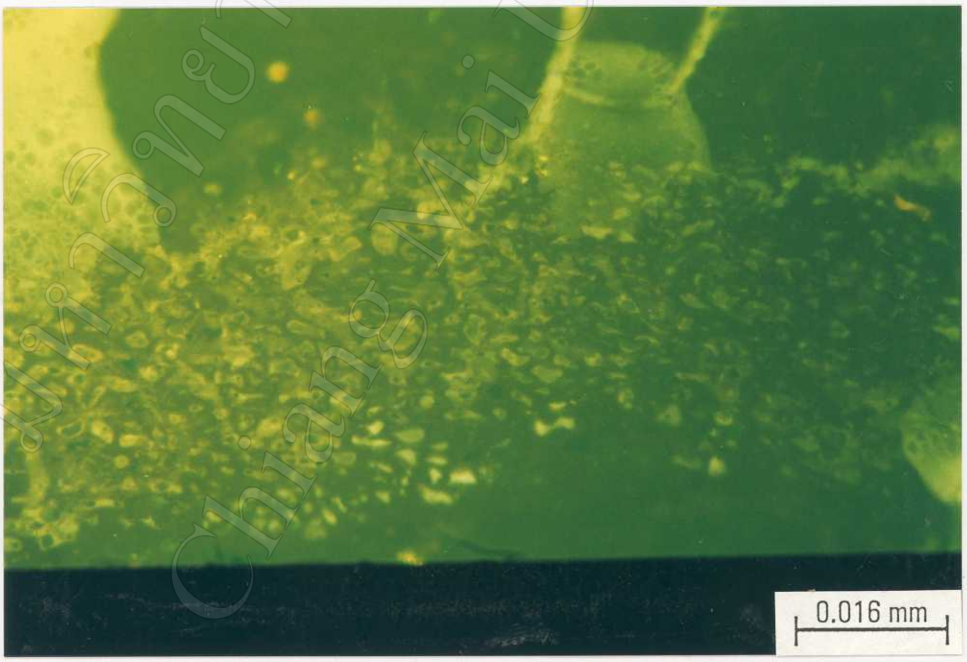

Figure 4.30 Photomicrograph showing pieces of sclerotinite filling with exsudatimnite in K coal seam under oil immersion fluorescenced, 50X

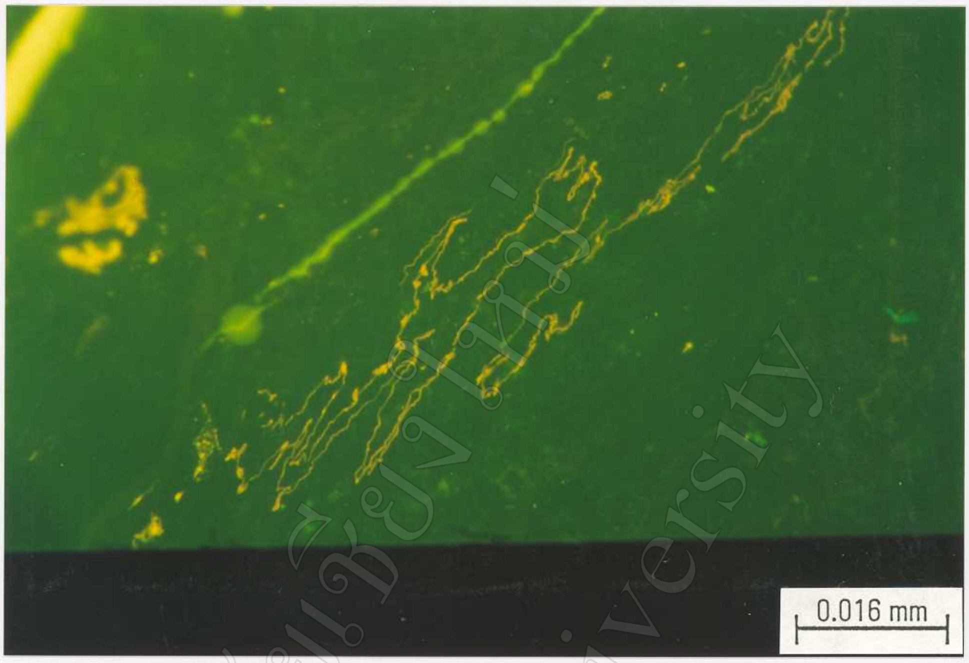

Figure 4.31 Photomicrograph showing cutinite and sporinite in the background of lipto-vitrinite in K coal seam under oil immersion, fluorescenced, 50X

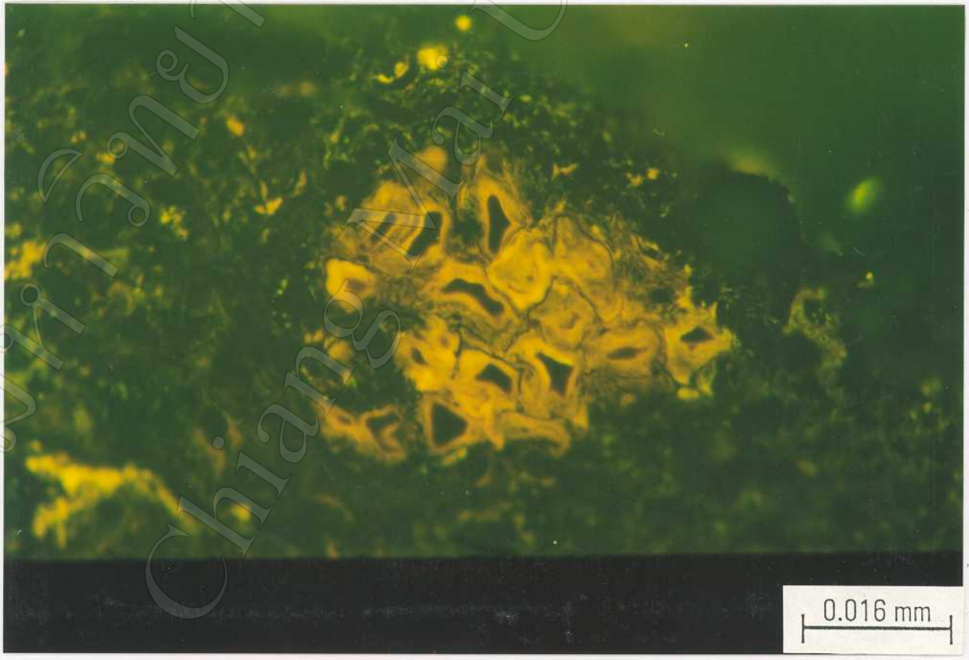

Figure 4.32 Photomicrograph showing sporinite and liptodetrinite in K coal seam under oil immersion, fluorescenced, 50X

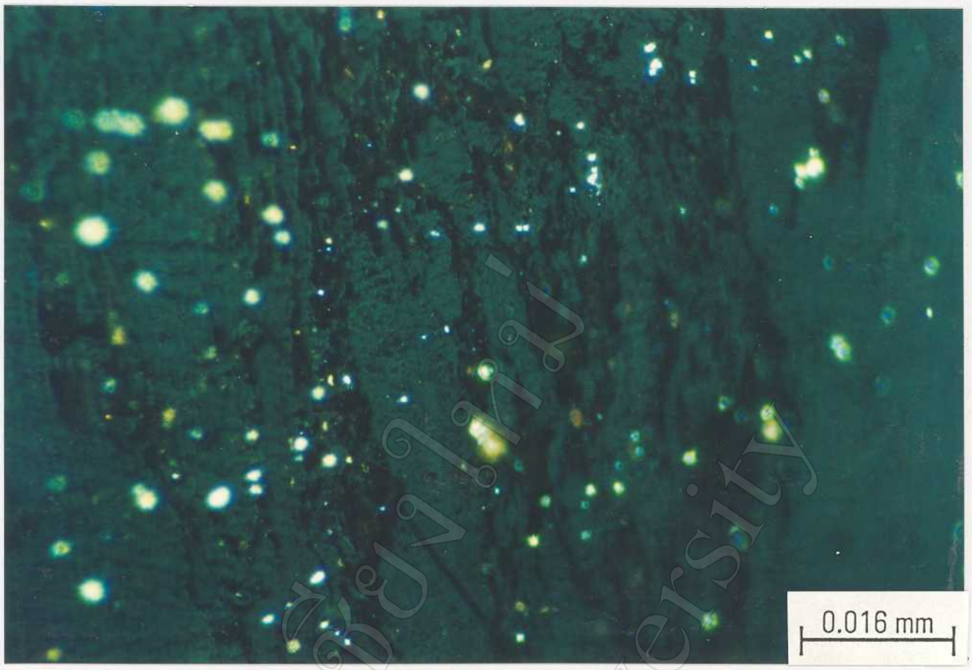

Figure 4.33 Photomicrograph showing densinite and white spots of pyrite in K-1 coal seam under oil immersion, fluorescenced, 50X

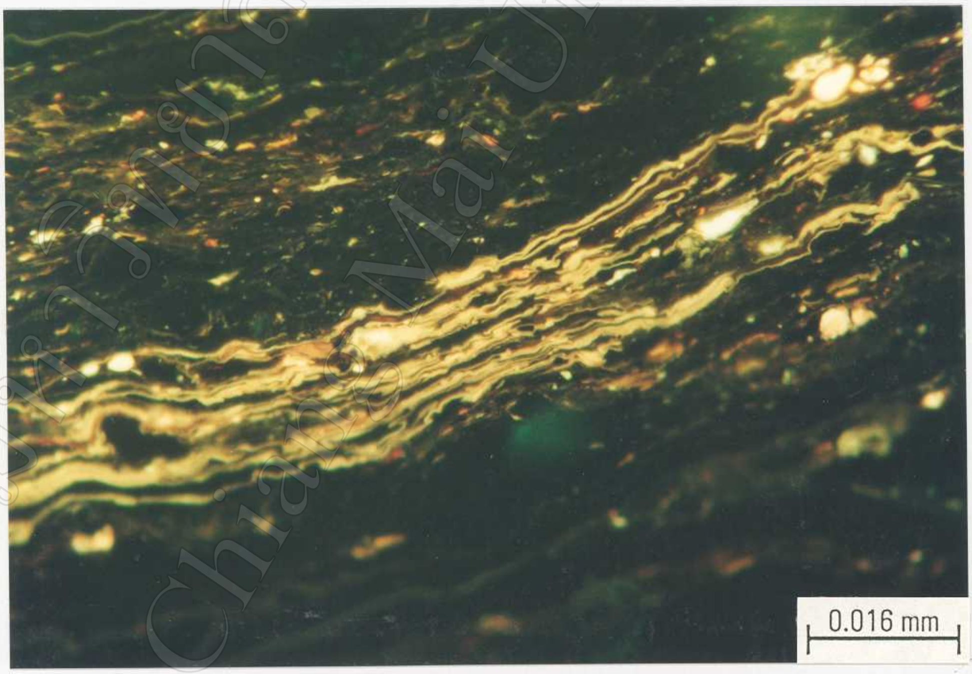

Figure 4.34 Photomicrograph showing association of alginite (Pila type-long yellowish and lamaginite-short greenish yellow)cutinite in K-3 coal seam under oil immersion, fluorescenced, 50x

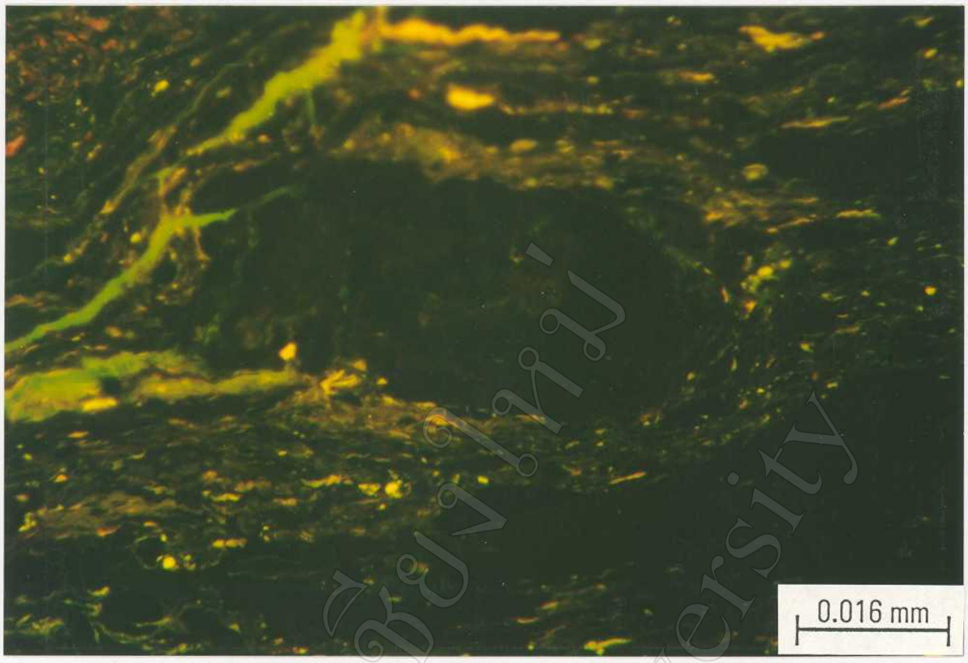

Figure 4.35 Photomicrograph showing liptodetrinite with some lamaginite, green colour is exudatinite in K-3 coal seam under oil immersion, fluorescenced, 50x

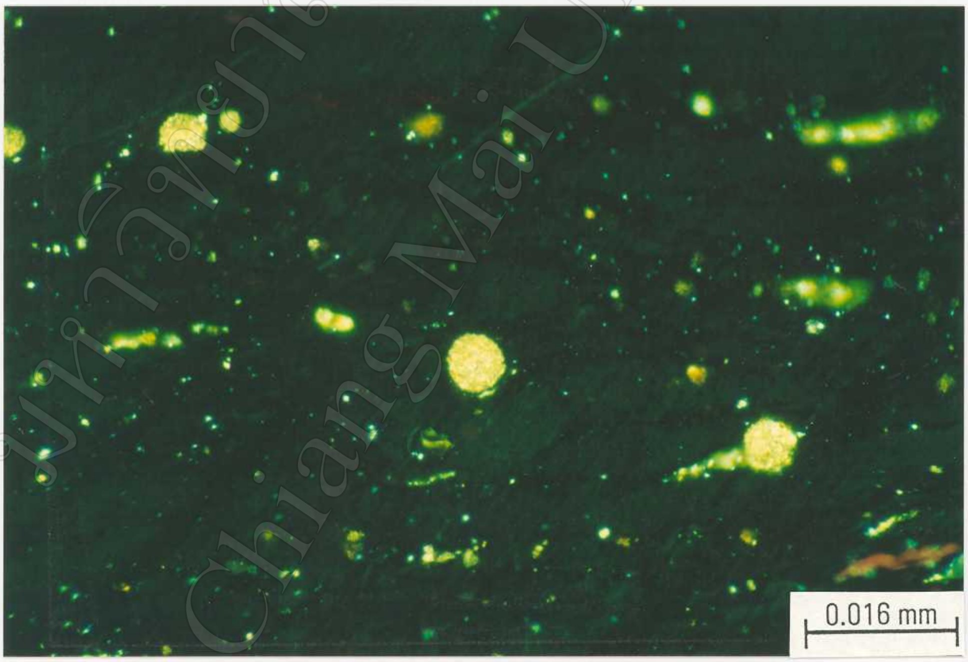

Figure 4.36 Photomicrograph showing framboidal pyrite in densinite in K-3 coal seam under oil immersion, fluorescenced, 50X

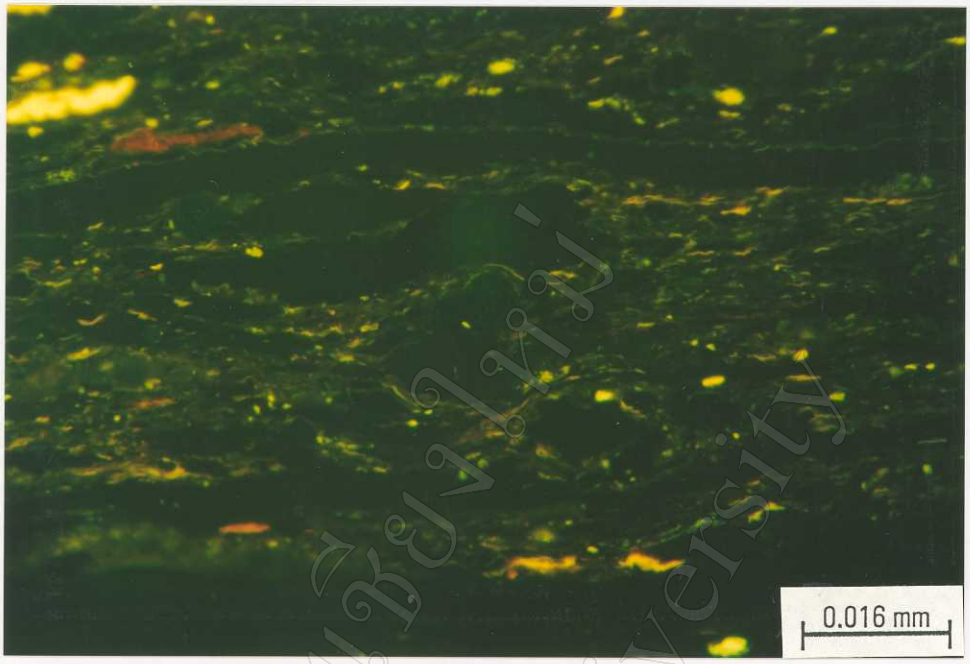

Figure 4.37 Photomicrograph showing lamaginite (short greenish-yellow) layer in K-3 coal seam under oil immersion, fluorescenced, 50X

Figure 4.38 Photomicrograph showing thick cutinite in K-3 coal seam under, oil immersion fluorescenced, 50X

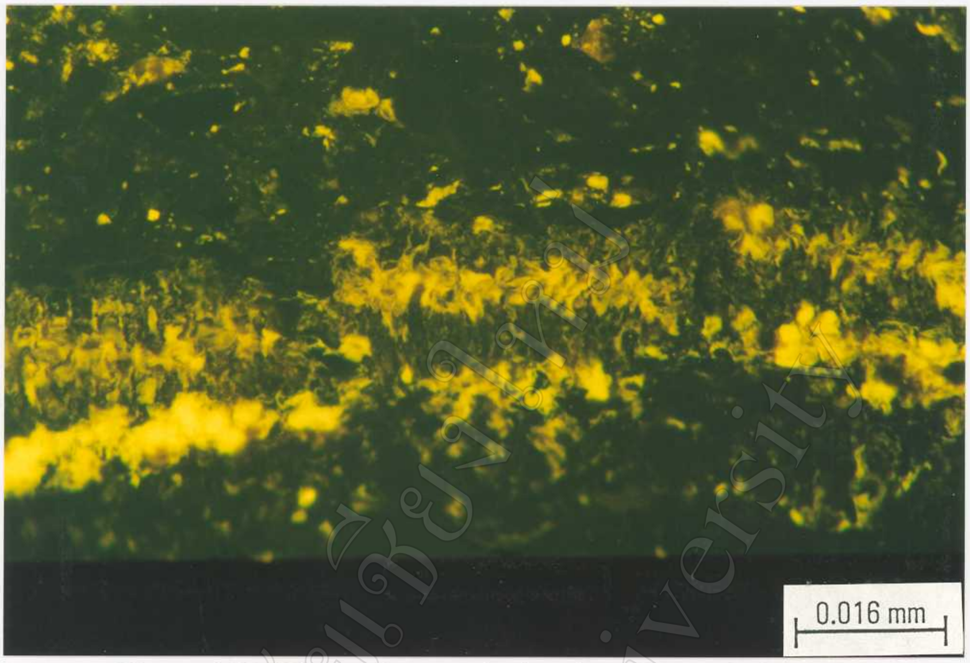

Figure 4.39 Photomicrograph showing disintegrating thick cutinite in suberinite in Q-1coal seam under oil immersion, fluorescenced, 50X

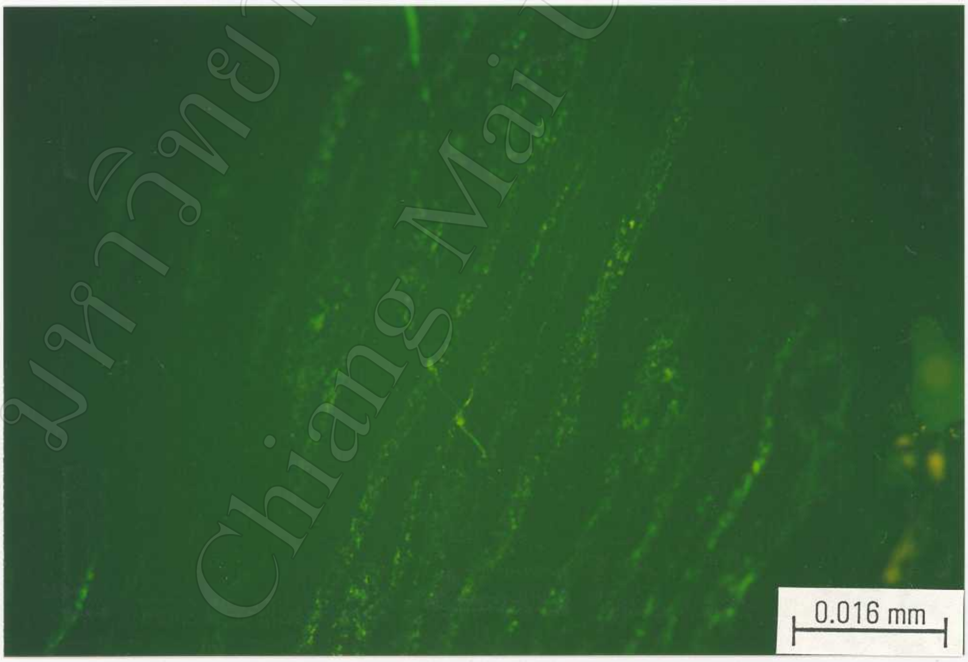

Figure 4.40 Photomicrograph showing liptodetrinite layer which could derived from high essential oil woody tissue under oil immersion, fluorescenced, 50x

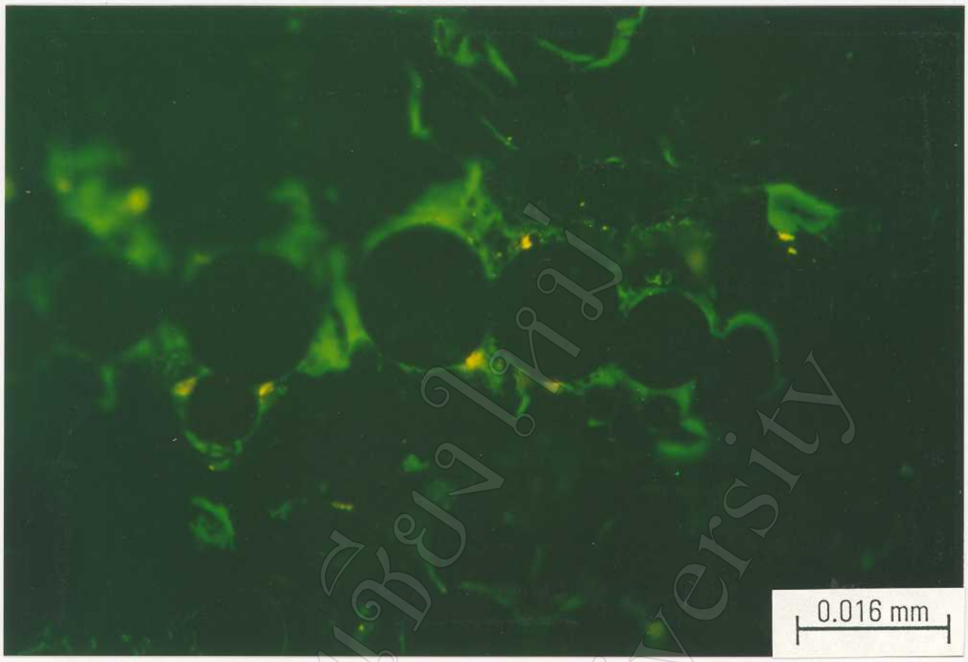

Figure 4.41 Phoromicrograph showing textinite bounded by exudatinite in Q-4 coal seam under oil immersion, fluorescenced, 50X

4.6 Sulfur isotope

4.6.1 Results and interpretation

The results of sulfur isotopic analysis of the 15 gypsum and pyrite samples are listed in Table 4.6. The δ^{34}S values of gypsum are very wide range extending from+0.5 to +20‰ whereas the δ^{34} values of pyrite are also very wide range from –13.6 to +19.9‰. The wide range of δ^{34}S values of both gypsum and pyrite encountered in coal formed in estuarine or brackish water environments, can be interpreted by applying the following assumptions; (a) very considerable variations in the isotopic composition of the dissolved sulfate must occur or (b) the extent of the sulfate must vary, or (c) under certain conditions, much greater proportions of the sulfide produced by the reduction of sulfate are incorporated into organic structures.

The high δ^{34}S values of pyrite samples named NWQPy-1, NWQPy-2, NEQPy-1 and NEQPy-2 taken from Q zone of NW and NE pit are 19.5, 18.8, 19.7 and 19.9‰ could occurred by plant debris indicated the strongly closed environment of fresh water environment and can be also indicated by gastropod shell fragments. Because sulfate reduction usually occurs in an organic-rich and relatively closed environment, dissolved sulfate may be significantly depleted, leading to an enrichment in δ^{34}S in the pyrite.

The high δ^{34}S values of gypsum samples named G-11, G-12 and G-31 which taken from red bed zone (Huai Luang Formation) NW Pit are 20.0, 18.8 and 16.4‰ respectively showing the source of this gypsum is from marine sulfate reacted with calcium ion from Triassic limestone in the eastern flank of the basin during the transgression.

The low δ^{34}S values of gypsum samples named G-21, G-22, GC-21, GC-22, GC-41 and GC-42 which taken from red bed zone (Huai Luang Formation) NW and SW Pits are 3.9, 3.5, 3.8, 3.8, 4.3 and 0.5‰ respectively could be the effected by volcanic eruption.

The very low δ^{34}S values of pyrite samples named SWIPy-2 and SWIPy-1 taken from SW Pit are –13.6 and –7.8‰ respectively showing the marine environment

Following deposition of the coal members, in a near shore (largely fresh water environment) submergence (by transgression) can occur resulting in a flooding of the beds by sea water. This could result in active sulfate reduction and production of a secondary sulfur phase by microbial sulfate reduction.

Table 4.6 Sulfur isotopic composition of the gypsum and pyrite samples

Sample No.	Sample location	Sulfur isotope values(‰)	std.Dev
G-11	red bed (NW-Pit)	20	0.033
G-12	red bed (NW-Pit)	18.8	0.061
G-21	red bed (NW-Pit)	3.9	0.083
G-22	red bed (NW-Pit)	3.5	0.01
GC-21	red bed (NW-Pit)	3.8	0.013
GC-22	red bed (NW-Pit)	3.8	0.044
G-31	red bed (NE-Pit)	16.4	0.114
SWIPY-1	I-zone (SW-Pit)	-7.8	0.051
SWIPY-2	I-zone (SW-Pit)	-13.6	0.121
G-41	K-zone (NW-Pit)	4.3	0.052
G-42	K-zone (NW-Pit)	0.5	0.055
NWQPY-1	Q-Zone (NW-Pit)	19.5	0.003
NWQPY-2	Q-Zone (NW-Pit)	18.8	0.036
NEQPY-1	Q-Zone (NE-Pit)	19.7	0.1
NEQPY-2	Q-Zone (NE-Pit)	19.9	0.018

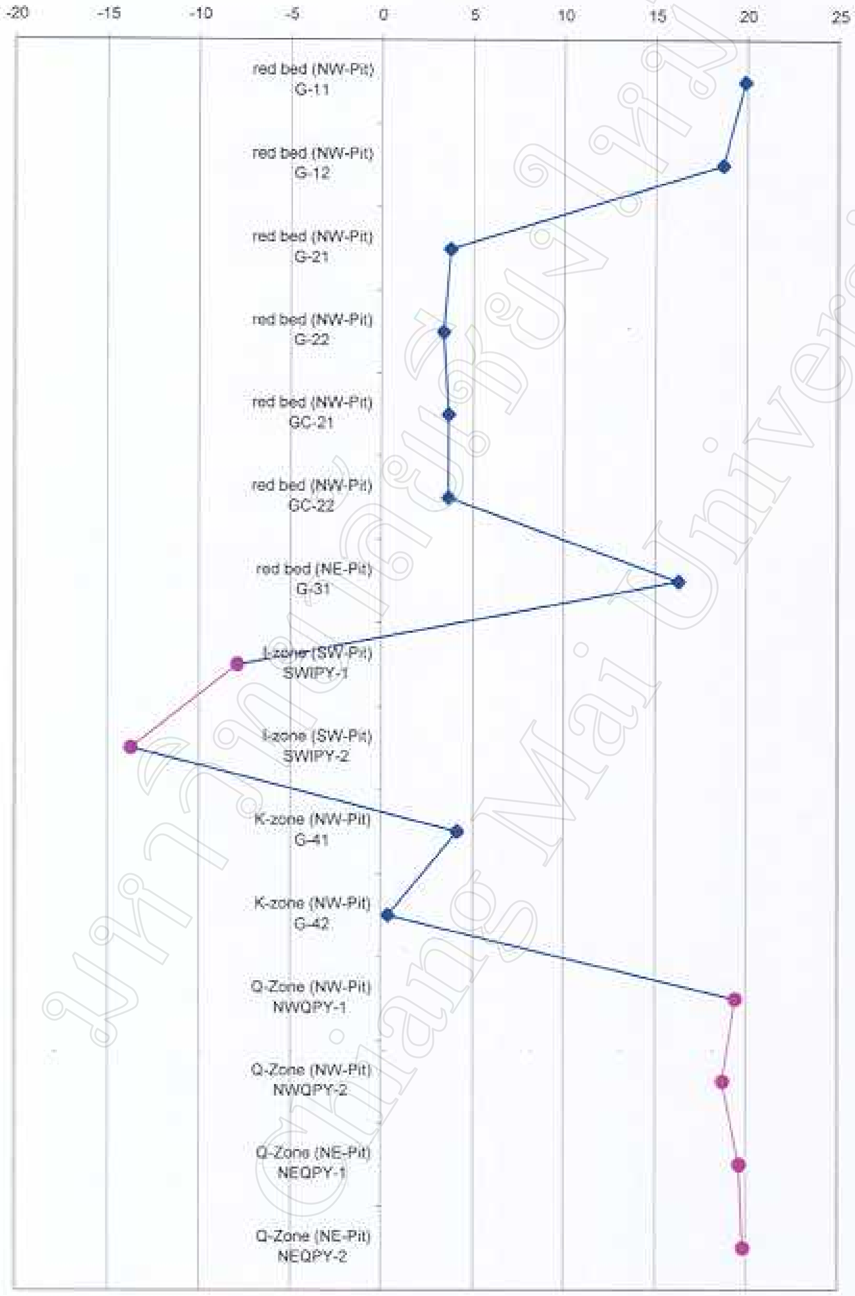

Figure 4.42 Sulfur isotopic values distribution in Mae Moh coal field