Influence of depositional environment on clay mineralogy in the coal-bearing lower Moreno Hill Formation, Salt Lake coal field, west-central New Mexico

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Introduction and Purpose

The lower Moreno Hill Formation is a coal-bearing sequence deposited during Late Cretaceous time in the Salt Lake coal field, west-central New Mexico. Cerro Prieto zone coals, up to 14 ft thick, in the lower Moreno Hill developed in coastal swamps shoreward of a minor transgression in an overall regressive sequence. Thinner coals of the Rabbit zone higher in the section developed in less stable, fluvial-dominated swamp environments as the shoreline retreated to the northeast. Clay minerals in the lower Moreno Hill Formation mudstones and shales above and below these coal zones were the focus of this study. X-ray diffraction analysis was used to identify clay minerals and their relative amounts. Results were analyzed to see if any changes in detrital influx, or environmental changes in this sequence predicted by previous studies were evident in the clay mineralogy.

Background and Study area

The Salt Lake coal field in west-central New Mexico is defined by the arcuate outcrops of the Moreno Hill Formation of Late Cretaceous Turonian age (Fig. 1). This formation is divided into three informal units, the lower, middle and upper members. The lower member of the Moreno Hill consists of channel sandstones and crevasse splays that grade laterally into siltstone, mudstone, and coal. Sandstone in this unit is fine-grained, well-

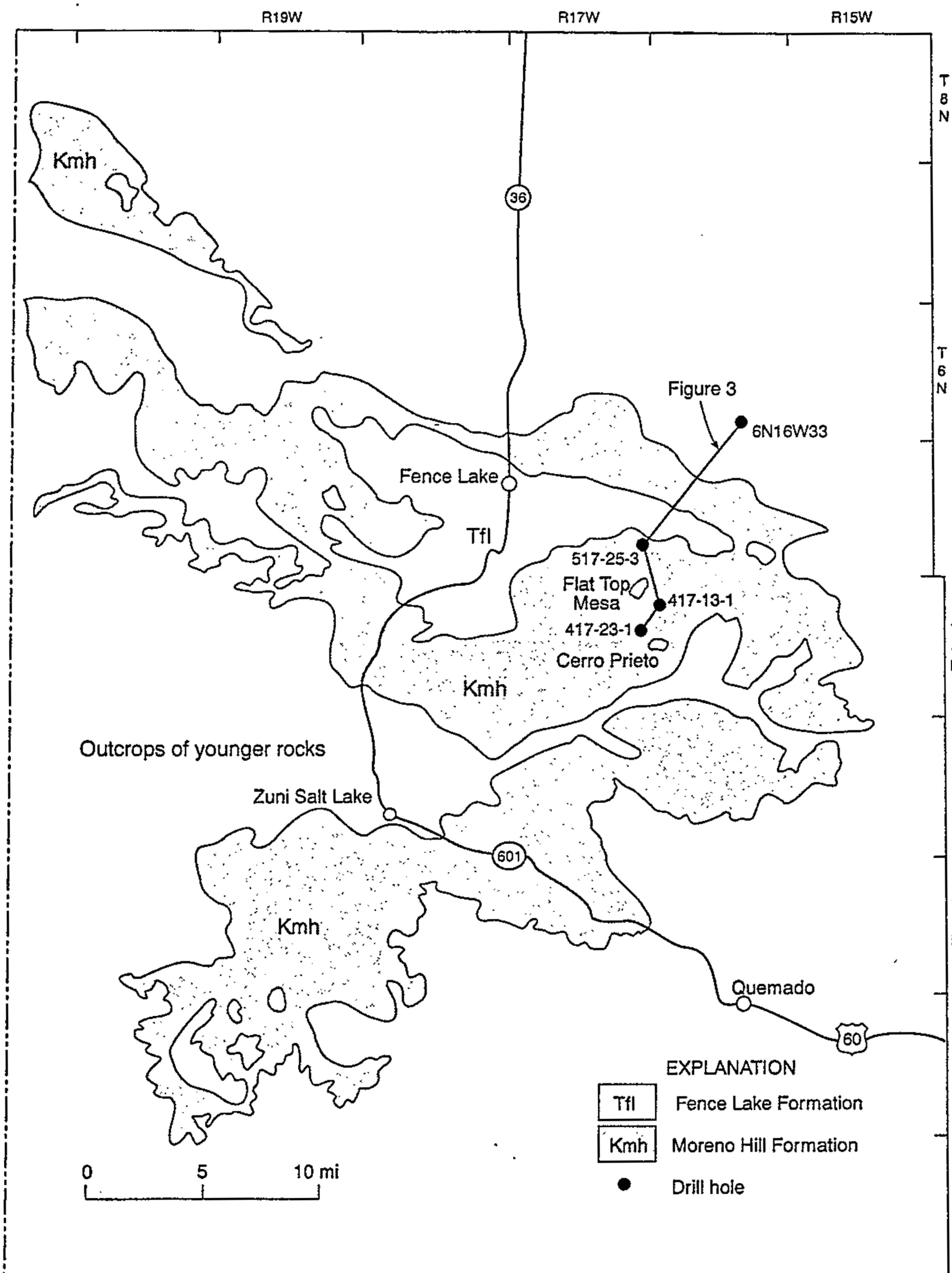

Figure 1. Salt Lake coal field, Moreno Hill Formation with drill site locations. Kmh=Moreno Hill Fm., Tfl=Fence Lake Fm, Base map modified from Dane and Bachman, 1965.

sorted, well-rounded, predominantly quartzose, and is generally cemented by siliceous material. Carbonaceous mudstone containing coalified plant fragments is common. These sediments were deposited on a broad coastal plain with a source area in southeastern Arizona, possibly the Bisbee Group, a thick sequence of quartzose to slightly feldspathic sandstone, interbedded with shale and marine limestone (Hayes, 1970). Thickness of the lower member varies from 100 to 400 ft, thinning toward the west. This member contains three coal zones, the Antelope, Cerro Prieto, and Rabbit zones, in ascending order (Fig. 2). The Cerro Prieto and Rabbit zones have the greatest lateral continuity within the coal field.

As many as five coal beds are in the medial Cerro Prieto zone, although only two of these coastal-plain coals have lateral continuity. These coals range from 1 to 14 ft thick, often contain persistent claystone (tonstein) partings originally of volcanic origin, or are interbedded with shales. Low sulfur (0.7%) Cerro Prieto coals represent most of the economic coal resource in the Salt Lake field. The Rabbit zone contains up to four coal beds of which the second bed above the base attains economic thickness (7.5 ft). These fluvial coals are interbedded with siltstones and the entire sequence becomes more siltstone and sandstone-dominated upward, suggesting a greater influx of coarser sediment during shoreline retreat.

Comparison of the Cerro Prieto and Rabbit zone total coal isopachs (Campbell, 1989) shows a change from a northwest to a northeast trend. These trends suggest a change during the retreat of the shoreline from coastal plain swamps that parallel the shoreline to fluvial-dominated swamps that parallel stream drainage patterns. Anderson and Stricker (1987) also noted the trend of the Cerro Prieto coal isopach by Campbell (1989) and the relatively thick coals in this zone. They related these factors to the proximity (6-8 mi) of the landward pinchout of the laterally

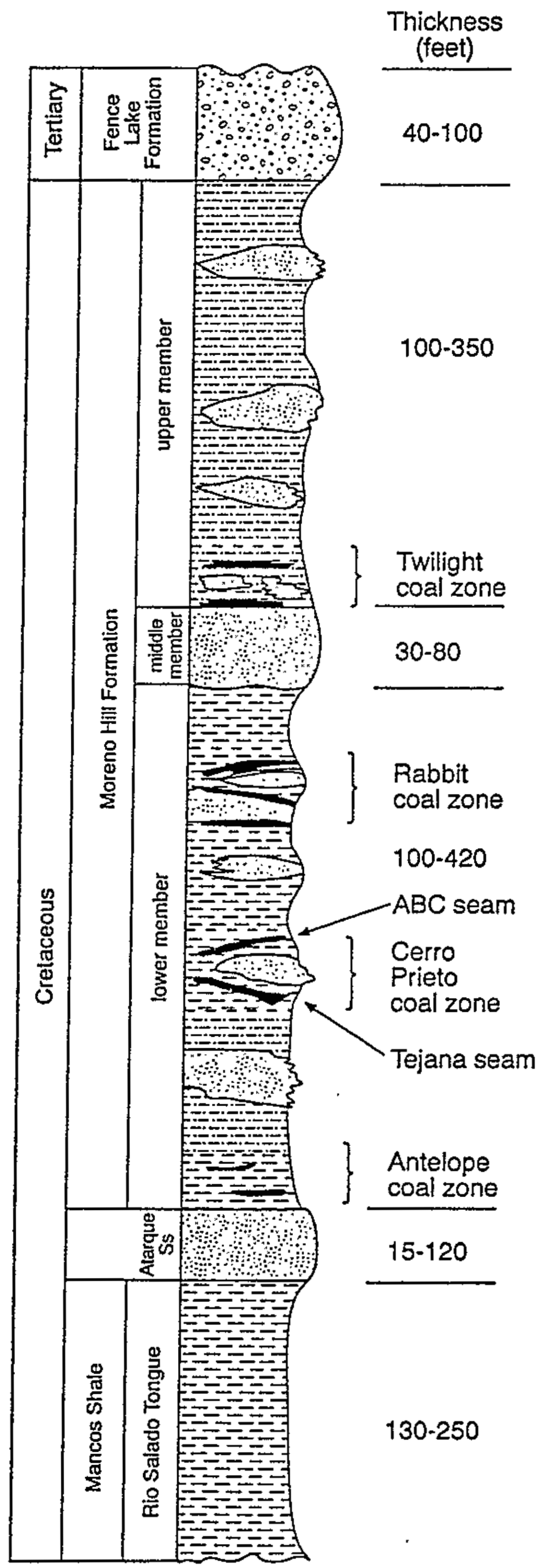

Figure 2. Generalized stratigraphic column of the Moreno Hill Formation, Salt Lake field with coal zones. Modified from Campbell, 1989.

equivalent Fite Ranch Member of the Tres Hermanos Formation to the northeast. The Fite Ranch is a minor transgressive barrier island sandstone deposited in a generally regressive phase (Molenaar, 1983). It is common for thicker coals to have developed landward of marine sandstone pinchouts that represent reversals in the direction of shoreline migration; nearly stable conditions are created in coastal swamps during these periods of reversal. The overlying Rabbit coals were deposited as the shoreline continued to retreat to the northeast.

Procedure

Four drill sites in the Salt Lake field (Fig. 1) from drilling programs conducted in the 1980s by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) were selected for sampling. These drill sites span a distance of approximately 11 mi along a northeast trend. Samples of drill cuttings from 5-ft intervals were available from two of the drill sites (417-13-1, 417-23-1) and 3-inch cores from selected depths were available from the other two sites (517-25-3, 616-33-1). Cuttings or core from two of these locations encompassed the entire Cerro Prieto through Rabbit coal zone sequence (417-13-1, 517-25-3). Drill hole 417-23-1 penetrated only the Cerro Prieto coal zone (417-23-1) and site 616-33-1 penetrated only the Rabbit coal zone. Samples were taken from the fine-grained sediments above and below the Cerro Prieto and Rabbit coals and from any other mudstone or shale sequence within the coal-bearing sequence. Thirty-four samples were collected from these four drill site locations.

Cutting samples were limited to the available 5-ft intervals. Lithologic changes decided the sampling interval in the core, and sample thickness varied from 0.2 ft to 4 ft. Core samples were crushed in a jaw crusher to pea-size material and split as often as needed to obtain a 10-g sample. Cutting samples were examined to find out if washing was necessary to remove drilling mud. Although a few samples were washed, most of the cuttings were free of drilling-mud residue. Samples were crushed using a mortar and pestle with a small amount of distilled water. The samples were dispersed in 100 ml of distilled water. Some samples did flocculate, but generally three washings followed by centrifuging for 4 minutes was adequate to keep the clay fraction in suspension. Oriented slides for X-ray diffraction (XRD) analyses were prepared using the sedimented slide method. After 10 minutes of undisturbed suspension, a $<2\mu m$ sample was extracted by pipette from the surface of the suspended material and placed on two glass slides. Often the XRD pattern from these slides showed intense quartz peaks. These slides were remade using a settling time of 30 minutes to allow for a greater depth of $<2\mu m$ fraction in the suspension, and hopefully eliminating the problem of removing larger-size material during the pipetting process.

Air-dried slides were scanned from 2-35° 2θ at 3°2θ/min using the Rigaku XRD unit using CuKα. The samples were exposed to ethylene glycol vapor for at least 24 hours and examined from 2-35°2θ at 3°2θ/min. A second scan from 15-18° 2θ at 1°2θ/min was done to find the position $002_{10}/003_{17}$ reflection of the mixed-layer illite/smectite (I/S) (Moore and Reynolds, 1989). Samples were heated to 375°C for 30 minutes and XRD scanned at 8-10°2θ and 2-15° 2θ at 3°2θ/min.

Using the NMBMR Clay Lab technique for semiquantitative analyses, the clay mineral fractions were determined. Peak height measurements above background at 12.35° 2θ air dried (kaolinite, 001), 5.25° 2θ and 8.8° 2θ glycolated (smectite, 001; illite, 001), and 8.8° 2θ heated (illite, 001) were taken from the diffractograms. These peak-height intensities were used to

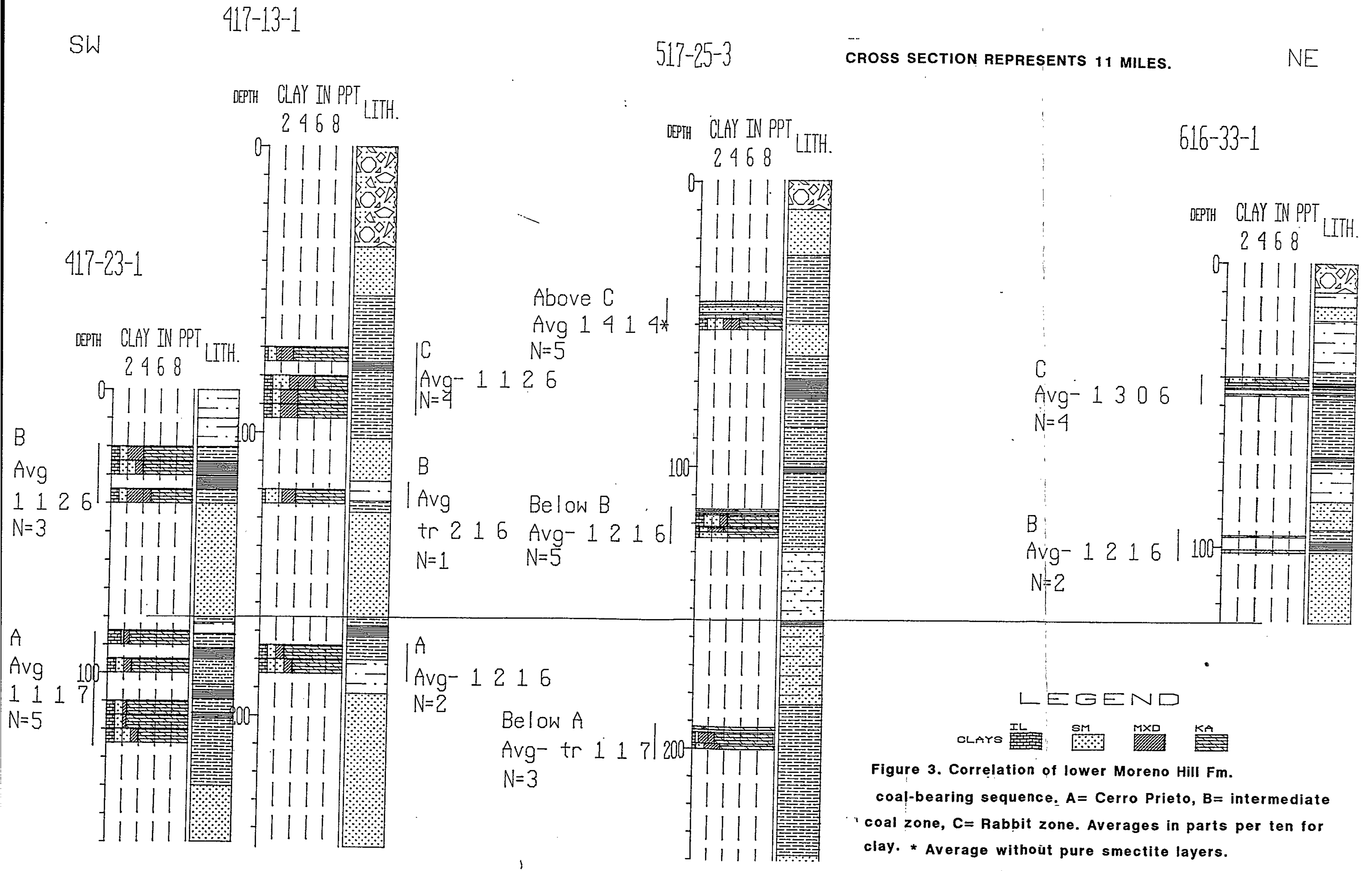

Figure 3. Correlation of lower Moreno Hill Fm. coal-bearing sequence. A= Cerro Prieto, B= intermediate coal zone, C= Rabbit zone. Averages in parts per ten for clay. * Average without pure smectite layers.

calculate parts in ten of illite, smectite, I/S, and kaolinite. The percent of illite in the I/S was determined from the $002_{10}/003_{17}$ peak position (Moore and Reynolds, 1989. p. 251). This XRD peak results from constructive interference between the 002 reflection of the 10Å illite layers and the 003 reflection of the 17Å smectite layers in the randomly interstratified mixed-layer clay. The peak migrates with the changing proportion of these layers (Reynolds and Hower, 1970) and therefore can be used to calculate the percentage of illite in the I/S clay.

Correlation of units

The lithology at each drill site was interpreted from geophysical logs and the samples. These lithologies and the parts-in-ten clay content were plotted (Fig. 3) using the Rockware Logger program. A cross section with the drill holes in their relative positions was constructed and the lithologies correlated to help find the stratigraphic relationships of the clay analyses. Because these coals are lenticular and the distance between drill holes is on the order of miles, correlation was not done on a bed basis. This cross section is essentially perpendicular to the Late Cretaceous shoreline that trends northeast-southwest.

Three coal zones are recognized in the drill holes. The A zone is the Cerro Prieto coal zone (Fig. 2), and the deepest sampled in this study. The B zone is separated from the A zone by a thick (30-40 ft) persistent sandstone to silty sandstone. The B zone generally has thin coals (1-2 ft) and is midway between what Campbell (1989) called the Cerro Prieto and Rabbit zones. The uppermost C zone in this study is the Rabbit zone of Campbell (1989). Coals in these three zones thin toward the northeast and the Late Cretaceous shoreline. Three of the drill sites, 417-23-1, 417-13-1, and 616-33-1 have clay analyses above and below these coals, the fourth drill site (517-25-3) has clay analyses from above zone A, below zone B, and below the lowermost C zone.

Results

Table 1 lists the semiquantitative results and percent illite in the I/S for all the samples and these are shown graphically in Figure 3 and 6a-d. Kaolinite is the most abundant clay mineral in the lower Moreno Hill samples analyzed, followed by smectite, I/S, and illite. The kaolinite peaks are generally narrow and represent a high degree of crystallinity (Fig. 4) except at the northeast end of the cross section where the peaks become broader (Fig. 5). The illite reflections are variable, although they show a higher degree of crystallinity in the sections farthest from the shoreline (Fig. 5). These clays are probably of a detrital origin, although because they are in a swamp environment some kaolinite probably is a result of chemical leaching. Variation in the amounts of these clays occurs vertically and laterally, although lateral changes are greater. Inland (417-23-1, Fig. 3), kaolinite makes up 6-7 parts in ten of the total clay content. From inland toward the Late Cretaceous shoreline, smectite becomes more predominant. In the B zone, which is present in all the sections, the average amount of smectite quickly goes from 1 part in ten to 2 parts in ten in a shoreward direction. I/S averages show the opposite trend in the B zone, decreasing from 2 parts in ten at the southwest to 1 part in ten in the northeast. The C zone also has an increase in smectite toward the northeast and a decrease in the I/S content.

Vertical comparison at each location

Table 1. Clay mineral content of samples from the Salt Lake field.

Drill Hole/Zone	Depth	Part in ten Illite	Smectite	Mixed Layer	Kaolinite	002/003 %Illite	Comment	Crystallinity* Kaolinite	Illite
417-23-1									
B	20-25	1	1	2	6	>10		high	high
B	25-30	1	2	1	6	>10	Above coal	high	high
B	35-40	1	1	2	6	70	Below coal	high	moderate
	AVG	1	1	2	6				
A	85-90	2	tr	1	7	75	Above coal	high	high
A	95-100	1	1	1	7	25	Below coal	high	high
A	110-115	1	1	tr	8	53	Below coal	high	high
A	115-120	1	1	tr	8	28		high	high
A	120-125	1	2	1	6	21		high to moderate	moderate to low
	AVG	1	1	1	7				
417-13-1									
C	70-75	tr	1	2	7	34	Above coal	high	moderate to low
C	80-85	1	2	3	4	34	Below coal	high	moderate
C	85-90	1	1	2	6	34		high	high
C	90-95	1	1	2	6	32		high	moderate
	AVG	1	1	2	6				
B	120-125	tr	2	1	6	27		high	low
A	175-180	1	2	1	7	16	Below coal	high	low
A	180-185	tr	2	1	6	>10		high to moderate	low
	AVG	1	2	1	6				
517-25-3									
Above C	42-42.2	0	9	0	1	0		moderate	
Above C	43.2-44	1	6	0	3	>10		high	moderate to low
Above C	44-46	0	10	0	tr	0		low	
Above C	46-46.8	tr	5	0	4	15		high	moderate to low
Above C	48-52	1	2	2	5	21		high	moderate
	AVG (w/o pure smectite)	1	4	1	4				
Below B	115-115.7	1	1	3	6	25		high	high
Below B	116.4-117	tr	tr	3	6	40		high	high to moderat
Below B	117-121	1	2	1	6	21		high to moderate	moderate to low
Below B	121.4-123	tr	1	2	7	24		high	moderate to low
Below B	123-125	tr	4	1	6	11		high	low
	AVG	tr	2	1	6				
Below A	192-193	tr	1	tr	9	>10		moderate	low
Below A	194-198	tr	tr	2	7			moderate	moderate
Below A	198-200	tr	1	2	7	24		moderate	moderate
	AVG	tr	1	1	8				
616-33-1									
C	40-42	tr	3	0	7	0	Above coal	moderate	low
C	42-43	tr	2	0	8	0	Between coal	high to moderate	low
C	44-44.35	1	4	0	5	21	Between coal	high to moderate	low
C	46-46.7	1	4	0	5	0	Below coal	high to moderate	low
	AVG	1	3	0	6				
B	96-96.5	1	2	1	6	16	Above coal	high to moderate	moderate to low
B	101-102	1	3	2	4	30	Below coal	moderate to low	low
	AVG	1	3	1	5				

* Crystallinity was qualitatively found from the peak width.

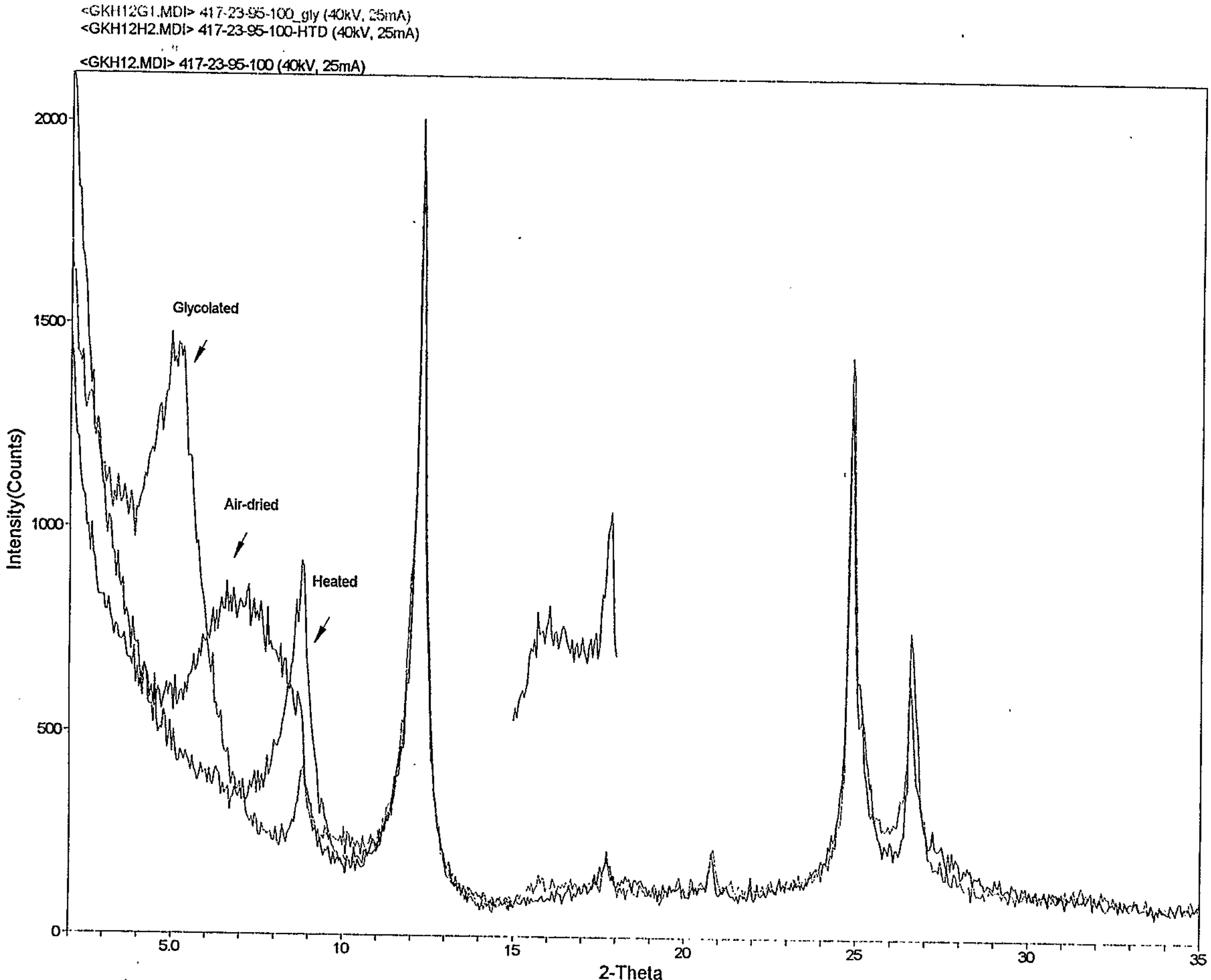

Figure 4. Diffractogram from 417-23-1, 95-100 ft, A zone(Cerro Prieto).

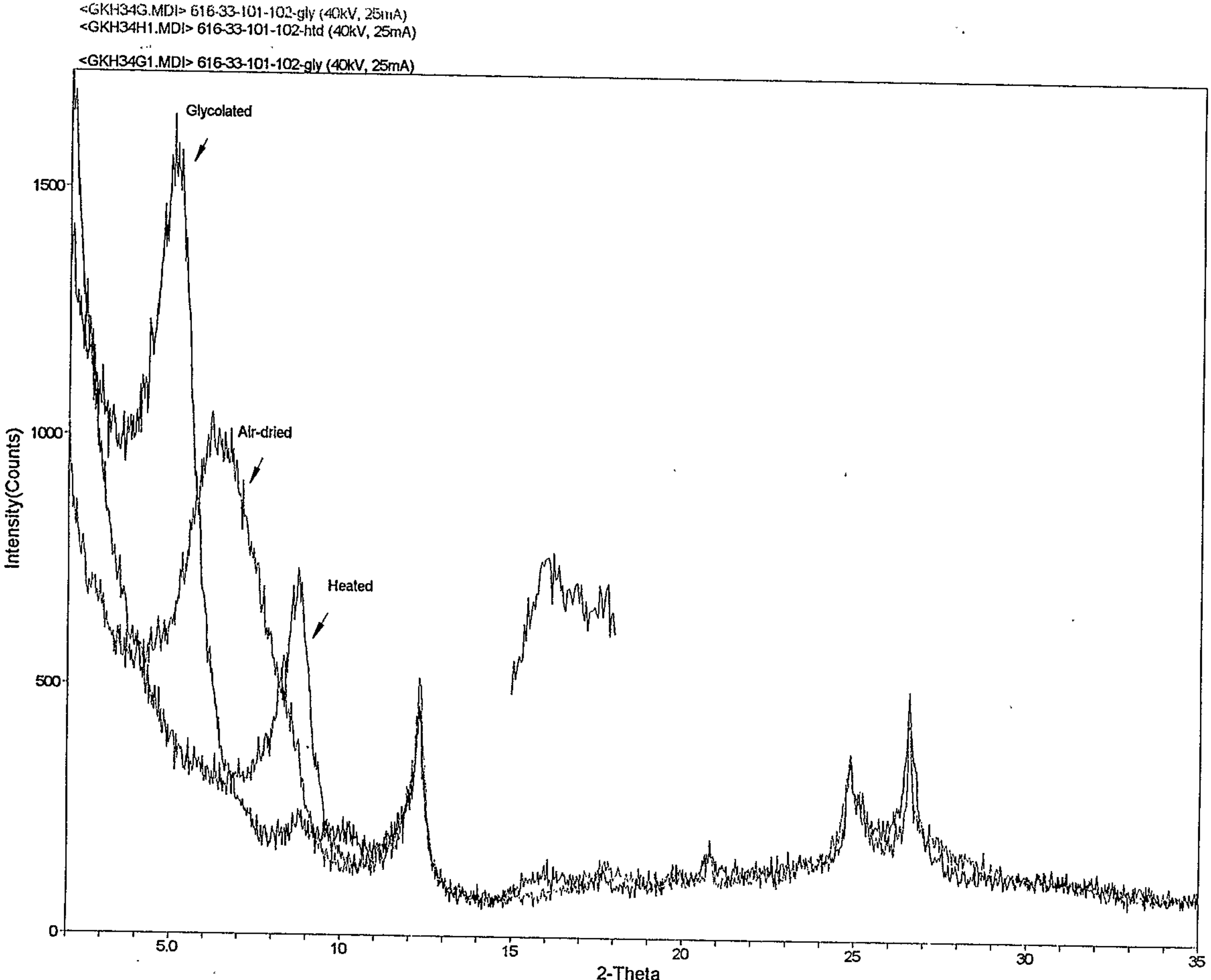

Figure 5. Diffractogram from 616-33-1, 101-102 ft, B zone.

There is a general decrease in average kaolinite content from the bottom to the top of the section sampled within the lower Moreno Hill. At the southwest end of the cross section (417-13-1), located in the middle of the thick coal area, the amount of I/S increases from C zone (Cerro Prieto) to A zone (Rabbit). The two drill sites at the northeast end of the cross section show an increase in smectite from the base of the section to the top. There is a slight decrease in the kaolinite, or kaolinite constitutes a smaller part of the total clay content.

Comparison of clay minerals within zones

Seven samples were taken within the A zone (41-23-1 and 417-13-1), three were directly below coal seams, one directly above a coal, and the remaining three samples were at least 5 ft below a coal. The coals in this zone are the thickest in the Moreno Hill Formation, indicative of a relatively stable swamp environment. Kaolinite is the dominant clay mineral (7-8 parts in ten) directly below the coal and decreases with a slight increase in smectite at greater depths below the coal bed. The one sample above the A zone coal has about the same amount of kaolinite (7 parts in ten) and has the highest amount of illite (2 parts in ten) seen in all of the samples analyzed for this study. Clay minerals in the A zone show the greatest lateral consistency, but the two drill sites (417-23-1, 417-13-1) that penetrate the A zone are the closest (approximately 2 mi) of all the drill sites sampled. Illite decreases and smectite slightly increases from southwest to northeast. The samples from 517-25-3 below the A zone are predominantly kaolinite (8 parts in ten) with minor amounts of I/S, smectite, and trace amounts of illite.

Only drill sites 417-23-1 (3 samples) and 616-33-1 (2 samples) have B zone coals. A laterally equivalent shale in 417-13-1 was sampled for clay analyses. Comparison of sample analyses from above and below the coal in 417-23-1 do not show an increase in kaolinite below the coal, instead the I/S component increases. The increase in I/S clays is indicative of a less acidic swamp than that where kaolinite increases under the coal. Less acidic swamps form in back barrier or deltaic swamp environments (Galloway and Hobday, 1983, p. 291). Below the B coal in 616-33-1 kaolinite is the predominant clay mineral (4 parts in ten), but smectite is only slightly less (3) followed by I/S and illite. The amount of kaolinite increases above this coal. Almost equal amounts of kaolinite and smectite may be a result of a short-lived swamp environment, reflected in a thin seam (2 ft) in 616-33-1. Smectite is greater in all of the samples from 616-33-1 compared with the other locations.

In the samples below the B zone from 517-25-3 (115-125 ft) kaolinite increases with depth, I/S clays decrease and are not found in the deepest sample. Smectite is variable and illite is very minor. The clay mineral proportions in the upper sample, 517-25-3-115-115.7', which is only 15 ft below the B coal, are very similar to the samples below the B coal in 417-13-1 and 616-33-1.

The C zone (Rabbit) was sampled above and below the coal in 417-13-1 (4 samples) and above, below, and in partings of the coal in 616-33-1 (4 samples). Kaolinite decreases directly below the coal in 417-13-1 and increases at greater depth below the coal. Kaolinite is the predominant mineral in the upper sample at this location. I/S are second in abundance, followed by smectite and illite. The clay mineral assemblage associated with the C coal in 616-33-1 is the most distinct of all samples analyzed. Kaolinite is still the predominant clay mineral, varying from 5 to 7 parts in ten, but none of the samples have any I/S, and smectite is a larger part of the clay mineral assemblage. Thin coals are separated by two partings sampled, suggesting the coal developed on the edge of the swamp or the swamp development was short-lived and interrupted by sediment influx. At 517-25-3 the samples taken above the A zone are very different from any other group samples. Some samples are almost totally smectite and probably represent ash falls. The other samples in this zone from 517-25-3 contain some kaolinite with minor amounts of I/S and illite.

Percent illite in I/S

The glycolated XRD scans have a strong reflection at 5-5.2° 2θ, suggesting the interstratification is random and rich in smectite (Moore and Reynolds, 1989). This peak is sharp and more pronounced when there are greater amounts of smectite in addition to the smectite in the I/S. The average mixed-layer I/S in the 417-23-1 samples is 1 part in ten. Depth versus the percent illite in the samples from 417-23-1 (Fig. 6a) shows a decrease in the percent illite with depth. At 20-25 ft and 25-30 ft there is less than 10% illite in the I/S. Below the B zone coal, the sample has 70% illite in the mixed layer I/S. The A zone has a sharp decrease in percent illite in I/S below the coal at 95 ft followed by an increase below the coal at 110 ft (115-125 ft) the percent illite decreases in the I/S.

Samples from 417-13-1 include all three zones. I/S clays average about 1 part in ten of the total clay content (Table 1). Percent illite in I/S (Fig. 6b) decreases with depth and there is no apparent change in this trend below the coals in this section. All of the C zone samples contain about 35% illite in the I/S. Of all the sections sampled in this study, 417-13-1 has the most consistent trend of percent illite in the mixed layer clays.

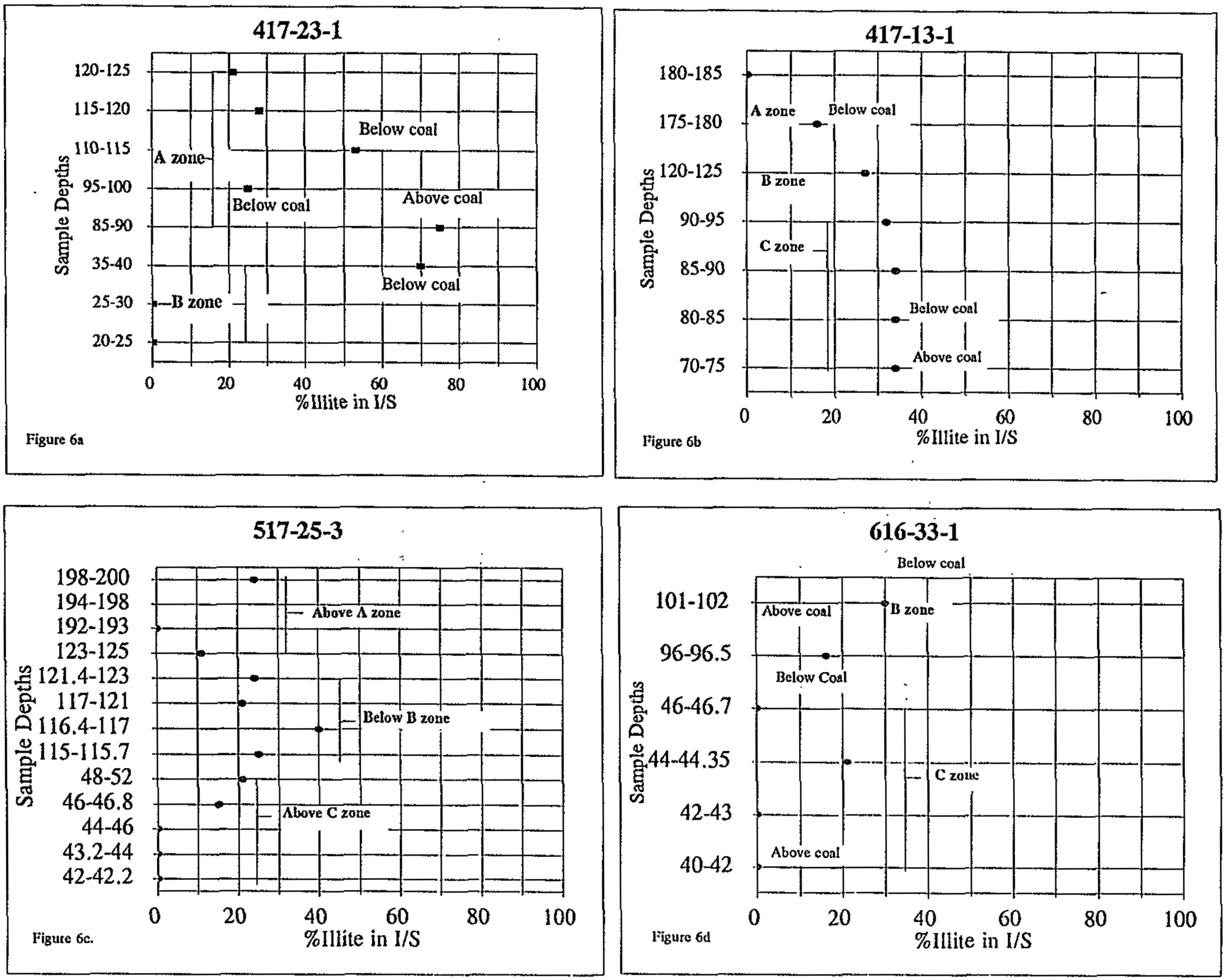

Figure 6. Percent illite in I/S for each drill site.

None of the samples analyzed in 517-25-3 are associated with coals. The uppermost samples have little or no I/S and two of the five samples are essentially pure smectite. Below the B zone (517-25-3) there is a general decrease with depth, from 40% to 10%, in the percent illite (Fig. 6c). There is no trend in the samples above the A zone from 517-25-3. The percent illite in I/S showed no trend in samples from 616-33-1 (Fig. 6d).

The $002_{10}/003_{17}$ peak data did not reveal any distinctive trends for the percent illite in the I/S. In part this may be attributed to the difficulty of measuring this peak because of interference from the illite (002) peak. Some of the broad, low intensity peaks in this region (15-18° 2θ) are barely resolvable. Only the samples from the two drill sites at the southeast end of the cross section show any type of trend that being a decrease in the percent illite in the I/S with depth. This is the reverse of what many studies (Hower et al., 1976, Hower, 1981) have found. One possible explanation for disparate results from this study is that only 100-150 ft of section was examined instead of the thousand of meters examined by Hower (1981) and the depth of burial is quite different from the Gulf Coast. Depth of burial is difficult to determine, but the area is not part of a major basin and probably the Moreno Hill sediments were overlain by at most 5,000 ft of sediments. The Moreno Hill coals are subbituminous A to high-volatile C in rank, indicating a temperature of about 100°C (Stach, 1982), which would suggest a greater burial depth of 10,000-15,000 ft. However, tertiary volcanics are present in the Salt Lake area and probably had some affect on the degree of coalification. A higher geothermal gradient could also affect the percent illite, but perhaps the sediments lacked adequate K^+ for illite formation. Chemical analyses of the these fine-grained rocks would help to answer this question.

The trend seen in the lower Moreno Hill is also the opposite of what Rimmer and Eberl

(1982) found in their study of underclays in Illinois. However, their study dealt with a 1.5 m underclay, with a maximum sample interval of 15 cm instead of composite samples of up to 5 ft. Rimmer and Eberl (1982) attributed the increase in I/S with depth to in situ leaching. In addition, the Illinois Basin deposits studied by Rimmer and Eberl (1982) are much older (Pennsylvanian) and are more clearly marine in origin than the Moreno Hill Formation sequence looked at in this study.

Conclusions

Kaolinite is the predominant clay mineral in the coal-bearing lower Moreno Hill Formation, particularly in the Cerro Prieto zone (A) where the thickest coals in the Salt Lake field are found. Kaolinite is indicative of the humid, swamp environment needed for thick peat development. It appears that some leaching may have occurred to the underclays of the thicker coals in the Cerro Prieto because of the increase in kaolinite. The Cerro Prieto coal zone clay mineralogy, including the samples 40 ft below the coal, suggests a warm, humid, environment with leaching taking place to remove most of the cations. There is an increase in the smectite content of the Cerro Prieto coals to the northeast, toward the shoreline, suggesting a more seaward position, but closeness of the sections sampled for this zone limit the validity of this statement.

The B zone is slightly higher in smectite and I/S than the Cerro Prieto zone, perhaps resulting from a change in environment or introduction of more sediment from a different source. I/S clays suggest a less acidic environment, such as a deltaic or fluvial back-swamp (Galloway and Hobday, 1983). The randomly ordered I/S are evidence of smectites in the first stages of transformation to illite.

Smectite can be evidence of a more seaward position than kaolinite. However, there is evidence in the lower Moreno Hill Formation for volcanic activity in the area. Tonsteins occur in the Cerro Prieto zone and samples from this study above the Rabbit zone are almost pure smectite, probably weathered ash falls. Smectite becomes more significant in the upper Rabbit zone (C zone), particularly in those samples that are closest to the shoreline. As mentioned before there are almost pure smectite layers above this zone, indicative of volcanic activity. Greater than half the clay minerals in the B and Rabbit zone are kaolinite, perhaps because of incomplete leaching of smectite. Incomplete leaching could occur because of a change from a warm, humid environment with stable, well-developed swamps, to a drier environment, with smaller swamp areas, resulting in thinner coals. The Rabbit coals, on average, are much thinner than the Cerro Prieto coals.

The conclusions from this study are limited because the samples were taken along a cross section that only encompasses about 11 mi, and the stratigraphic section is only 100-150 ft thick. The trend from kaolinite dominant to kaolinite-smectite dominant clays may indicate a change from a warm, humid, acidic environment to a less acidic or drier climate, and a change in sediment influx from local volcanic activity. However, it would be difficult to conclude that the coal swamps changed from being coastal-plain to fluvial from the clay data alone. For a better understanding of changes in environment more samples from throughout the coal field should be analyzed and chemical and particle size analyses run.

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