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CLAY MINERALOGY, ALTERATION HISTORY, AND ECONOMIC GEOLOGY OF THE WHITEMUD FORMATION, SOUTHERN SASKATCHEWAN, CANADA

ROBERT J. PRUETT[1] AND HAYDN H. MURRAY
Department of Geosciences, Indiana University, Bloomington, Indiana 47405

Abstract—The Upper Cretaceous (Maastrichtian) Whitemud Formation is a potentially commercial kaolin deposit located in southern Saskatchewan and southeastern Alberta. The Whitemud Formation contains a lower kaolinitic sandstone, a middle lignite and carbonaceous shale, and an upper interbedded siltstone and claystone. The sediments that comprise the rocks of the Whitemud Formation were deposited on alluvial or upper deltaic plains located along the northwest flank of the Williston Basin.

Mineralogy and textures were determined by X-ray powder diffraction, scanning electron microscopy, and optical microscopy. Kaolinite abundance increases upward from the underlying rocks of the Eastend Formation through the Whitemud Formation, and the abundance of smectite, micas, and feldspars decreases from the Eastend Formation into the Whitemud Formation. Vermiform kaolinite crystals are in close spatial association with feldspar and mica grains. Near the top of the Whitemud Formation, etched quartz and feldspar grains, and gibbsite suggest the presence of a strong chemical leaching environment.

Mineral distributions, presence of root remains, pedologic mottles, grain coatings composed of clay, and soil horizons indicate the Whitemud Formation sediments were modified by intense weathering in a paleosol environment.

Kaolin concentrated from selected kaolinitic sandstone deposits, and beneficiated by oxidation, leaching, and high-intensity wet-magnetic separation has a product brightness up to filler quality. Recovery of low-abrasion kaolin is low and viscosity of a fine-particle kaolin fraction is high. Economics of producing a wet-processed filler-grade kaolin is marginal.

Key Words—Abrasion, Brightness, Eastend Formation, Frenchman Formation, Kaolin, Kaolinite, Paleosol, Whitemud Formation.

INTRODUCTION

The Upper Cretaceous (Maastrichtian) Whitemud Formation is a kaolinitic facies that crops out in southern Saskatchewan and southeastern Alberta (Figure 1). The kaolinitic nature of the Whitemud Formation makes it an important marker unit in the generally smectitic Upper Cretaceous rocks of the region (Figure 2). Studies were made of the Whitemud Formation to determine whether the kaolin is a product of *in situ* alteration (Fraser *et al.,* 1935) or is sediment derived from a kaolinitic provenance (Byers, 1969). Other studies have evaluated the clay for use in refractories, stoneware, and whiteware (Worcester, 1950), or, following beneficiation, as a filler- or coating-grade kaolin (Spyker *et al.,* 1954). There has been renewed interest by minerals companies in producing commercial, wet-processed kaolin from the lower kaolinitic sandstone of the Whitemud Formation.

The present study considers the origin of the kaolinite contained in the Whitemud Formation. Kaolin deposits in sedimentary rock are either the product of *in situ* alteration caused by weathering or diagenesis, or they are deposits of kaolinitic sediment derived from kaolinitic source rocks, or both. A knowledge of kaolin genesis is important for economic evaluation of a clay deposit because it aids exploration, mining and processing. Data relevant to some economic characteristics of the Whitemud Formation kaolin will be presented.

GEOLOGIC SETTING

The study area is located in the northwest portion of the Williston Basin (Figure 1). Throughout the Cretaceous Period, the region received increasing amounts of clastic sediments from the west because of orogenic activity along the western North American plate margin. Eastward progradation of delta complexes from the Laramide orogenic belt accompanied the withdrawal of the Bearpaw Sea from the study area during the Late Cretaceous. Sediment in rocks of the Eastend, Whitemud, Frenchman, and Ravenscrag Formations (Figure 2) were deposited as part of this advancing clastic wedge. The Bearpaw Sea is represented by dark smectitic shales of the Bearpaw Formation (Figure 2).

Sedimentation during the Late Cretaceous in the area of southern Saskatchewan was centered in small coal basins that formed sediment traps because of high subsidence rates. Origin of these coal basins has been attributed to complicated tectonic movements resulting from dissolution of Devonian evaporites, subsidence

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[1] Present address: ECCI (Americas), Technology Center, P.O. Box 471, Sandersville, Georgia 31082.

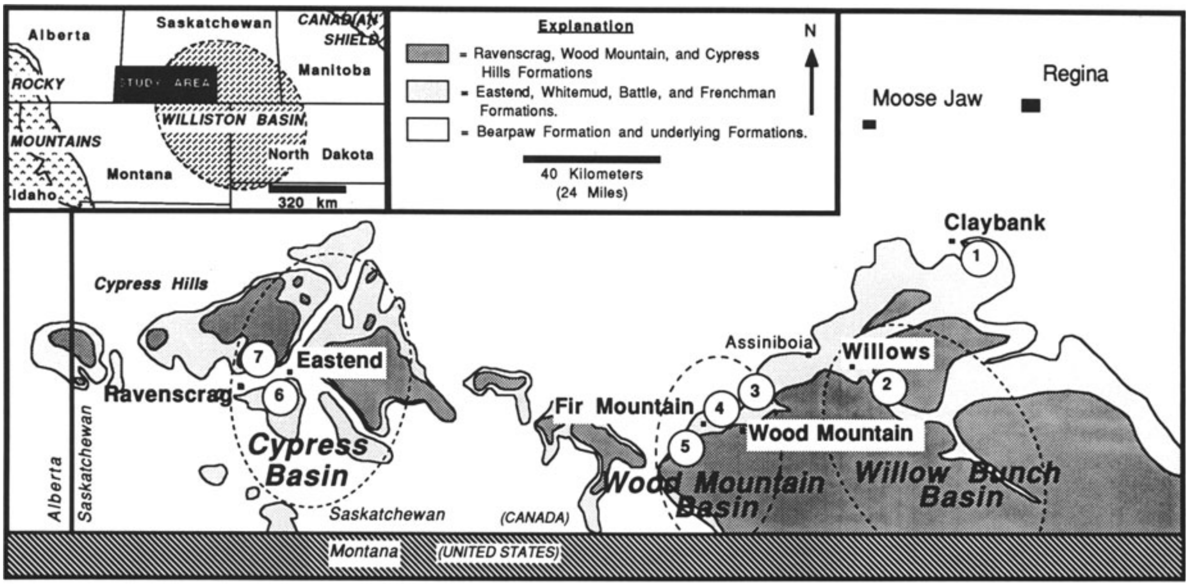

Figure 1. Geological map of south-central and southwestern Saskatchewan showing outcrop pattern of Upper Cretaceous and Tertiary rock units from Whitaker and Pearson (1972). The Eastend, Whitemud, and Frenchman Formations are exposed in the regions shaded light gray. The Ravenscrag, Wood Mountain, and Cypress Hills Formations are exposed in the regions shaded dark gray. Shown are the locations of the Cypress, Wood Mountain and Willow Bunch coal basins from Broughton (1977). Sample localities correspond to: (1) Claybank, (2) Willows, (3) Wood Mountain, (4) drill core site, (5) Fir Mountain, (6) Eastend, and (7) Ravenscrag.

of the Williston Basin, and Laramide orogenic activity (Broughton, 1977). Broughton (1979) suggested that the Whitemud Formation sediments were deposited in the upper deltaic plains of delta complexes prograding into these coal basins. According to Broughton, the kaolinitic Whitemud facies are distributed along the margins of the coal basins in the subsurface and are located in the east-central portion of the Cypress basin, along the west and northwest margins of the Wood Mountain basin, and along the northwest margin of the Willow Bunch basin. Broughton noted that the standard Eastend-Whitemud-Battle-Frenchman sequence described in the Cypress Hills does not persist to the east. Instead, he shows the Whitemud Formation is a stratigraphically higher, and therefore younger, kaolinitic facies within the Frenchman Formation (Figure 2).

METHODS AND MATERIALS

Sample locations and sampling methods

Samples were collected in areas where kaolin contained in the Whitemud Formation has been examined for use as a mineral filler. Samples were collected from six field localities examined in the study area and from drill core provided by Ekaton Industries, Inc. The sampled locales are located (Figure 1) from Claybank in south-central Saskatchewan to Ravenscrag Butte in southwestern Saskatchewan. At each locale the stratigraphic section was measured and described, and 2-kg channel samples were collected of each lithology. Representative 32-kg samples of lower kaolinitic sandstone were collected for economic evaluation from the Willows, Fir Mountain, and Eastend localities.

X-ray powder diffraction and petrographic methods

Standard X-ray powder diffraction (XRD) techniques were used to determine the mineral content of 127 samples. XRD analysis was performed on unoriented whole-rock samples and on dispersed slurries that were dried on glass slides to orient the clays. Powders of whole-rock samples were examined using a Scintag PAD IV instrument (45 kV, 40 mA, CuKα radiation), whereas oriented slides were examined using a Philips instrument (45 kV, 20 mA, Ni-filtered CuKα radiation). Oriented slides were glycolated for 48 hr before a second diffraction scan and were heated to 450°C for 2 hr before a third diffraction scan. The kaolinite : illite 001 peak-height ratio and the degree of kaolinite crystallinity were estimated using XRD data obtained from glycolated, oriented <5-μm material on glass slides. A <5-μm size fraction contains most of the viable commercial kaolin. Kaolinite crystallinity was estimated by dividing the width of the 001 peak at half peak height by the height of the 001 peak (Gardner *et al.,* 1988).

Petrographic data were obtained with a scanning electron microscope (SEM) and from optical examination of thin-sections. Freshly broken chips of sample,

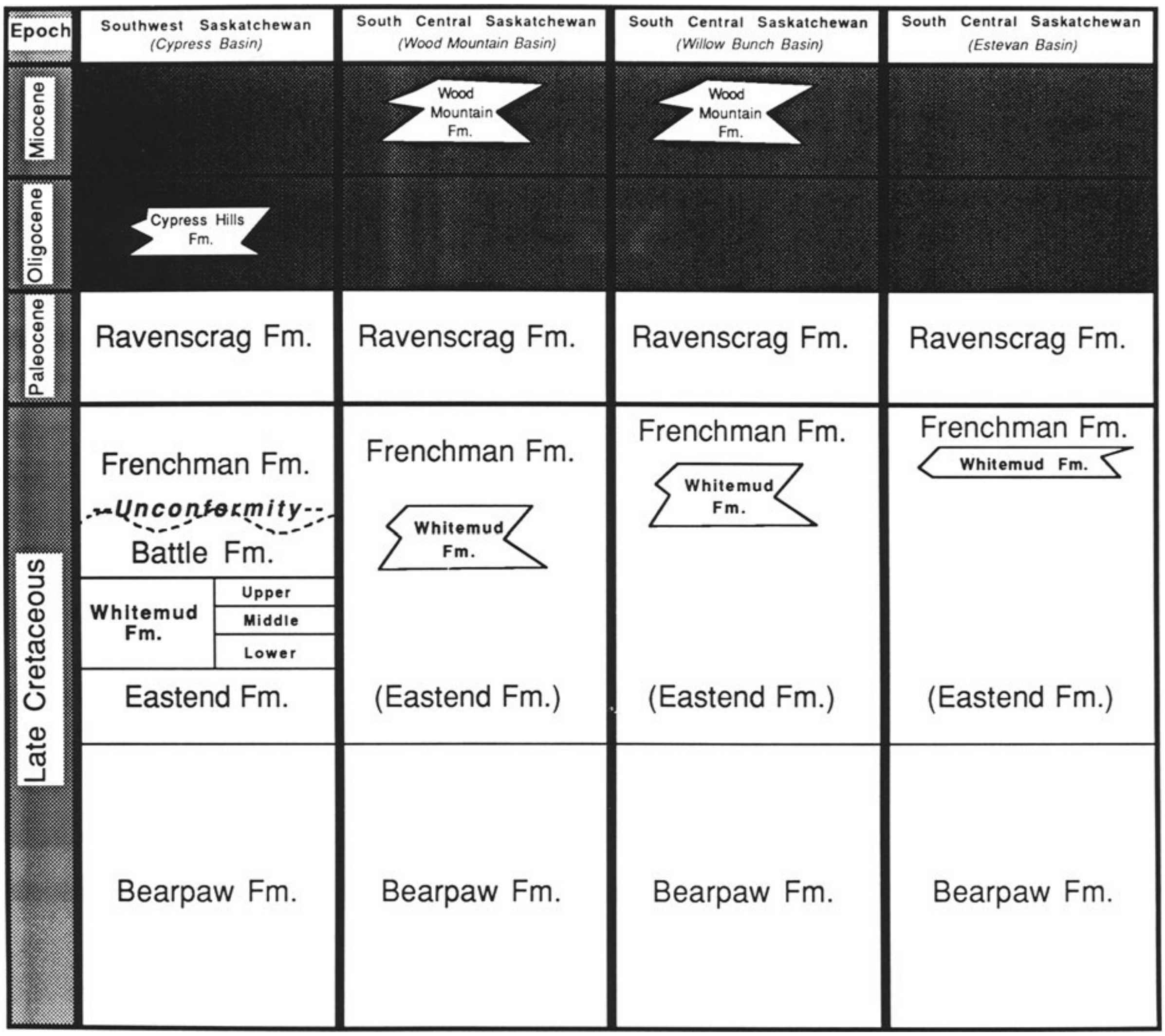

Figure 2. Generalized stratigraphic chart of Upper Cretaceous and Tertiary rocks exposed in southwestern and south-central Saskatchewan. Stratigraphic age relationship of Whitemud facies in the Cypress, Wood Mountain, and Willow Bunch coal basins are interpreted from Broughton (1979).

coated with a mixture of gold and palladium, were examined using a Cambridge Stereoscan 250 MKZ equipped with a Tracor Northern energy-dispersive X-ray system.

Mineral evaluation methods

Kaolin recovery was determined by particle size fractionation. Crude kaolin was blunged for 2 min using a Waring® blender with enough deionized water to make up a 30%-solids slurry containing 0.25 wt. % sodium hexametaphosphate dispersant. Particles >45 μm were removed by a 325 mesh screen. Particle size fractions <45 μm were settled out of suspension. Each kaolin fraction was dried at 100°C and pulverized. Kaolin brightness was measured at 457 nm with a Technibrite TB-1 brightness and opacity tester. Kaolin abrasion was measured with an Einlehner AT-1000 abrasion tester using the method described by Neubold *et al.* (1982). Brookfield viscosity was determined at 10 rpm on screened kaolin in a 70%-solids slurry at optimum dispersion. Brightness improvement was attempted by chemical oxidation for 24 hr with sodium hypochlorite, by high-intensity wet-magnetic separation in a 20 Kgauss field, and by chemical leaching for 20 min with sodium hydrosulfite.

RESULTS

Field observations

In the Cypress Hills (Figure 1), the Eastend Formation is a yellow-to-gray, laminated-to-massive, very fine-grained to fine-grained smectitic wackestone. The contact between the Eastend Formation and overlying

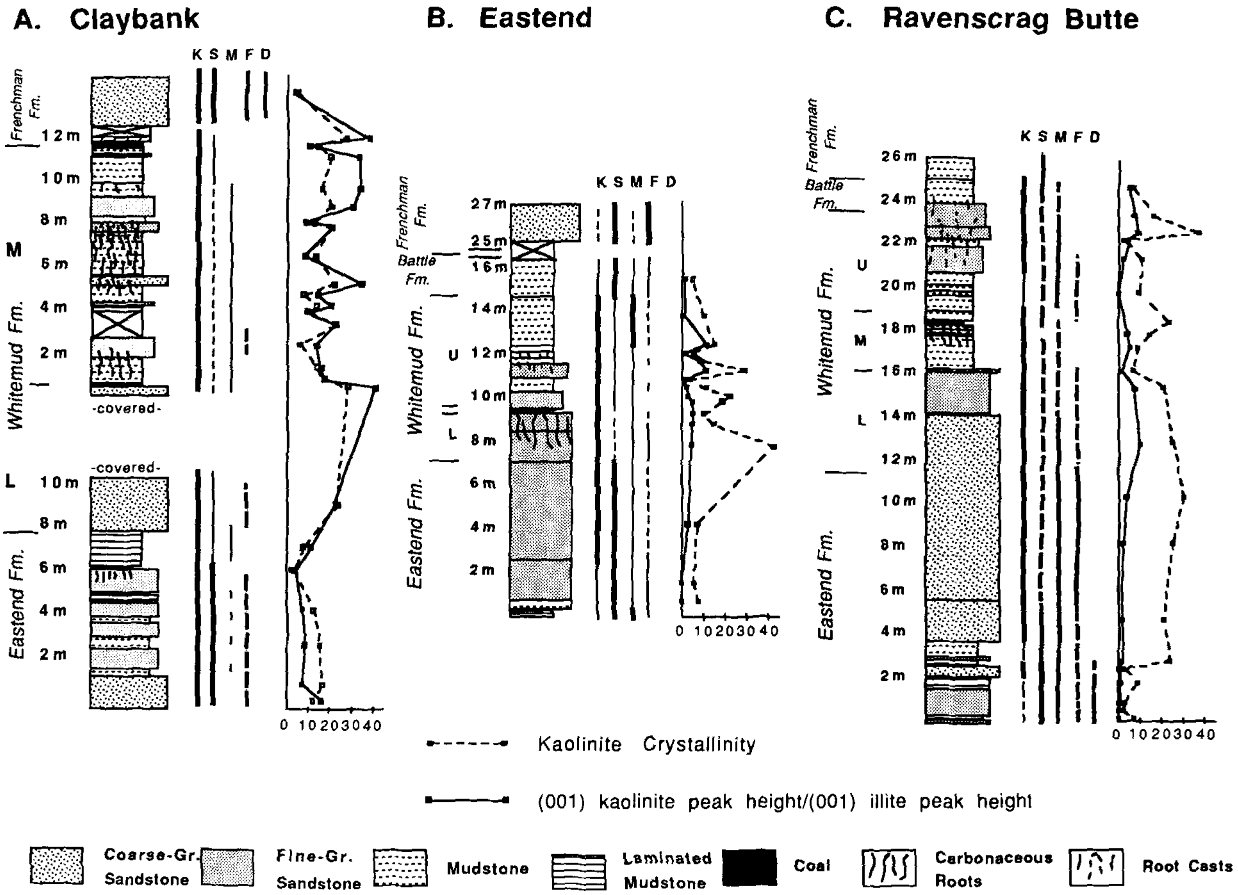

Figure 3. Graphic representation of stratigraphic sections measured near (A) Claybank, (B) Eastend, and (C) Ravenscrag. Kaolinite-to-illite ratio, crystallinity and relative mineral abundance data are plotted against the lithology. Kaolinite, smectite, mica (including illite), feldspar (<45 μm), and dolomite line thicknesses represent relative abundance.

Whitemud Formation is conformable and is identified by a color change. The gray kaolinitic Whitemud Formation is divided into lower, middle, and upper units. The lower unit is a massive or trough cross-stratified, light-gray to medium-gray, fine-grained to coarse-grained kaolinitic quartzose wackestone. The middle unit contains one or more 0.02- to 0.3-m thick beds of lignite interbedded with brown, gray, and olive claystones, siltstones, and shales. The upper unit contains interbedded gray, brownish-gray, or greenish-gray kaolinitic siltstones and claystones. In the Cypress Hills area, the Whitemud Formation conformably underlies a purple-black bentonitic shale named the Battle Formation. Unconformably overlying the Battle Formation is the Frenchman Formation, which contains brown, yellow, or greenish-gray, medium cross-stratified, fine-grained to medium-grained smectitic wackestones intertongued with gray, green, or purple smectitic claystones. Smectitic clastic rocks of the Tertiary Ravenscrag Formation (Paleocene) conformably overlie the Frenchman Formation.

Field evidence for soil development (see Retallack, 1988) within the Whitemud Formation sediments include: 1) plant remains (lignitic and mud casts of roots in growth position, leaf casts, lignite), 2) pedologic mottles, and 3) gradational vertical changes in mineralogy, color, and texture. Within the middle and upper Whitemud Formation, there are accumulations of plant material, lignites, and places where roots in growth position are truncated by overlying beds (Figure 3). Pedologic mottles are observed in several beds within the middle and upper Whitemud Formation.

Sandstone petrology

Mining companies have focused on the kaolinitic sandstone that characterizes the lower Whitemud Formation. Optical petrographic observations show rock fragments makeup 40–55% of framework grains within the Whitemud and Eastend Formations. Many rock fragments have altered to clay and have been compacted to fill pore space. Volcanic rock fragments contain euhedral to anhedral mica, quartz, and feldspar

Table 1. Average of (001) kaolinite: (001) illite peak heights, and the average of kaolinite crystallinities for the lower kaolinitic sandstone zone from the Cypress Hills (southwestern Saskatchewan) and from the Wood Mountain, Willows, and Claybank areas (south-central Saskatchewan).

	Southwest Saskatchewan	South-central Saskatchewan
$\frac{\text{001 kaolinite peak}}{\text{001 illite peak}}$	7.2	29.6
Kaolinite crystallinity	28.6	22.3

crystals randomly oriented in brown clay that apparently replaced the aphanitic matrix minerals or glass (Figure 5b). Metamorphic rock fragments make 1–4% of framework grains and include foliated mica-rich grains containing quartz displaying undulatory extinction under crossed nicols (Figure 5b). Sedimentary rock fragments makeup <2% of framework grains, and include siltstone, shale, and chert.

Descriptive mineralogy

XRD data are summarized for representative stratigraphic sections in Figure 3. Quartz is observed in all samples. Kaolinite abundance increases relative to illite, smectite and feldspar stratigraphically upward from the Eastend Formation into the Whitemud Formation (Figure 3A, 1.5- to 10.8-m interval; Figure 3B, 0.0- to 8.5-m interval; Figure 3C, 3.0- to 15.0-m interval, Figure 4). Kaolinite abundance decreases relative to illite, smectite, and feldspar stratigraphically upward from the Whitemud Formation into the Battle or Frenchman Formations (Figure 3A, 11.0 m to top; Figure 3B, 11.6- to 16.4-m interval; Figure 3C, 21.8- to 24.6-m interval). Kaolinite crystallinity is highest within Whitemud Formation sandstones and decreases stratigraphically upward in the Whitemud (Figure 3). Trace amounts of gibbsite were observed in the upper Whitemud Formation at Willows and at Wood Mountain. Average kaolinite-to-illite ratios of the lower Whitemud Formation rocks are lower in the Cypress Hills than to the east (Table 1). No regional difference in the average kaolinite crystallinities was noted (Table 1).

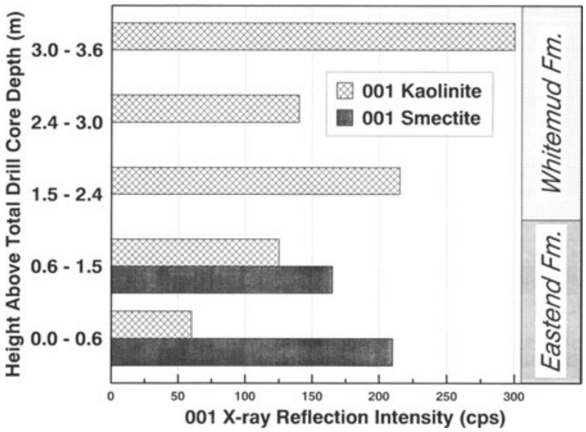

Figure 4. X-ray powder diffraction (XRD) intensities of 001 kaolinite and 001 smectite reflections plotted versus height from core bottom. XRD data are recorded from oriented, glycolated clay slides of the <5-μm particle size fraction. The section of drill core sampled from locality 4 in Figure 1 is a massive, medium-grained to coarse-grained sandstone showing a gradational contact between the pale yellow, smectite-rich Eastend Formation and light gray, kaolinitic Whitemud Formation. XRD data show reciprocal increase in kaolinite with decreasing smectite abundance from core bottom, 0.0 m, to 3.6 m above total depth.

Kaolinite morphology ranges from coarse vermiform crystals to coalesced-overlapping sheets. The coarse (>10 μm) vermiform kaolinite crystals have a "c-axis" length up to 2 mm and have rounded to irregular edges that show no evidence of abrasion (Figure 5A). Quartz inclusions and etch pits are observed on the basal cleavage surface of some large kaolinite crystals. The vermiform kaolinite stacks are the largest grains observed within the sandstones and are commonly interlocked with surrounding framework grains (Figure 5B). Some large kaolinite stacks, observed under crossed nicols, contain plates having a second-order red birefringence characteristic of muscovite, and are texturally associated with large mica grains of similar cross-sectional dimension. Small (<10 μm) kaolinite stacks are abundant and have rounded hexagonal to irregular hexagonal edges. These small kaolinite stacks are located in the sandstone and siltstone matrix, and within altered grains. Small kaolinite stacks are observed associated with detrital potassium feldspar framework grains (Figures 5C, D). Kaolinite grain coatings in Whitemud Formation sandstones consist of platy kaolinite flakes with crudely hexagonal edges. Ragged-edge kaolinite flakes with a swirl texture typify Whitemud Formation claystones (Figure 6A).

Smectite is observed as curled flakes (<4 μm) that form honeycomb aggregates (Figure 6B) or are coalesced into a swirl texture similar to the kaolinite in the claystones. Smectite is rare in the Whitemud Formation, but it is very abundant in rocks of the Battle, Frenchman, and Eastend Formations.

Micas are observed in all samples. Muscovite and biotite grains have irregular edges and concentrate along bedding planes. Some mica grains, particularly in the Whitemud Formation, have kaolinite alteration rims. Alteration of muscovite and biotite to vermiform kaolinite stacks is clearly shown under the optical microscope by the intercalation of mica with kaolinite, and by what appears to be a gradation from mica grains having kaolinitic alteration rims to large kaolinite stacks containing mica-like layers. Flakes of illite are common in the sandstone matrix, or are coalesced into layers within the claystones.

Rounded-to-angular quartz grains with clay coatings

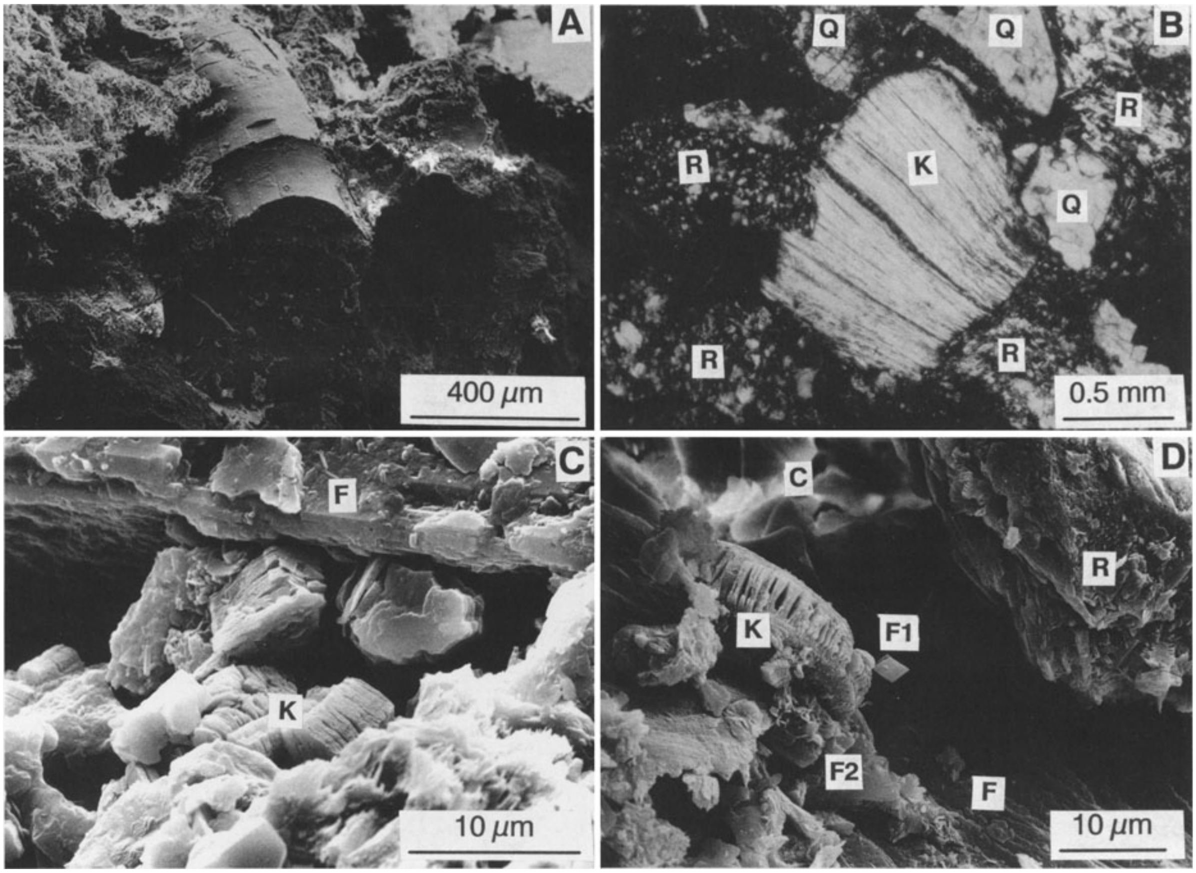

Figure 5. Scanning electron micrographs (SEM) and visible light photomicrograph (VLP) of vermiform kaolinite contained in the Whitemud and Eastend Formations. A) SEM of a large (0.5-mm diameter, 1.0-mm length) kaolinite stack from Whitemud Formation kaolinitic sandstone bed near Claybank, Saskatchewan. Large kaolinite stack is surrounded by quartz grains and rock fragments coated with kaolinite. B) VLP taken with crossed-nicols of a large kaolinite crystal (K) surrounded by quartz grains (Q) and rock fragments (R). Large kaolinite crystals form an interlocking texture with surrounding mineral grains and rock fragments, indicating *in situ* growth. Sample collected from Whitemud Formation near Wood Mountain, Saskatchewan. C) SEM of 5-μm, vermiform kaolinite crystals (K) adjacent to detrital potassium feldspar grain (F). Sample collected from upper Eastend Formation near Wood Mountain, Saskatchewan. D) SEM of a vermiform kaolinite crystal (K) and an attached fragment of potassium feldspar (F1). The kaolinite crystal apparently nucleated on a potassium feldspar grain (F2). Also present are: large chlorite crystal (C), large potassium feldspar grain (F) and kaolinized rock fragment (R). Sample collected from lower Whitemud Formation sandstone near Claybank, Saskatchewan.

are abundant in all sandstones and siltstones examined. Many quartz grains in the Whitemud Formation are etched and friable, and exhibit a honeycomb texture (Figure 6C). SEM revealed some 80-μm, doubly-terminated, subhedral quartz grains that are thinly coated with amorphous-appearing silica in the Whitemud Formation.

Plagioclase and potassium feldspars are more abundant in the Eastend and Frenchman Formations than in the Whitemud Formation. In the Whitemud Formation, feldspar occurs in trace amounts and is most abundant at the base of the lower kaolinitic sandstone. SEM and optical petrography show detrital plagioclase framework grains that exhibit etched surfaces adjacent to secondary pores (Figure 7A). Potassium feldspar is more abundant than plagioclase in the Whitemud Formation. Potassium feldspar occurs as detrital framework grains with evidence of dissolution (Figures 5C,D) and replacement by kaolinite. Potassium feldspar also occurs as tabular, euhedral, 4-μm crystals usually associated with etched plagioclase grains (Figure 7B).

Nodular siderite is contained in some samples of medium-grained to coarse-grained sandstone. The siderite (var. sphalosiderite) is brown, has a subspherical morphology, and contains opaque inclusions of organic material. Some siderite is in close textural association with large kaolinite stacks (Figure 7C) and apparently has replaced some kaolinite within the stacks.

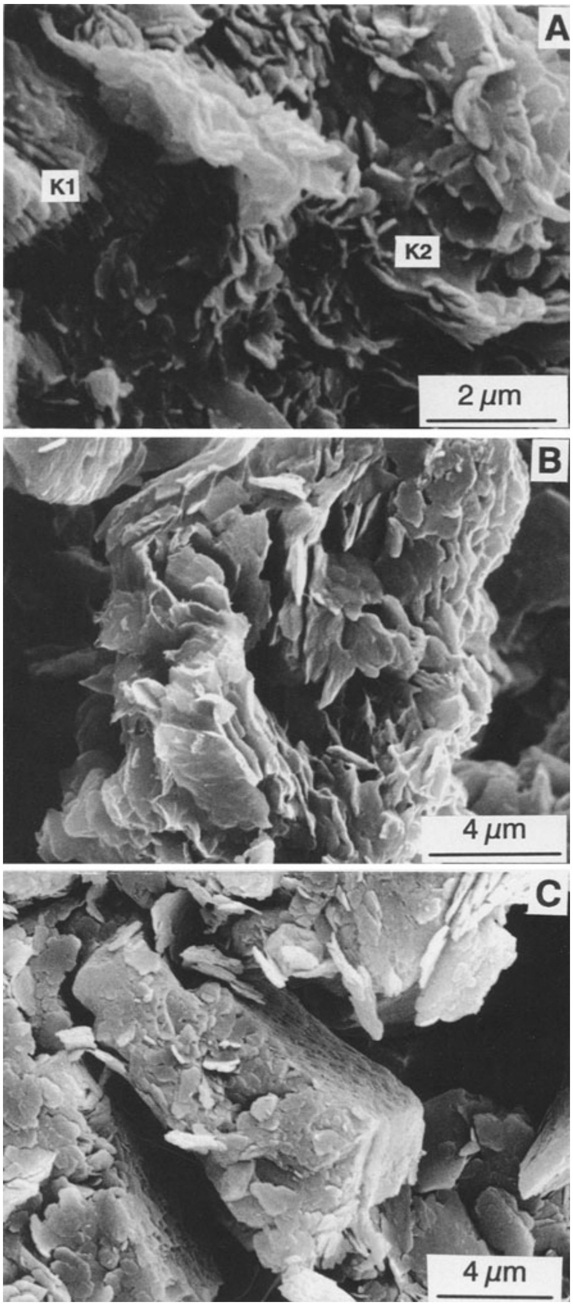

Figure 6. Scanning electron micrographs of kaolinite, smectite, and quartz from the Whitemud and Eastend Formations. A) kaolinite stack (K1) and ragged-edge flakes of kaolinite (K2) in a swirl texture. Smectite-rich rocks of the Eastend Formation have a similar swirl texture. Sample was collected from Whitemud Formation claystone near Fir Mountain, Saskatchewan. B) An aggregate of ragged-edge smectite flakes typical for rocks of the Eastend Formation. Sample collected from a sandstone near Claybank, Saskatchewan. C) Fractured, severely etched, kaolinite-coated quartz grain. Sample collected from Whitemud Formation sandstone near Willows, Saskatchewan.

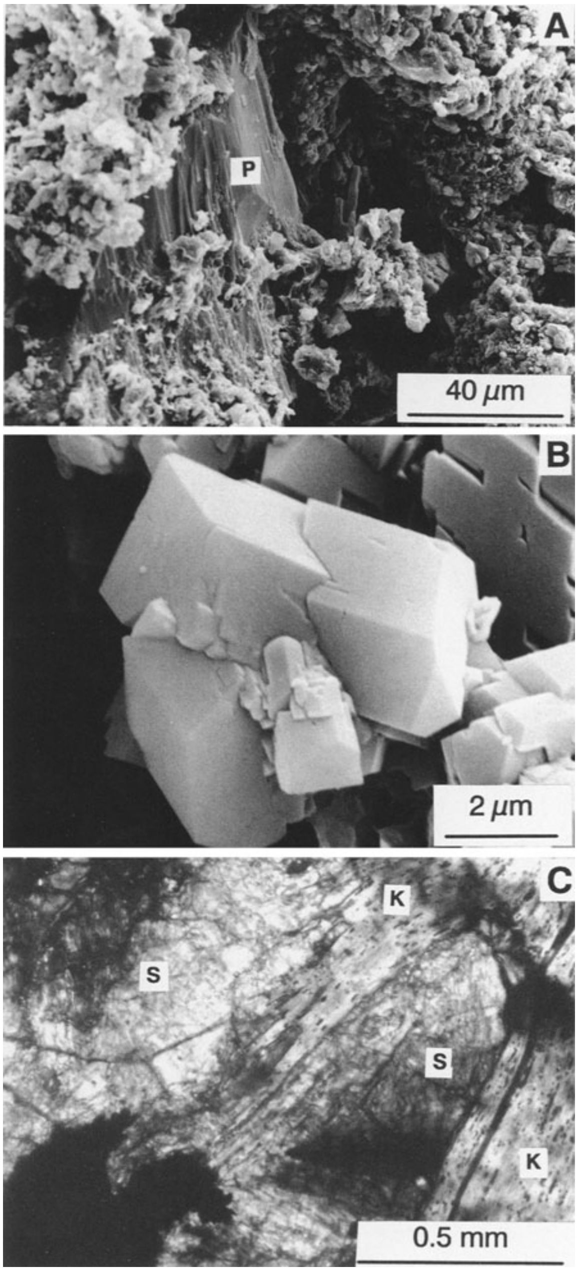

Figure 7. Scanning electron micrographs (SEM) of feldspars from the Eastend Formation, and a visible light photomicrograph (VLP) of kaolinite and siderite in the Whitemud Formation. A) Partly-dissolved plagioclase grain (P). Wall of pore created by plagioclase dissolution is coated with small euhedral crystals of authigenic potassium feldspar. Sample collected from sandstone located near Claybank, Saskatchewan. B) Close-up of euhedral potassium feldspar crystals coating pore walls adjacent to partly-dissolved plagioclase grain shown in (A). C) VLP (crossed-nicols) of nodular siderite (S) invading a large kaolinite crystal (K). The siderite nodule apparently nucleated on a fragment of carbonaceous material (opaque). Sample collected from a drill core located near Wood Mountain, Saskatchewan.

Table 2. Kaolin brightness values for selected processed kaolins.

Sample	Initial	Oxidized	Magnet	Leached
Willows				
<45 μm	70.8	70.6†	75.7	76.5* 76.3** 76.7***
		71.1‡	75.4	77.4**
<2 μm	72.0	72.0†	74.9	75.7* 76.0** 76.3***
0.5–45 μm	72.1	73.7†	80.7	81.2** 81.2***
1–15 μm	72.2	73.5†	79.1	79.8* 80.5** 80.6***
Fir Mountain				
<45 μm	57.7	58.9†	60.2	60.4* 60.7** 60.8***
		58.6‡	60.5	60.8* 61.0** 61.0***
<2 μm	58.5	52.8†	58.4	59.8* 59.0** 59.1***
Eastend				
<45 μm	64.5	67.8†	70.8	71.2* 71.6** 72.7***
<2 μm	65.4	66.9†	65.5	65.7* 65.8** 66.8***

† Treated with 4.17 ml/kg (1 gal/T) sodium hypochlorite.
‡ Treated with 8.35 ml/kg (2 gal/T) sodium hypochlorite.
* Treated with 0.15 wt. % sodium hydrosulfite.
** Treated with 0.3 wt. % sodium hydrosulfite.
*** Treated with 0.45 wt. % sodium hydrosulfite.

Kaolin properties

Crude kaolin brightness gradually increases upward from the Eastend Formation (44–52%) to the Whitemud Formation (48–70%). Brightness values are low in rocks containing high abundances of illite, smectite, and carbonaceous material. Kaolinitic sandstone from the Willows locality has the highest crude and processed brightness (Table 2). Table 2 shows chemical oxidation improves brightness an average of 3%, magnetic separation an average of 7%, and leaching an average of 2%. Some size fractions from the Willows locality contain kaolin that can be processed above 80%, the minimum brightness for filler-grade clay. Two size fractions contain the purest kaolin, the 2–5-μm fraction (4.2 wt. % recovery) which contains mostly kaolinite stacks, and the <0.5-μm fraction (31.8 wt. % recovery) which contains mostly platy kaolinite (Figure 8). The data in Table 3 show that brightness after chemical oxidation and magnetic separation is similar for both size fractions. Leaching is deleterious to the <0.5-μm fraction. Einlehner abrasion values (Figure 9) exceed the standards set for fine-particle filler clay (6–10-mg screen abrasion) and No. 2 coating clay (4–5-mg screen abrasion) (Neubold *et al.,* 1982). The Brookfield viscosity measured at 10 rpm on the <5-μm kaolin fraction is 7000 centipoise at 70% solids, and optimum dispersion at 0.25 wt. % sodium hexametaphosphate. Commercial kaolins have Brookfield viscosities no more than a few hundred centipoise at similar solids concentration.

DISCUSSION

Post-depositional alteration of the Whitemud Formation sediments explains many observed mineralogical textures and trends. XRD and petrographic results show that extensive alteration of labile minerals occurred in rocks of the Whitemud Formation and lesser alteration of labile minerals occurred in rocks of the Eastend Formation. The abundance of minerals containing cations mobile in acidic environments (K^+, Na^+, Mg^{2+}, Fe^{2+}, Ca^{2+}) is significantly less in rocks of the Whitemud Formation. There is a significant decrease in illite and smectite abundance relative to kaolinite, and a near absence of feldspar within the very permeable, coarse-grained Whitemud Formation sandstone lithologies. Gibbsite present near the top of the Whitemud at some localities is an indicator of extreme leaching conditions.

The kaolinite contained in the Whitemud Formation appears to be primarily an authigenic alteration product of mica, feldspar, and smectite. Kaolinite rims on mica grains and intercalation of kaolinite between mica

Table 3. Brightness values for 2–5 μm and <0.5 μm processed kaolin from Whitemud Formation kaolinitic sandstone collected near Willows, Saskatchewan.

	2–5 μm	<0.5 μm
Crude brightness	69.7	69.0
Processing Run Number 1:		
Sodium hypochlorite treatment 4.14 ml/kg (1 gal/T)	71.2	71.4
Magnet treatment	78.4	80.4
Sodium hydrosulfite treatment 0.45 wt. %	78.8	72.5
Sodium hypochlorite treatment 8.35 ml/kg (2 gal/T)	79.1	78.4
Processing Run Number 2 (using Run Number 1 product):		
Sodium hypochlorite treatment 3.35 ml/kg (2 gal/T)	80.1	79.2
Magnet treatment	80.6	80.1
Sodium hydrosulfite treatment		
0.15 wt. %	80.1	76.2
0.30 wt. %		77.1
0.45 wt. %		76.7
1.25 wt. %		75.3

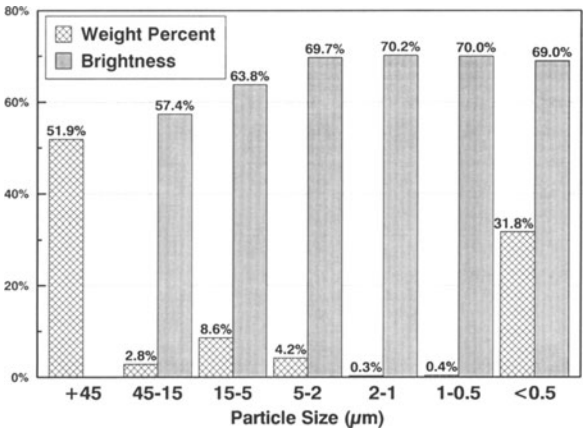

Figure 8. Particle size distribution and brightness of a kaolin crude fractionated from Whitemud Formation kaolinitic sandstone collected near Willows, Saskatchewan. Kaolinite makes up most of the 15–2-μm fraction with vermiform crystals and most of the <5-μm fraction with platy crystals. Brightness values display little variation in kaolin <5 μm.

layers are evidence for mica alteration to kaolinite by replacement and by epitaxial growth of kaolinite on mica substrates (Banfield and Eggleton, 1988). Acidic conditions, similar to those present in soils, are required for epitaxial growth of kaolinite on mica (Wilson, 1966). Kaolinite is the product of potassium feldspar alteration as evidenced by its close textural relationship with fine kaolinite stacks (Figures 5C,D), and the partial replacement of feldspar by kaolinite observed under the optical microscope. Kaolinite stacks derived from potassium feldspar are finer grained than those associated with mica. Alteration of smectite to kaolinite is suggested by the presence of curled kaolinite flakes morphologically similar to smectite, and by the reciprocal relationship between kaolinite and smectite abundance (Figure 4). Keller (1976) and Tyrrell (1963) presented similar evidence for alteration of smectite to kaolinite in volcanogenic sediments.

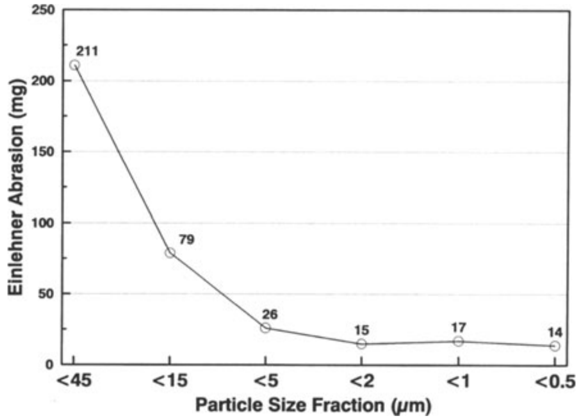

Figure 9. Einlehner abrasion values for different size fractions of kaolin fractionated from Whitemud Formation kaolinitic sandstone collected near Willows, Saskatchewan.

The texture of detrital quartz and the presence of authigenic siderite and potassium feldspar provide supporting evidence for a soil environment. The porous, honeycomb nature of detrital quartz grains is evidence for strong chemical weathering conditions with a high flux of meteoric water. Shanmugam and Higgins (1988) describe similar severe etching of quartz grains caused by the rapid flushing of acidic meteoric solutions through sandstones and siltstones. Siderite apparently precipitated in a reduced chemical environment localized around the organic material now observed as inclusions within sphalosiderite. Reading (1986) describes sphalosiderite formation in waterlogged to partly emergent soils typical of humid climates. Siderite replacement of kaolinite indicates the sphalosiderite formed after the large vermiform kaolinite crystals. Authigenic potassium feldspar precipitated in a chemical environment rich in alumina and silica adjacent to dissolving plagioclase grains. High potassium concentration in pore solutions could come from detrital potassium feldspar or mica dissolving elsewhere in the soil, or from decaying plant materials (R. E. Hughes, personal communication). Potassium feldspars precipitated as a late soil product under waterlogged or partly emergent conditions, or precipitated under diagenetic conditions with high alkali concentrations.

Diagensis accounts for compaction, additional labile mineral alteration, and potassium feldspar precipitation. Rock fragments weakened by alteration were compacted during lithification and filled any existing pore spaces. Alteration of micas, feldspars, and smectite to kaolinite may have continued in the acidic conditions connected with decaying organic materials.

Brightness values apparently relate to the degree of leaching the Whitemud Formation rocks experienced during post-depositional weathering. Brightness is lower in kaolins containing iron-bearing phases (biotite, illite, smectite, and siderite) and organic materials. Mica and smectite removal by dissolution or alteration to kaolinite improves kaolin brightness.

INTERPRETATION

The Whitemud Formation appears to be a paleosol with the characteristics of an ultisol-type soil. Traces of roots in growth position, plant remains, pedologic mottles, and soil horizons are conclusive evidence for a paleosol. The massive claystone at the top of the Whitemud Formation has gradational mineralogical, color, and textural changes likely caused by bioturbation or pedological activity at the top of a soil profile. The truncation of *in situ* rooted horizons observed in several different stratigraphic positions at all field localities suggest multiple periods of soil development are represented in the Whitemud Formation rocks. Mineralogical trends, similar to those described for the Whitemud Formation, are observed in Cretaceous rocks in Alabama and Georgia and are interpreted by Hester (1974) to be caused by post-depositional weathering.

Ultisol-type soil profiles develop in humid, temperate climates on ground with a depressed groundwater table (Buol *et al.*, 1980). The humid, temperate climate indicated by the Whitemud flora described by Berry (1935) would favor ultisol development. Present-day ultisol profiles have mineralogical trends similar to those described for the Whitemud Formation. Ultisols show an upward decrease in plagioclase, potassium feldspar, mica, and smectite abundance and an upward increase in kaolinite and gibbsite abundance. Grain coatings and etched quartz grains would support the ultisol-type paleosol interpretation for the Whitemud rocks. Nodular siderite and potassium feldspar could have precipitated in water saturated zones within the soil.

Sediments alter to kaolinite where the groundwater table is depressed to allow leaching of cations from labile minerals. During Whitemud time, the groundwater table probably fell, coincident with base level fall caused by a fall in sea level. According to Lerbekmo (1987), Whitemud Formation rocks in the Cypress Hills region have magnetostratigraphic dates of 68 m.y. that correspond with the 68 m.y. sequence boundary (Haq *et al.*, 1987). Younger Whitemud facies east of the Cypress Hill may correspond with a sea level fall around 67 m.y. (Haq *et al.*, 1987).

Two or more periods of kaolin development may partly explain the difference between Whitemud Formation rocks located in the Cypress Hills and Whitemud Formation rocks to the east. Whitemud Formation rocks in the Cypress Hills have lower kaolinite-illite ratios and lower brightness that could relate to less severe chemical weathering, which prevented complete alteration of labile minerals to kaolinite. Provenance may also explain differences between kaolins of the two regions. Paleocurrent, heavy mineral, and petrologic data collected by Misko and Hendry (1979), and Rahmani and Lerbekmo (1975) indicate rocks in southwestern and western Montana, and volcanics in British Columbia are the source for Late Cretaceous sediments deposited in the Cypress Hills area. Rahmani and Lerbekmo (1975) show Late Cretaceous rocks located east of the Cypress Hills have sediment sources located northwest in British Columbia and western Alberta.

The Whitemud Formation kaolin has many properties typical for a primary kaolin deposit because the kaolinite resulted from the *in situ* weathering of feldspar, micas, and smectite. Spatial variability in kaolin purity and brightness is common in most primary kaolin deposits due to incomplete and inconsistent alteration. Quartz particles liberated from corroded detrital framework grains and rock fragments are present in the fine particle-size fractions and result in an abrasive kaolin product.

CONCLUSIONS

The Whitemud Formation is a multiple paleosol with features of an ultisol that developed on sediments from the Laramide orogenic belt. Most kaolinite contained in the Whitemud Formation originated from *in situ* alteration of feldspar, mica, and smectite. Rocks rich in smectite, in the upper portion of the Eastend Formation and the Frenchman Formation, were deposited on the same alluvial or deltaic plain, but were located in a hydrologic realm that did not allow kaolinitic alteration. Lithification and diagenesis caused compaction of grains weakened by weathering and possibly further alteration of mica, feldspar, and smectite by acidic waters from decaying organic materials. The possibility of recovering a commercial, filler-grade kaolin is problematic because of low kaolin recoveries, a high abrasion product, and spatial variability of deposits that can be beneficiated to meet only minimum brightness for filler-grade clay.

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