

## BENTONITE CHARACTERISTICS FROM DEPOSITS NEAR ROSALIND, ALBERTA

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**Abstract**—Two bentonite deposits having average thicknesses of 10 and 4 ft are exposed within nonmarine strata of Late Cretaceous age along the Battle River near Rosalind, Alberta. They are characterized by scarcity of  $>44 \mu\text{m}$  material and variable  $44\text{--}2 \mu\text{m}$  and  $<2 \mu\text{m}$  contents. Material  $>44 \mu\text{m}$  in size in excess of 2 per cent is primarily attributable to secondary calcite, and  $<2 \mu\text{m}$  content may be related to the amount of  $44\text{--}2 \mu\text{m}$  material that has altered diagenetically from volcanic glass to montmorillonite. Rhyodacite was the probable composition of the parent ash; therefore, the high iron content in one deposit is probably due to diagenesis. The blocking effect of iron on exchange sites can explain differences in exchangeable Na and Ca in different deposits. High exchangeable Na found in finer subdivisions of fractionated clay can be explained by increased purity of the bentonite.

Multiple regression analysis of the analytical data shows that 48 per cent of the variation in yield (bbl/T.) of 15 centipoise drilling mud can be attributed to concomitant variation in seven interrelated compositional properties. Sequential analysis shows that  $<0.2 \mu\text{m}$  clay content is the most important contributor to variation in yield. The remaining variables (total clay content, exchangeable Na, exchangeable Ca + Mg,  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  contents, and CEC) contribute little additional precision to the regression analysis when  $<0.2 \mu\text{m}$  clay content is included in the equation.

### INTRODUCTION

BENTONITES are common in the thick succession of Cretaceous and Paleocene strata which form the bedrock formations underlying much of the Alberta Plains and Foothills. However, most of the bentonite beds are thin and discontinuous, and though several deposits have been mined for local use in the past, only a few have potential for large scale development.

At present, bentonite is mined in two areas in central Alberta. One area is near Onoway, about 30 miles northwest of Edmonton, and the other is along the Battle River near Rosalind, about 60 miles southeast of Edmonton. The Rosalind deposits, with which this paper is concerned, have been developed by Dresser Minerals, a division of Dresser Industries Inc., which mines and processes from 10,000 to 12,000 tons of bentonite per yr, producing a variety of clay products for the foundry, construction and drilling industries in western and northern Canada. This paper presents the results of a detailed mineralogical study of the Rosalind bentonites. It is an attempt to characterize the properties of the different types of bentonites observed in the field and to relate these properties to variations in quality.

### DESCRIPTION OF DEPOSITS

The Rosalind bentonite deposits occur in the 'Lower Edmonton' member of the Upper Cretaceous

Edmonton Formation (Allan and Sanderson, 1945), which has been renamed the Horseshoe Canyon Formation of the Edmonton Group by Irish (1970). The Edmonton Group is a thick succession of dominantly nonmarine, coal-bearing, clastic strata, which crops out over a wide area in east-central Alberta. The Horseshoe Canyon Formation is composed of white to pale grey, feldspathic, 'salt-and-pepper'-type sandstones and siltstones interbedded with grey and brown, montmorillonitic, carbonaceous shales and silty shales. Coal seams and ironstone beds are common, and the formation has a distinctly variegated appearance when viewed in outcrop.

Along the Battle River south of Rosalind, the Horseshoe Canyon beds are exposed beneath glacial drift (ground moraine) in a series of coulees and small gullies, which together create an incipient badland-type of topography similar to that found along the larger rivers in southeastern Alberta. The regional dip of the strata is to the southwest at the rate of a few feet per mile, but for practical purposes the beds are nearly flat-lying.

The bentonites comprise at least four stratigraphically distinct deposits, but only two of these presently are being mined. The main deposit is found along the south side of the Battle River and is mined in open pits in Sec. 31, Tp. 42, R. 17, W. 4th Meridian (Fig. 1, Locality 1). At this locality the bed is 8.5–10.5 ft thick and

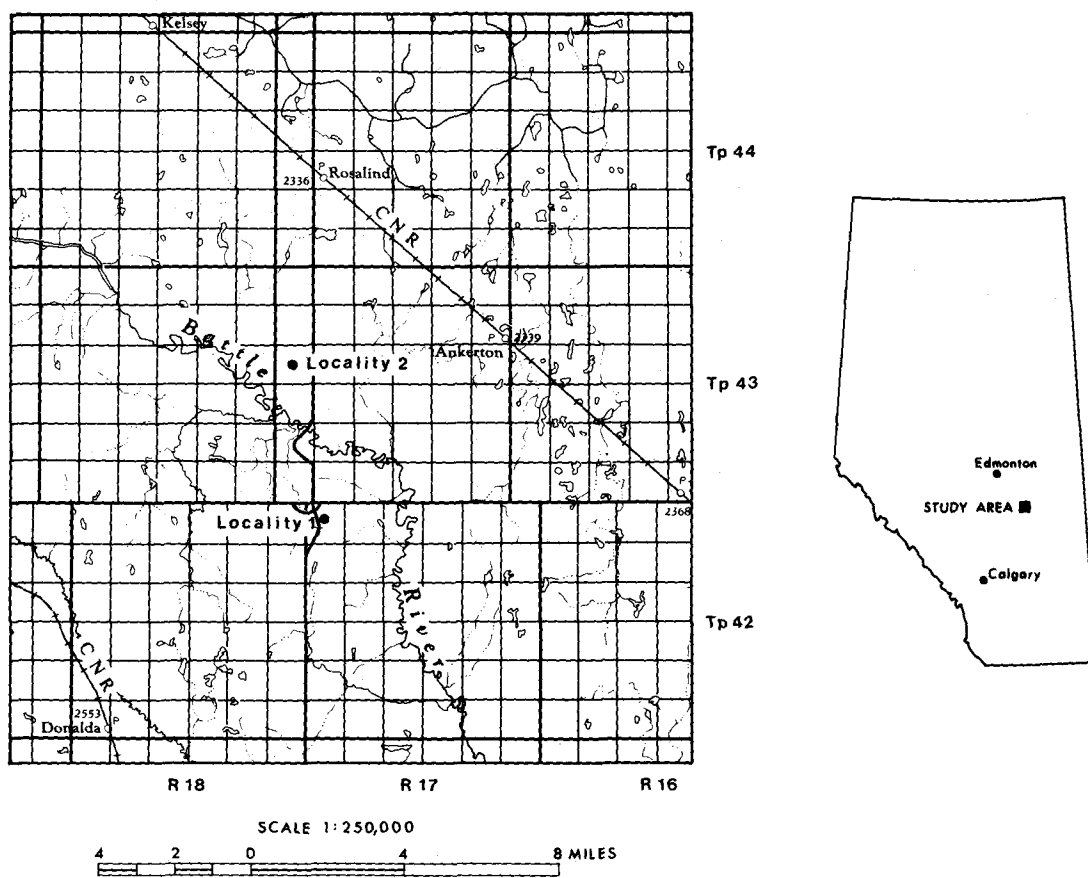


Fig. 1. Bentonite sampling localities.

drilling reveals a deposit 500 ft wide over a distance of 3600 ft along the valley (Ross, 1964). Overburden composed of Horseshoe Canyon beds and till attains thicknesses of as much as 25 ft, and black carbonaceous shale underlies the deposit. The beds strike N.N.W and dip westerly at  $14 \text{ ft mile}^{-1}$  with only minor folding or slumping (Carter, personal communication).

The second deposit occurs approximately 160 ft stratigraphically below the main deposit and is mined north of the river in Sec. 19, Tp. 43, R. 17, W. 4th Meridian (Fig. 1, Locality 2). It is 4–6 ft thick, and consists of olive-weathering bentonite resting on black silty shale and overlain by grey sandstone.

Most of the bentonite mined by Dresser Minerals at Rosalind is sold for bonding foundry sands. One type is used for grey iron casting and a second type is used in steel foundries. Some material has been shipped to eastern Canada for tests in iron ore-pelletizing plants, but no large orders have been placed to date. Drilling mud is produced from a high grade bed at Locality 1 and by beneficiating other material from Localities 1 and 2 (Fig. 1). Rosalind bentonite also has been used

as grouting clay and for manufacture of products such as roofing materials, feed pellets and paper, and as bonding material for bricks made from fly ash.

#### SAMPLING

Pit faces left after mining the previous year were sampled at Localities 1 and 2 (Fig. 1). A diagrammatic sketch of the main deposit exposed in an open pit face at Locality 1 is shown in Fig. 2. Previous testing by Dresser Minerals indicated that the bentonite at this locality can be divided into the following three units based on suspension properties. (1) The lowermost unit is the 'Bottom Bed' which is a light olive-grey to greyish-olive, massive, blocky fracturing bentonite in sharp contact with underlying black shale. (2) 'Arrow-head' clay is bentonite varying in color from dusky yellow-green to dusky yellowish-brown. It is dominantly green colored and is discolored along fractures, laminae surfaces, and entire laminae by the reds and browns of oxidized iron. This material generally breaks into  $\frac{1}{2}$ -in. blocks. (3) The 'Grey' bentonite

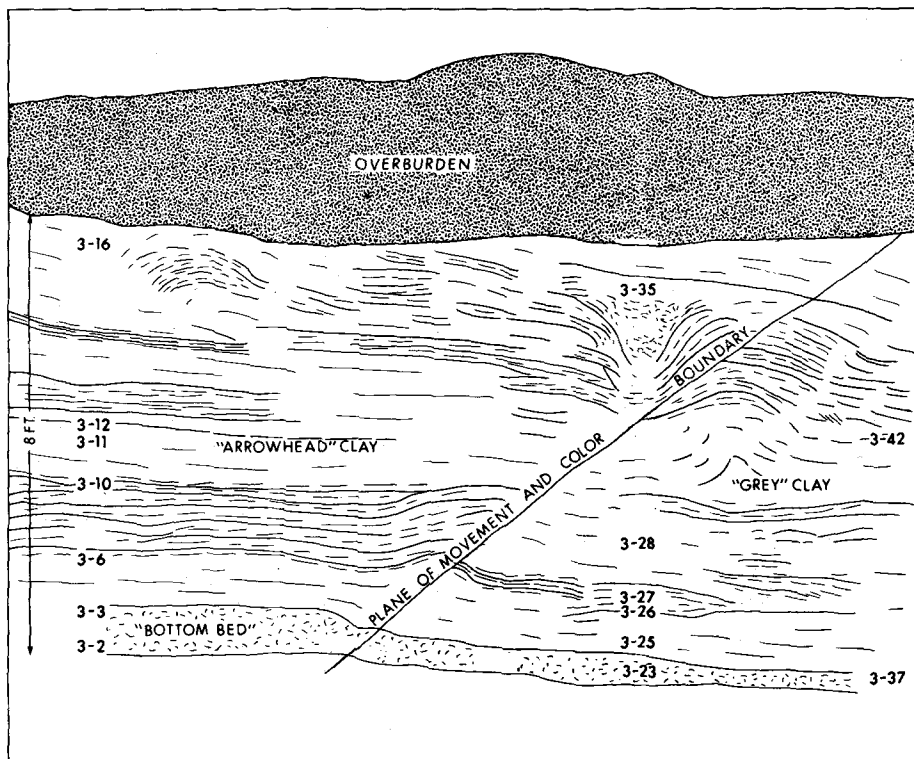


Fig. 2. Diagrammatic sketch of pit face at Locality 1 showing sample distribution (3-∞).

varies between light olive-grey and olive-grey in color. Laminae can be traced into the Arrowhead clay across the color boundary. The apparent plane of movement between Arrowhead and Grey bentonites is only a local phenomenon, and little displacement has taken place along it.

The bentonite at Locality 2 rests on black, laminated, silty shale and is overlain by green 'salt-and-pepper' sandstone. The clay is massive and most of it breaks into 1-1½ in. blocks. It is medium dark grey to greyish olive-green material and weathers to olive-grey. Along the color contact, 'eggs' of grey clay surrounded by olive are common. In most cases the olive color also extends along fractures.

Trenches were dug far enough into the pit faces to expose moist bentonite. Samples were taken at color changes or at 6-12 in. intervals where the color is uniform. The freshly dug material was placed in double-walled plastic bags and sealed to preserve moisture and color.

#### ANALYTICAL TECHNIQUES

Laboratory processing commenced with color coding each sample using the Rock-Color Chart (Rock-Color Chart Committee, 1963). Apparent viscosity

was determined on suspensions of 6 and 9 per cent by weight according to procedures for testing oilwell drilling fluid materials (American Petroleum Institute, 1969a, b).

The grit-size (>44 μm) material was obtained by wet-sieving a hydrated suspended sample through a Canadian Standard 325-mesh sieve. The weight of the grit-size material was determined, an X-ray powder pattern was obtained, and heavy minerals were separated using tetrabromoethane (s.g. 2.96 at 20°C). Heavy minerals were mounted in Aroclor ( $n = 1.66$ ) and the light minerals in Lakeside 70 ( $n = 1.54$ ) for optical examination with a petrographic microscope.

The minus 325-mesh material was separated into 44-2 and <2 μm fractions. The <2 μm material was separated further into 1-2, 0.5-1, 0.2-0.5 and <0.2 μm fractions using procedures only slightly modified from those of Jackson *et al.* (1950), and Tanner and Jackson (1948). X-ray powder patterns of the 44-2 μm material were obtained for mineral identification.

The sedimentation method was used to prepare glass slide mounts of each fraction within the <2 μm material for X-ray identification of minerals. Slides were equilibrated at 50 and 80 per cent relative humidity (r.h.) for 24 hr, and r.h. was maintained during X-radiation by utilizing a modified goniometer radiation

shield (Gillery, 1959). X-ray diffractograms were obtained from Cu K $\alpha$  radiation produced by a Philips X-ray generator set at 40 kV and 20 mA. Recorder settings of 300 cps and time constant 3 were used with the exception of a 1000 cps setting for Bottom Bed samples. Each <2  $\mu\text{m}$  fraction was freeze-dried prior to determination of exchangeable Ca and Mg by atomic absorption, and Na and K by flame photometry procedures.

#### PROPERTIES OF THE ROSALIND BENTONITES

##### Mineralogy

Several observations of the coarser nonclay minerals in the bentonite were made by studying all samples with a petrographic microscope. Angular quartz usually is present as the most abundant nonclay mineral. Feldspar is the next most common impurity, and most of it is angular plagioclase having a composition near the oligoclase-andesine boundary. Minor quantities of K-feldspar also are present in a few samples. Essentially fresh volcanic glass is observed in only one sample. Partly devitrified glass is found in many samples from Locality 1 and under polarized light it is observed to be mainly aggregates of very fine grained cristobalite and montmorillonite. Secondary calcite and gypsum formed authigenically and aggregates consisting of iron oxide material also are present in several samples. Calcite is the major nonclay mineral in those samples containing more than 2 per cent grit-sized grains. Biotite is the dominant accessory heavy mineral in the bentonite. Minerals commonly present in trace amounts include zircon, apatite and marcasite (?). Barite and siderite are in a few samples.

Quartz, plagioclase, biotite, and in a few cases K-feldspar, are the minerals identified in the 44–2  $\mu\text{m}$  fractions. Cristobalite is present only in samples from Locality 1. The method of Goodyear and Duffin (1954) was used to determine that oligoclase-andesine is the most common plagioclase composition in this material.

Except for a trace of kaolinite in a few of the 1–2  $\mu\text{m}$  fractions, montmorillonite is the only clay mineral detected in all four fractions of <2  $\mu\text{m}$  material. Biotite, quartz and (in a few samples) plagioclase are other minerals found in the 1–2  $\mu\text{m}$  fraction. Quartz and biotite are present in fractions smaller than 0.5  $\mu\text{m}$  in a few samples. Cristobalite is present in size fractions smaller than 2  $\mu\text{m}$  only from Locality 1.

Representative X-ray diffractograms of <0.2  $\mu\text{m}$  fractions are illustrated in Fig. 3. At 50 per cent r.h. the Bottom Bed sample shows a main peak at 13.2  $\text{\AA}$ , but the fact that the peak is skewed toward low angles shows that some of the montmorillonite in the sample has expanded more than the rest. A relatively sharp,

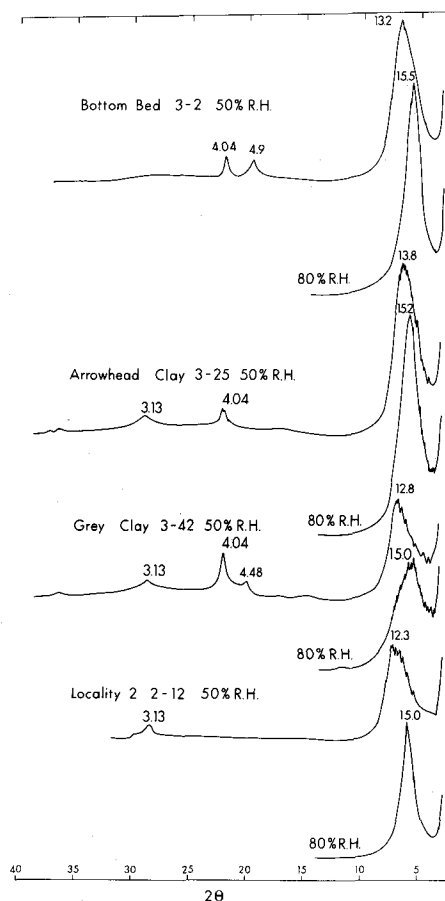


Fig. 3. Representative X-ray diffractograms of <0.2  $\mu\text{m}$  fractions at 50 and 80 per cent r.h.

symmetrical peak at 15.5  $\text{\AA}$  is produced at 80 per cent r.h. The Arrowhead clay at 50 per cent r.h. has a relatively broad first order peak skewed toward low angles which sharpens at 80 per cent r.h. but not as much as the Bottom Bed pattern. The 50 per cent r.h. pattern for Grey clay contains a broad, more skewed, less intense first order peak than the Arrowhead pattern. The first order peak at 80 per cent r.h. is broad and slightly skewed to higher angles, indicating that not all montmorillonite particles have expanded to an equal degree. The 4.9  $\text{\AA}$  peak in the Bottom Bed sample and the 4.48  $\text{\AA}$  peak in the Grey clay sample indicate the presence of thick or aggregate clay particles that settle on the slide unoriented. All samples from Locality 1 show a 4.04  $\text{\AA}$  cristobalite peak but this peak is absent from the Locality 2 pattern. The first order montmorillonite peak on the pattern from Locality 2 is broad and skewed toward low angles, but the 80 per cent r.h. pattern shows a relatively sharp, symmetrical peak.

Table 1. Size and suspension properties of Rosalind bentonites

Sample	Predominant color when moist		Mechanical analysis (weight %)				Clay size fractions (weight % total sample)			Yield (bbl/T)
			>44 $\mu$ m	44–2 $\mu$ m	<2 $\mu$ m	1–2 $\mu$ m	0.5–1 $\mu$ m	0.2–0.5 $\mu$ m	<0.2 $\mu$ m	
Bottom bed										
3-2	5Y	5/2	6	9	85	6	9	10	60	100
3-3	10Y	4/2	0.3	6	94	4	9	10	71	96
3-23	5Y	5/2	12	17	71	3	6	4	58	112
3-37	10Y	4/2	2	7	91	8	8	7	68	104
Average			5	10	85	5	8	8	64	103
Arrowhead clay										
3-6	5GY	6/1	0.5	12	88	5	8	12	63	75
3-10	10YR	2/2	0.2	19	81	9	5	11	56	73
3-11	10Y	6/2	2	21	77	7	6	11	53	75
3-12	5Y	4/1	1	20	79	6	3	10	60	74
	5GY	5/1	3	17	80	9	4	13	54	83
	5Y	5/6	8	14	78	5	4	3	66	78
Average			2	17	80	7	5	10	59	76
Grey clay										
3-25	5Y	3/2	0.2	18	82	40	2	17	23	72
3-26	5Y	3/2	1	36	63	30	7	10	16	65
3-27	5GY	5/2	2	21	77	10	18	21	28	65
3-28	5Y	3/2	2	13	85	9	13	15	48	70
3-42	5Y	2/1	0.1	39	61	13	8	7	33	65
Average			1	25	74	20	10	14	30	67
Locality 2 clay										
2-4	5Y	3/2	1	26	73	7	7	9	50	80
2-5	5Y	4/4	3	23	74	5	8	12	50	75
2-9	5Y	3/2	0.3	22	78	5	7	13	53	78
2-12	5GY	3/2	2	26	72	5	10	14	43	82
2-13	5Y	3/2	4	22	74	6	10	11	47	84
Average			2	24	74	6	8	12	49	80

### Particle size distribution

Particle size data (Table 1) clearly illustrate domination of all samples by <2  $\mu$ m material. Secondary calcite aggregates make up most of the >44  $\mu$ m content greater than 2 per cent, except for altered volcanic ash in one sample (2-4) and quartz and barite in another (3-25).

The Bottom Bed contains the least amount of 44–2  $\mu$ m material among the four clay types. The Bottom clay contain the greatest amounts of 44–2  $\mu$ m material but Grey clay has wider variations of this material. Average 44–2  $\mu$ m content of Arrowhead clay is intermediate between that of the Grey clay and Bottom Bed.

Some differences are evident in distribution of <2  $\mu$ m material among the four clay types. The bottom Bed contains the highest proportion of total <2  $\mu$ m material as well as the greatest proportion of <0.2  $\mu$ m material. Arrowhead clay has the next greatest proportion of total <2  $\mu$ m material and <0.2  $\mu$ m material. Grey clay contains approximately the same amount of

total <2  $\mu$ m material as Locality 2 clay, but <0.2  $\mu$ m content is noticeably lower. There is no obvious gross correlation between <2  $\mu$ m material and corresponding average yield values (barrels of mud with viscosity of 15 centipoise  $\text{ton}^{-1}$  of bentonite) except that Bottom Bed samples have consistently greater yields than samples of the other three clays. If <0.2  $\mu$ m contents are plotted against yield the association in Fig. 4 emerges. The scatter diagram suggests a positive correlation between yield and <0.2  $\mu$ m content, confirmed by analysis of data variance. However, deviations from regression are still relatively high, especially towards greater clay content values where all of the Bottom Bed samples fall above the calculated regression curve. Although visual inspection of the scatter diagram suggests that a curvilinear relationship may provide a better 'fit' for the data, analysis of data variance demonstrates this is not the case.

### Exchangeable cations

Exchangeable Na is the most abundant cation in samples from Locality 1 (Table 2). Exchangeable Ca is

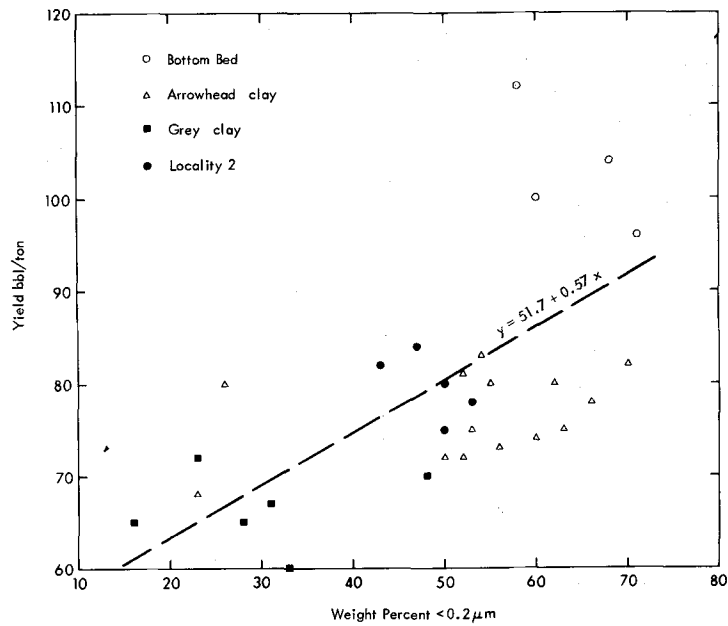


Fig. 4. Relationship between yield and &lt;0.2 μm fractions.

Table 2. Cation exchange data for &lt;2 μm material

Sample	Ca	Total exchange (m-equiv 100 g <sup>-1</sup> )			K	Cation exchange capacity (m-equiv 100 g <sup>-1</sup> )	$\frac{\text{Ca} + \text{Mg}}{\text{CEC}}$ (%)
		Mg	Na				
<b>Bottom bed</b>							
3-2	25	5	58	15	103	29	
3-3	14	3	52	18	87	19	
3-23	38	3	48	3	92	45	
3-37	30	2	137	4	173	19	
<b>Arrowhead clay</b>							
3-6	9	2	41	16	68	16	
3-10	13	3	62	18	96	17	
3-11	18	4	50	8	80	27	
3-12	11	2	36	7	56	23	
3-16	15	3	56	9	83	22	
3-35	53	2	86	4	145	38	
<b>Grey clay</b>							
3-25	15	7	62	2	87	26	
3-26	24	1	71	2	98	26	
3-27	23	1	80	2	106	23	
3-28	25	2	88	3	118	23	
3-42	26	2	53	5	86	33	
<b>Locality 2 clay</b>							
2-4	24	5	38	2	69	42	
2-5	28	5	28	1	62	53	
2-9	30	5	29	2	66	53	
2-12	33	5	48	2	88	43	
2-13	33	7	28	2	70	57	

more abundant than Mg or K at Localities 1 and 2 and equals or exceeds the content of exchangeable Na in 3 of the 5 samples from Locality 2. Ratios of Ca + Mg to CEC in Table 2 seldom fall into the 40–60 per cent range, where small changes in amount of Ca or Na can induce large changes in yield (Williams *et al.*, 1953a). Ratios for Locality 2 clays are exceptions; however, yield values for Locality 2 samples are similar to those for Arrowhead clays for which Ca + Mg/CEC ratios are generally much lower than the 40 per cent minimum.

Decreasing clay size (Table 3) is marked by a progressive increase of exchangeable Na. The other three cation contents remain almost constant with the exception of an increase of K content in the Bottom Bed with decreasing size.

*Iron content*

Foster (1953, 1955) and Davitz and Low (1970) suggest that iron oxidation (among other variables) might be significant in changing swelling properties of a bentonite. At first glance this hypothesis appears to merit

Table 3. Cation exchange of four particle sizes of Rosalind bentonites

Sample	Size (µm)	Ca	Mg (m-equiv 100 g <sup>-1</sup> )	Na	K
<b>Bottom bed</b>					
	1-2	20	5	11	2
3-2	0.5-1	22	5	20	10
	0.2-0.5	34	7	28	17
	<0.2	24	5	96	21
<b>Arrowhead clay</b>					
	1-2	12	2	23	2
3-11	0.5-1	17	5	23	8
	0.2-0.5	18	5	69	3
	<0.2	13	3	61	15
<b>Grey clay</b>					
	1-2	20	1	44	2
3-26	0.5-1	23	1	49	2
	0.2-0.5	27	2	53	3
	<0.2	26	3	138	2
3-28	1-2	22	1	58	2
	0.5-1	25	1	85	3
	0.2-0.5	28	4	49	4
	<0.2	26	2	261	3
<b>Locality 2 clay</b>					
	1-2	22	4	6	1
2-4	0.5-1	28	6	26	1
	0.2-0.5	27	6	28	2
	<0.2	23	6	93	2
2-5	1-2	24	4	7	1
	0.5-1	27	5	13	1
	0.2-0.5	36	5	22	2
	<0.2	27	7	71	1

Table 4. Iron contents (in percent) of Rosalind bentonites

Sample	FeO	Fe <sub>2</sub> O <sub>3</sub>	FeO/Fe <sub>2</sub> O <sub>3</sub>
<b>Bottom bed</b>			
3-2	0.83	2.53	0.33
3-3	0.41	2.00	0.21
3-23	0.22	2.62	0.08
3-37	0.70	2.13	0.33
Average	0.56	2.32	0.24
<b>Arrowhead clay</b>			
3-6	0.53	2.01	0.26
3-10	0.32	1.82	0.18
3-11	0.42	2.33	0.18
3-12	0.62	2.44	0.25
3-16	0.34	3.43	0.10
3-35	0.51	2.21	0.23
Average	0.46	2.37	0.20
<b>Grey clay</b>			
3-25	0.26	2.25	0.12
3-26	0.27	2.77	0.10
3-27	0.16	2.95	0.05
3-28	0.29	2.74	0.11
3-42	0.36	2.85	0.13
Average	0.27	2.71	0.10
<b>Locality 2 clay</b>			
2-4	0.38	6.30	0.06
2-5	0.31	6.21	0.05
2-9	0.31	6.77	0.05
2-12	0.31	6.69	0.05
2-13	0.30	5.33	0.06
Average	0.32	6.26	0.05

investigation with respect to the Rosalind bentonites for subtle but distinct color differences exist among the four bentonite types in the field. The three Locality 1 clays exhibit color differences (Table 1) apparently caused by conversion of ferrous to ferric iron. The distinction between Arrowhead and Grey clays is especially noticeable. Locality 2 clays exhibit striking color changes along joints where sharp color breaks occur between dark grey clay and olive-grey or olive-brown clay.

The amount of FeO at Locality 1 (Table 4) decreases from Bottom Bed through Arrowhead clay to Grey clay whereas the amount of Fe<sub>2</sub>O<sub>3</sub> increases in the same sequence. The quantity of FeO in Locality 2 clays is intermediate between Arrowhead clay and Grey clay but the magnitude of Fe<sub>2</sub>O<sub>3</sub> is more than twice that found in Grey clay. Locality 2 clays have the smallest FeO:Fe<sub>2</sub>O<sub>3</sub> ratios. Ratios increase in Locality 1 clays from Grey through Arrowhead clay to Bottom Bed.

*Suspension properties*

Yields of 15 centipoise mud listed in Table 1 are calculated from apparent viscosity values (what flow

appears to be measured in centipoise) using Dresser Minerals yield curves of pit material. Apparent viscosity is related to interparticle forces of the clay plus mechanical friction between solid particles of the mud, solids and liquid, and shearing of the liquid itself.

Yields range from 65 to 112 bbl/T. The Bottom Bed samples exhibit higher values (96–112 bbl/T) than the other three clay types, and Grey clay the lowest range of values (65–72 bbl/T).

The relationship between yield and other properties of the samples is analyzed in some detail below.

#### MULTIPLE REGRESSION ANALYSIS

The analytical data show that suspension properties of Rosalind bentonites vary markedly from one clay type to the next, and to a lesser extent among individual samples within each clay type. Variation in yield can be related in part to variations in other properties (e.g.  $<0.2 \mu\text{m}$  clay content), but in some cases (e.g. CEC) there is no obvious correlation with yield values. Consequently, since there does not appear to be a simple set of interrelationships among yield and various compositional and textural properties which can be used to determine causes and effects, a multivariate statistical technique is used to evaluate relative importance of these properties on yield values.

Multiple regression is the technique selected for analysis of data in Tables 1, 2 and 4, in which an equation of the form shown below is calculated according to the procedure shown in most standard statistical reference books:

$$y = a + b_1x_1 + b_2x_2 \dots b_nx_n$$

where  $y$  = dependent variable

$x_n$  = independent variable

$b_n$  = partial regression coefficients.

Yield is designated the dependent variable ( $y$ ); and total clay content,  $<0.2 \mu\text{m}$  clay content, ferrous and ferric iron contents, exchangeable Na and Ca + Mg contents, and CEC are the independent variables.

Values for these properties are from the 20 samples representing the four clay types in Tables 1, 2 and 4, and the corresponding multiple regression equation is calculated to be:

$$y = 20.5038 + 0.3495x_1 + 0.3934x_2 + 3.3313x_3 - 0.3037x_4 - 0.0483x_5 + 0.4058x_6 + 0.0411x_7$$

where  $x_1$  = per cent clay content

$x_2$  = per cent  $<0.2 \mu\text{m}$  clay content

$x_3$  = per cent  $\text{Fe}^{2+}$

$x_4$  = per cent  $\text{Fe}^{3+}$

$x_5$  = exchangeable Na (m-equiv 100  $\text{g}^{-1}$ )

$x_6$  = exchangeable Ca + Mg (m-equiv 100  $\text{g}^{-1}$ )

$x_7$  = CEC (m-equiv 100  $\text{g}^{-1}$ ).

Partial regression coefficients indicate the average

increase or decrease (depending on the sign) in the dependent variable  $y$  per unit increase in the corresponding variable  $x$ , independent of other variables in the equation. However, because different units of measurement are associated with the independent variables, partial correlation coefficients cannot be compared directly to determine the relative contribution of each variable to variation in yield values. Furthermore, the independent variables themselves are interrelated, and values of the partial regression coefficients will change if variables are dropped from or added to the equation.

To assess relative importance of the independent variables in predicting yield values, several approaches may be used. That selected here is to calculate standard partial regression coefficients ( $b'$ ) (Snedecor, 1956), listed for the above equation in Table 5. The  $b'$  values in Table 5 indicate the relative contribution or importance of each independent variable to observed fluctuations in yield values, i.e. the extent to which yield values will change in response to changes in the respective independent variables. From this it is seen that for samples from Localities 1 and 2 ( $N = 20$ )  $x_2$  ( $<0.2 \mu\text{m}$  clay content) is the most important contributor to variation in yield values, and  $x_4$  ( $\text{Fe}^{3+}$  content) the least important. The value for  $R^2$  (square of the multiple correlation coefficient) represents the fraction of total variation in the dependent variable ( $y$ ) attributable to the regression. For the first trial in Table 5,  $R^2$  is 0.4814; i.e. 48 per cent of the total variation in yield values can be attributed to or 'explained' by concomitant variation in the seven independent variables. (The remaining 52 per cent of the variation in yield values is 'unexplained' or 'random' variation.)

To evaluate further the relative importance of independent variables, the least important ( $\text{Fe}^{3+}$ ) is omitted from analysis and the multiple regression equation and  $b'$  values recalculated for the remaining six variables (second trial, Table 5). The second trial shows that  $x_2$  is still the most important contributor to variation in yield values ( $b' = 0.4326$ ), and that the  $R^2$  value has dropped only slightly from 0.4814 to 0.4808. In other words, the six independent variables listed under the second trial in Table 5 together 'explain' about 48 per cent of the total variation in yield values;  $\text{Fe}^{3+}$  (the deleted variable) contributes only an additional fraction of a per cent to the 'explained' variation in yield.

This sequential approach to evaluation of the seven independent variables is performed by omitting the least important variable over a series of seven trials, each of which involves recalculating a new regression equation,  $b'$  and  $R^2$  values. By the sixth trial, only two



Table 5. Multiple regression analysis of yield

Variable	<i>N</i> = 20 Standard partial regression coefficients ( <i>b</i> )			
	First trial	Second trial	Sixth trial	Seventh trial
$x_1$ —Clay content	0.2149	0.2077		
$x_2$ —<0.2 $\mu\text{m}$ clay content	0.4353	0.4326	0.6160	0.6272
$x_3$ — $\text{Fe}^{2+}$	0.0414	0.0415		
$x_4$ — $\text{Fe}^{3+}$	−0.0392			
$x_5$ —Na	−0.0925	−0.1728		
$x_6$ —Ca + Mg	0.3234	0.2732	0.2491	
$x_7$ —CEC	0.0861	0.2006		
$R^2$	0.4814	0.4808	0.4554	0.3934
<i>N</i> = 15				
$x_1$ —Clay content	0.3142	0.3117		
$x_2$ —<0.2 $\mu\text{m}$ clay content	0.4515	0.4709	0.6237	0.6453
$x_3$ — $\text{Fe}^{2+}$	0.0356			
$x_4$ — $\text{Fe}^{3+}$	0.1511	0.1501		
$x_5$ —Na	−0.1311	−0.1490		
$x_6$ —Ca + Mg	0.3439	0.3312	0.3385	
$x_7$ —CEC	0.0607	0.0906		
$R^2$	0.5154	0.5146	0.4759	0.4164

variables remain ( $x_2$  and  $x_6$ ), which together account for 45.5 per cent of the total variation in yield values. Thus, efficiency of the regression equation is reduced by less than 3 per cent by omitting five of the seven independent variables: <0.2  $\mu\text{m}$  clay content ( $x_2$ ) and Ca + Mg content ( $x_6$ ) together are nearly as efficient as all seven variables in predicting yield values of Rosalind bentonites.

If Ca + Mg content is omitted, and the regression of <0.2  $\mu\text{m}$  clay content ( $x_2$ ) alone on yield is calculated, then the  $R^2$  value drops from 0.4554 to 0.3934 (seventh trial, Table 5). This is a loss of approximately 6 per cent in the efficiency of the regression analysis; this suggests that <0.2  $\mu\text{m}$  clay content is the only variable among the seven properties considered which has a significant relationship with yield of Rosalind bentonites. The six other independent variables contribute relatively little additional precision to regression analysis (accounting for less than 10 per cent of the total variation in yield values when considered simultaneously with <0.2  $\mu\text{m}$  clay content) and can be disregarded in attempting to relate variation in yield to the basic compositional properties of Rosalind bentonites.

The same multiple regression approach is applied to the 15 samples from the three clay types exposed at Locality 1 ( $N = 15$ ), for  $\text{Fe}^{3+}$  contents, particularly of Locality 2 samples, appear significantly different from those of the other three clay types (Table 4). Results of the analysis are essentially the same as those obtained for all 20 samples: <0.2  $\mu\text{m}$  clay content ( $x_2$ ) is the

most effective contributor to variation in yield values, followed by Ca + Mg content ( $x_6$ ). The  $R^2$  values for the series of regression equations are:

No. of independent variables ( $x$ )	$R^2$ ( $N = 15$ )	$R^2$ ( $N = 20$ , Table 5)
7 ( $x_1 - x_7$ )	0.51	0.48
2 ( $x_2, x_6$ )	0.48	0.46
1 ( $x_2$ )	0.42	0.39

Comparison of  $R^2$  values for the first set of equations ( $N = 20$ , Table 5) with those for the second set ( $N = 15$ ) indicates little significant difference in the relationships between independent variables and yield; in both cases <0.2  $\mu\text{m}$  clay content appears to be the only property associated with yield values of the Rosalind bentonites.

## DISCUSSION OF RESULTS

### Composition and origin

The composition of bentonite is a function of (1) the parent material (predominantly volcanic ash), (2) effects of diagenetic processes following deposition of parent material and (3) effects of weathering (mainly oxidation) if the deposit is exposed or is near the surface.

The oligoclase–andesine plagioclase, quartz, and low K–feldspar contents suggest that rhyodacite was the parent material for the Rosalind bentonites. However, Lerbekmo (1968) suggests parent rocks that range

from rhyolite to dacite with a preponderance of rhyodacites for Upper Cretaceous and Paleocene bentonites from the Alberta Foothills.

Paucity of grit-size material in Rosalind clays compares favorably with bentonites from north-central United States (Knechtel and Patterson, 1956, 1962; Berg, 1969; Slaughter and Earley, 1965). Much of the grit fraction is of authigenic (secondary) origin; with two exceptions calcite is responsible for most grit in excess of 2 per cent of the total sample. Thus, the parent ash of Rosalind bentonites presumably contained little grit-size detritus (quartz, feldspars) other than particles of volcanic glass, which since have altered to montmorillonite and cristobalite.

The low 44–2  $\mu\text{m}$ , high  $<2 \mu\text{m}$  relationship in the Bottom Bed can be interpreted as the result of diagenetic alteration of the same ash from which the intermediate 44–2  $\mu\text{m}$ , intermediate  $<2 \mu\text{m}$  content Arrowhead and high 44–2  $\mu\text{m}$ , low  $<2 \mu\text{m}$  content Grey clay was formed. Locality 2 clay was formed from a similar ash. As average  $<2 \mu\text{m}$  content decreases from the Bottom Bed through Arrowhead to Grey clay, average 44–2  $\mu\text{m}$  content increases in approximately equal steps in reverse order. This suggests that  $<2 \mu\text{m}$  content increases by diagenetic processes which alter 44–2  $\mu\text{m}$  material to montmorillonite. Volcanic glass altering to cristobalite and montmorillonite seen in  $>44 \mu\text{m}$  material is an easily observed manifestation of the same intermediate steps taking place in 44–2  $\mu\text{m}$  material. No mineralogical difference other than an absence of cristobalite in Locality 2 clays is observed in any fraction between Locality 1 and Locality 2 clays.

Cristobalite is usually authigenic in bentonites (Henderson *et al.*, 1971). This is indicated by the presence of stacking disorder in the crystal structure, common in cristobalite formed at low temperatures (Güven and Grim, 1972). Diffraction patterns of Rosalind bentonites show broadening of the 101 cristobalite peak (4.04 Å) plus diffuse scattering of the peak towards lower angles, which suggest the presence of stacking disorder. Patterns of  $>44 \mu\text{m}$  and 44–2  $\mu\text{m}$  material (not shown) contain sharper peaks, but the scattering effect is generally present. These features suggest that cristobalite in Rosalind bentonites is authigenic, i.e. derived from alteration of volcanic glass to cristobalite and montmorillonite. Absence of cristobalite in the Locality 2 samples probably reflects different diagenetic conditions from those at Locality 1.

The origin and distribution of Na and Fe contents in Rosalind bentonites (Tables 2, 3, 4), and the role which these constituents play in determining suspension properties, are more difficult to explain. Na and other exchangeable cations presumably can originate

from breakdown of parent materials (volcanic glass, plagioclase) during diagenesis, or be adsorbed by the clays from groundwater at a later stage, including the weathering phase. Conversely, these constituents can be removed by groundwater flow systems, or by leaching at the outcrop face. There is little evidence to show a preference for any of the mechanisms among the three clays from Locality 1 (Table 2), but it is worth noting that Na content of these three clays is higher than that of Locality 2 bentonite.

Williams *et al.* (1953b) suggest that the iron starts as exchangeable  $\text{Fe}^{2+}$ , is oxidized to  $\text{Fe}^{3+}$ , then hydrolyzes to hydrous ferric oxide which is irreversibly removed near the outcrop as overburden thickness decreases giving shades of green, yellow or red to weathered bentonite. Exchange sites left open by iron removal can be filled by Na and Ca but much Ca can be removed as gypsum or calcite with Na left as the most abundant exchangeable cation. This could explain the greater amount of Na than Ca at Locality 1, but hydrous ferric oxide also may exert a blocking effect on exchange sites (Williams *et al.*, 1953b). This blocking effect, caused by the high amount of  $\text{Fe}^{3+}$  at Locality 2, may explain the low amount of Na compared to Ca at Locality 2.

No indication of why Locality 2 clays contain more iron than Locality 1 clays can be gained from the depth of overburden or from the mineralogical analyses. Depths of overburden between Localities 1 and 2 are similar and the bentonites seem to have formed from parent ashes of similar composition; therefore, different diagenetic conditions between Localities 1 and 2 may explain the differences in iron concentration as well as the differences in cristobalite concentration mentioned earlier.

Cation exchange results for fractionated material shown in Table 3 may be due to bentonite being a heterogeneous mixture of essentially Na–montmorillonite particles and essentially Ca–montmorillonite particles (McAtee, 1958). Also, Na–montmorillonite is composed of individual particles in dilute suspension but Ca–montmorillonite particles form aggregates unless subjected to prolonged mixing (Mungan and Jessen, 1963). All Ca–montmorillonite aggregates probably are not of equal size; therefore, Ca–montmorillonite aggregates are present in all fractions  $<2 \mu\text{m}$  in size from Rosalind bentonites, and prolonged mixing associated with fractionation may modify aggregate size so that Ca–montmorillonite concentration remains relatively constant in each size fraction. Some Na–montmorillonite particles may aggregate when clay concentration is highest and be removed in the larger size fractions, but as fractionation continues relatively more Na–montmorillonite is present in finer fractions

because of the tendency of Na-montmorillonite to form smaller individual particles.

#### *Suspension properties*

Prior to the work of Foster (1953) much attention was given to the effect of CEC and of the exchangeable cation on swelling of montmorillonite. Foster (1953, 1955) found that swelling was unrelated to CEC, but decreased with increasing octahedral substitution, and that oxidation of  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$  in octahedral position increased swelling markedly. Davidtz and Low (1970) agreed that ion substitution is important but believed that oxidation of substituted  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$  decreased the *b*-dimension of the crystal lattice. Swelling increased because the silica tetrahedra rotated and adjusted to the dimensions of the octahedral layer which in turn affected the water structure attached to the silica tetrahedra. Relative partial molar free energy of water was related to swelling pressure and when partial molar free energy changed in response to tetrahedra rotation, swelling changed.

Ravina and Low (1972) found that exchangeable cations can affect the configuration of the montmorillonite lattice and therefore the swelling capacity. Mungan and Jessen (1963) found that montmorillonites with calcium as the exchangeable cation gave lower yield values than montmorillonites of equal particle size with Na as the exchangeable cation.

Results of multiple regression analysis used in this study reveal that  $<0.2 \mu\text{m}$  clay content is the only independent variable which has a significant relationship with the dependent variable (yield). Six other independent variables (clay content,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ ), exchangeable Na, exchangeable Ca + Mg, and CEC account for less than 10 per cent of total variation in yield when considered simultaneously with  $<0.2 \mu\text{m}$  clay content.

Mungan and Jessen (1963) showed that as particle size decreased within  $<2 \mu\text{m}$  material, yield increased. Determinations of yield and percentages of  $<2 \mu\text{m}$  material in the samples investigated (Fig. 4) show this observation is also applicable to the Rosalind bentonites. The Bottom Bed clay has the greatest amount of  $<0.2 \mu\text{m}$  material and the greatest yield, and Grey clay has the least amount of  $<0.2 \mu\text{m}$  material and the lowest yield. Arrowhead and Locality 2 clays have intermediate contents of  $<0.2 \mu\text{m}$  material and intermediate yields. The effect of  $<0.2 \mu\text{m}$  material is not surprising when one considers that yield is calculated from apparent viscosity, which is related to the interparticle forces of the clay plus mechanical friction between solid particles of the mud, friction between solids and liquid, and shearing of the liquid itself. If equal weights of clay contain different numbers of particles, the clay with the greater number of particles

(greater amount of  $<0.2 \mu\text{m}$  material) will have greater interparticle forces due to more exposed surface area, will produce greater friction between particles due to more particles per unit volume, and will produce greater friction between particles and liquid due to more particles per unit volume; therefore, yield will be greater. Although exchangeable cations, iron substitution, clay size content, and CEC contribute to yield, their contribution apparently is not significant for Rosalind bentonites.

#### CONCLUSIONS

Bentonite mined from Upper Cretaceous sediments at two locations near Rosalind, Alberta contains a small amount of grit material composed mostly of secondary calcite if grit concentration is greater than 2 per cent. Content of  $<2 \mu\text{m}$  material may be related to the amount of  $44-2 \mu\text{m}$  material that has altered diagenetically from volcanic glass to montmorillonite. Different diagenetic conditions may explain high iron content at Locality 2 and the high iron content may block exchange sites causing differences in exchangeable Na and Ca between Localities 1 and 2. High exchangeable Na in finer subdivisions of fractionated  $<2 \mu\text{m}$  samples can be explained by concentration of Na-montmorillonite in the finer subdivisions of heterogeneous mixtures of Ca- and Na-montmorillonites due to the tendency of Na-montmorillonites to form individual particles rather than aggregates. As expected from the definition of yield, multiple regression analysis shows that  $<0.2 \mu\text{m}$  material is the only variable of consequence, when considered simultaneously with six other basic compositional properties used to assess variation in yield of the Rosalind bentonites.

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**Résumé**—Deux dépôts de bentonite d'une épaisseur moyenne de 10 et 4 pieds sont visibles à l'intérieur de stratifications non marines du crétacé supérieur, le long de la Battle River près de Rosalind, Alberta. Ils sont caractérisés par la rareté du matériel  $>44 \mu\text{m}$  et des teneurs variables en matériels  $44\text{--}2 \mu\text{m}$  et  $<2 \mu\text{m}$ . Le matériel  $>44 \mu\text{m}$  présent à une concentration supérieure à 2 pour cent est principalement attribuable à une calcite secondaire et la teneur en matériel  $<2 \mu\text{m}$  peut être reliée à la quantité de matériel  $44\text{--}2 \mu\text{m}$  qui a été altéré en montmorillonite par diagenèse à partir d'un verre volcanique. La cendre initiale avait probablement la composition d'une rhyodacite; de la sorte, la teneur élevée en fer dans l'un des dépôts est probablement due à la diagenèse. L'effet de blocage des sites d'échange par le fer peut expliquer les différences en Na et Ca échangeables dans les différents dépôts. La teneur élevée en Na échangeable trouvée dans les fractions granulométriques les plus fines de l'argile, peut être expliquée par une pureté accrue de la bentonite.

L'analyse de régression multiple des résultats analytiques montre que 48 pour cent de la variation du rendement (bbl/T.) en boue de forage à 15 centipoises, peuvent être attribués à la variation concomitante de sept facteurs intercorrélés affectant la composition. L'analyse séquentielle montre que la teneur en argile  $<0,2 \mu\text{m}$  contribue le plus fortement à la variation du rendement. Les autres variables (teneur totale en argile, Na échangeable, Ca + Mg échangeables, teneurs en  $\text{Fe}^{2+}$  et  $\text{Fe}^{3+}$  et CEC) contribuent légèrement à améliorer la précision de l'analyse de régression quand la teneur en argile  $<0,2 \mu\text{m}$  est incluse dans l'équation.

**Kurzreferat**—Zwei Bentonitlagerstätten mit einer durchschnittlichen Mächtigkeit von 3 und 1,2 m sind entlang dem Battle-Fluß in der Nähe von Rosalind, Alberta, innerhalb nichtmariner Schichten der Oberkreide aufgeschlossen. Sie sind durch Armut an Material  $>44 \mu\text{m}$  und wechselnde Gehalte an den Fraktionen  $44\text{--}2 \mu\text{m}$  und  $<2 \mu\text{m}$  gekennzeichnet. Das Material  $>44 \mu\text{m}$  ist, soweit die Gehalte 2 Prozent übersteigen, in erster Linie auf sekundären Calcit zurückzuführen. Die Fraktion  $<2 \mu\text{m}$  steht mit der Menge der Fraktion  $44\text{--}2 \mu\text{m}$ , die diagenetisch aus vulkanischem Glas zu Montmorillonit umgewandelt wurde, in Beziehung. Die mutmaßliche Zusammensetzung der ursprünglichen Asche bestand aus Rhyodacit. Der hohe Eisengehalt in einer Lagerstätte ist daher wahrscheinlich durch Diagenese bedingt. Die blockierende Wirkung des Eisens auf die Austauschplätze vermag die Unterschiede im austauschbaren Na und Ca in den verschiedenen Lagerstätten zu erklären. Die in feineren Korngrößenunterteilungen des fraktionierten Tones ermittelten hohen Gehalte an austauschbarem Natrium können durch zunehmende Reinheit des Bentonits erklärt werden.

Die multiple Regressionsanalyse der analytischen Daten zeigt, daß 48 Prozent der Varianz des Ertrages (bbl/T) einer Bohrflüssigkeit von 15 Centipoise der gleichzeitigen Varianz von sieben in Wechselbeziehung stehenden, die Zusammensetzung betreffenden Eigenschaften zugeschrieben werden kann. Die Sequenzanalyse zeigt, daß der Gehalt von Ton  $< 0,2 \mu\text{m}$  die wichtigste Bestimmungsgröße der Ertragsvarianz darstellt. Die verbleibenden Variablen (Gesamttongehalt, austauschbares Na, austauschbares Ca + Mg,  $\text{Fe}^{2+}$ - und  $\text{Fe}^{3+}$ -Gehalt und Austauschkapazität) tragen wenig zur zusätzlichen Genauigkeit der Regressionsanalyse bei, wenn der Gehalt an Ton  $< 0,2 \mu\text{m}$  in die Gleichung einbezogen wird.

**Резюме** — В Альберте по реке Баттл около Розалинда имеется два обнаженных месторождения бентонита, неморского отложения позднего мелового периода, средней толщиной 10 и 4 фута. Они характеризуются недостатком вещества  $44\text{--}2 \mu\text{m}$  и  $< 2 \mu\text{m}$ . Более двух процентов вещества размером  $> 44 \mu\text{m}$  прежде всего приписывается кальциту наносного происхождения, а содержание  $< 2 \mu\text{m}$  может быть отнесено к веществу  $44\text{--}2 \mu\text{m}$ , которое диагенетически изменялось из вулканического стекла в монтмориллонит. Составом материнского пепла, вероятно, был риодацит; высокое содержание железа в одном из залежей по всей вероятности является результатом диагенеза. Эффект торможения производимый железом на местоположения обмена, объясняет разницу в обменных Na и Ca в различных отложениях. Высокообменный Nd, найденный во фракциях глины можно приписать чистоте бентонита.

Рассмотрение данных множественной регрессии показало, что сорок восемь процентов в выходе (bbl/T) можно отнести к сопровождающему изменению связанных между собой свойств смеси. Последующий анализ выявил, что  $< 0,2 \mu\text{m}$  содержания глины является самым важным вкладчиком в изменение выхода. Остальные переменные (общее содержание глины, обменный Na, содержание обменных Ca + Mg,  $\text{Fe}^{2+}$  и  $\text{Fe}^{3+}$ , и С.Е.С.) не вносят добавочную точность к анализу регрессии, если  $< 0,2 \mu\text{m}$  содержания глины включается в уравнение.