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CRITERIA FOR DIFFERENTIATING THE McMURRAY AND CLEARWATER FORMATIONS IN THE ATHABASCA OIL SANDS

by

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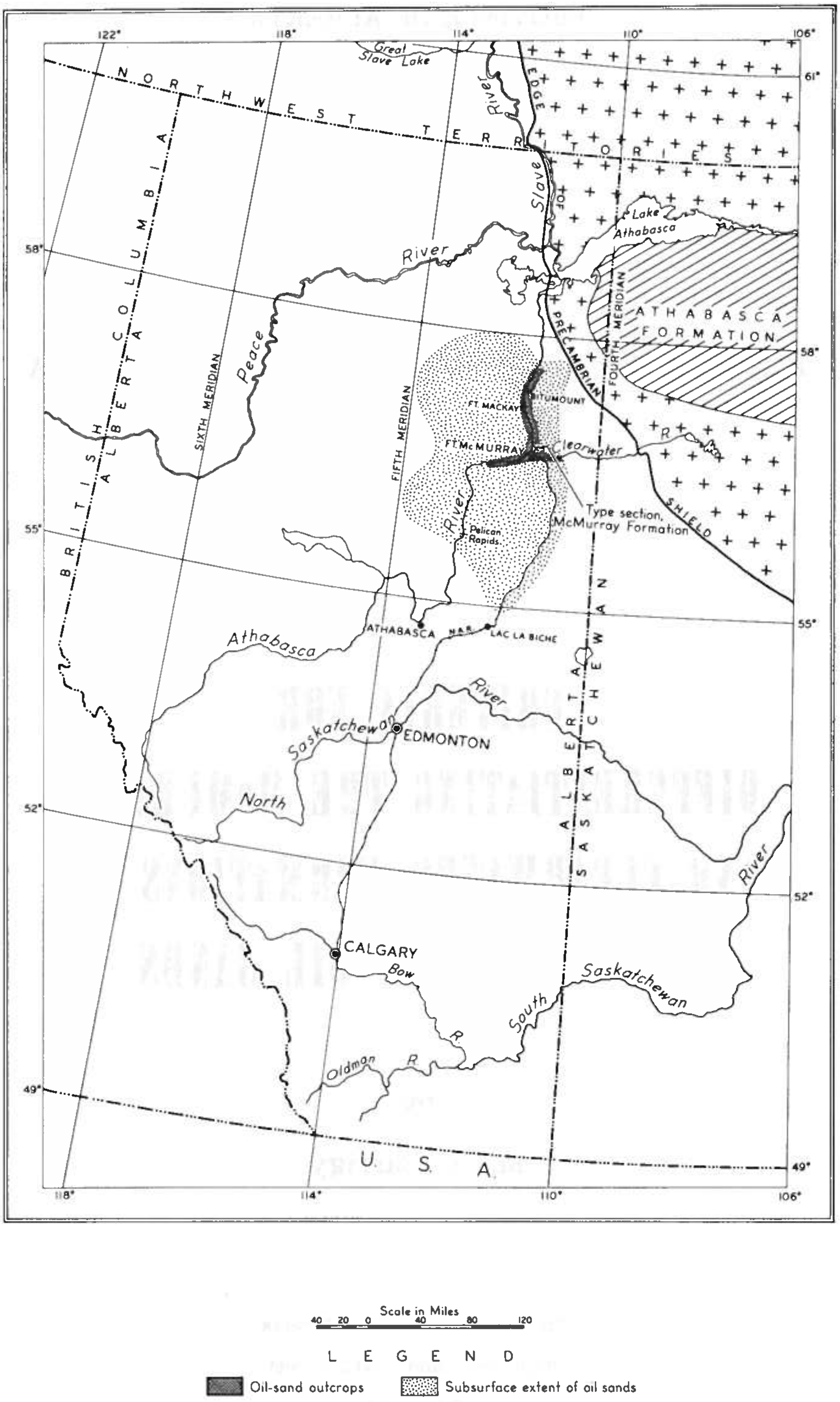

FIGURE 1. Index map showing the location of the Athabasca Oil Sands.

Criteria for Differentiating the McMurray and Clearwater Formations in the Athabasca Oil Sands

ABSTRACT

In the absence of fossil evidence the presence of the following minerals in sample of Athabasca oil sand identifies it as belonging to the Clearwater Formation: (1) glauconite pellets, (2) euhedral biotite flakes, (3) montmorillonite, (4) euhedral grains of plagioclase feldspar. Other diagnostic characteristics of the oil sands of this formation include the presence of felsite grains and of more than 10 per cent of chert grains in the sand fraction.

INTRODUCTION

Scope of the Report

Until recently it was believed that the heavy-oil impregnation in the lower Athabasca River area was confined to the McMurray Formation, although as early as 1897 a well drilled by the Geological Survey of Canada at Pelican Rapids, 80 miles southwest of the town of Fort McMurray, encountered heavy oil similar to that found in the McMurray Formation in the stratigraphically higher beds of the Grand Rapids and Clearwater Formations (Dowling *et al.*, 1919). However, no outcrops showing oil impregnation in these formations have been found, and none of the test holes drilled in the Athabasca River Valley adjacent to the oil-sand outcrops prior to 1958 had encountered any significant quantities of oil above the McMurray-Clearwater contact.

In 1958, in several wells drilled to the west of the outcrops on the Athabasca River, core samples were recovered from thick beds of oil-impregnated sediments in and above the glauconite sands of the basal Clearwater Formation. As all of the oil sands have the same megascopic appearance it seemed desirable to determine whether they could be distinguished on the basis of their petrographic properties. If some reliable criteria could be found for distinguishing between oil-impregnated sands of the McMurray and Clearwater Formations, then the relationships between oil impregnation and the sedimentary, stratigraphic and structural factors of the sands could be evaluated more readily (Carrigy and Zamora 1960, p.44).

To solve this problem a detailed investigation of the mineral composition and microfossil content of outcrop and core samples from above and below the assumed McMurray-Clearwater boundary was undertaken by the writer. The results of this study are embodied in this report.

Definition and Location of the Athabasca Oil Sands

The Athabasca Oil Sands as defined by Carrigy and Zamora (1960, p.44) include the oil-impregnated portions of the Lower Cretaceous strata found in northeastern Alberta in the lower Athabasca River area. They take their name from the steep, oil-soaked cliffs of the McMurray Formation found in the valleys of the Athabasca River and its tributaries in the vicinity of the town of Fort McMurray. In the subsurface these oil sands underlie an area of about 20,000 square miles, extending from latitudes 55 to 58 degrees north between the Fourth and Fifth Meridians (Fig. 1).

Acknowledgments

The writer is indebted to the Pan American Petroleum Corporation for granting him permission to publish the data on the Honolulu Union House River Well 6-25-81-13W4. The cores from the other wells were made available to the Research Council under the terms of the regulations governing the disposition of bituminous sands rights of the Mines and Minerals Act.

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[1] Name officially changed from McMurray in 1962.

STRATIGRAPHY AND STRUCTURE

Stratigraphy

Northeastern Alberta is underlain by rocks of Precambrian, Paleozoic and Mesozoic ages. The lower Cretaceous rocks are divisible into five formations with an average aggregate thickness of 900 feet (Table 1).

Table 1. Post-Paleozoic Formations in the Vicinity of Fort McMurray

System		Rock unit	Lithology
Quaternary			Loose gravel, sand and silt
		Unconformity	
Cretaceous		La Biche Fm.	Shale
		Pelican Fm.	Sandstone
		Joli Fou Fm.	Shale
	Mannville Group	Grand Rapids Fm.	Sandstone, siltstone
		Clearwater Fm.	Shale, siltstone
		Wabiskaw Mbr.	Sandstone, glauconitic
		McMurray Fm.	Sandstone, siltstone and shale
		Unconformity	
Devonian		Beaverhill Lake Fm. and others	Limestone, argillaceous limestone

The basal Cretaceous strata are composed mainly of lenticular beds of conglomerate, sand and silt, filling depressions on a pre-Cretaceous landscape developed on Paleozoic carbonates. These basal beds are called the McMurray Formation and are correlated with the basal quartz sands of the Mannville Group beneath the plains of central Alberta. They are believed to be fresh-water deposits, and in many areas they are impregnated with oil. The marine sands and shales of the Clearwater Formation overlie the McMurray Formation. The basal sand member of this formation is an argillaceous glauconitic sand called the Wabiskaw Member by Badgley (1952), and it is this sand or its equivalent that is impregnated with oil in the core samples of the Clearwater Formation described below.

The Clearwater Formation is overlain by the Grand Rapids Formation of sands and silts which in turn are overlain by the Joli Fou Shale and the Pelican Sandstone. These strata are thought to be dominantly of Albian age (Mellon and Wall, 1956).

The Upper Cretaceous beds in this area consist of the shales of the La Biche Formation which has a thickness of up to 1,000 feet beneath the highest hills.

Erosional activity in Tertiary times removed much of the Cretaceous cover, and in parts of the lower Athabasca River drainage system Paleozoic limestones and dolomites were exposed. During the retreat of the Pleistocene continental ice-sheet, a layer of drift of varying thickness was deposited over the Tertiary erosion surface. Recent erosion is now exhuming the preglacial landscape.

Structure

The Athabasca Oil Sands are located near the eastern rim of the Alberta syncline and have a slight regional dip to the southwest at a rate of about 10 feet to the mile. There is no evidence of tectonic disturbance in the Cretaceous strata; local domes and depressions superimposed on the regional slope in the oil-sands area are attributed to deformation caused by solution of underlying evaporite beds (Carrigy, 1959).

DISPOSITION OF SAMPLES

This report is based on the analysis of 114 samples: 99 of these were core samples from six wells and 15 were from five outcrops — 30 of the core samples contained microfossils or were stratigraphically above samples containing marine fossils and were thus reliably identified as Clearwater Formation samples. From these samples together with 4 outcrop samples of glauconitic sand the characteristic mineral composition of this formation was established.

Nine samples containing small quantities of glauconite pellets were taken from a 25-foot interval below the first marine fossils in two of the wells (Figs. 2 and 3). This interval has tentatively been called a "transition zone". Of the remaining samples, 65 were from the McMurray Formation: 11 from the type section outcrop and 54 from cores. The remaining 6 samples analyzed were from the Paleozoic limestone beneath the oil sands. Graphic logs of the wells and the locations of the core samples are shown in figures 2 and 3.

DESCRIPTIONS OF SECTIONS SAMPLED

Outcrops

In the Athabasca River Valley no difficulty is experienced in defining the upper boundary of the McMurray Formation as it coincides with the division between oil-impregnated and barren sands. The barren green sand bed of the lower Clearwater Formation is easily identified, and mineralogical analyses of samples collected from the outcrops of this bed are given in table 2.

Type Section of the McMurray Formation

The type section is located on the east bank of the Athabasca River about 3 miles north of Fort McMurray and was described by Carrigy (1959, p.39). It consists of 237 feet of rich oil sand and, unlike the cores from the wells to the west of the Athabasca River, is composed of dominantly sand-size sediment. Cross-stratification is well developed in the basal 45 feet; the middle 147 feet is massive oil sand, and the upper 45 feet of sediment is horizontally bedded oil sand interbedded with thin beds of ironstone, the top 12 feet or so being an oil-impregnated silt.

Above the type section of the McMurray Formation 26 feet of Clearwater Formation strata are exposed. The basal unit is a 15-foot bed of uncemented, green, salt and pepper sand including several ironstone bands about 1 foot in thickness. The remaining 11 feet exposed are shale.

Samples were collected at intervals throughout the type section of the McMurray Formation and the results of the petrographical analyses are given in table 3.

Wells

Socony-Vacuum Exploration Company Hole No. 27

A 220-foot interval was cored in this well. There is no oil impregnation in the Clearwater Formation, and no difficulty was experienced in distinguishing between the McMurray and Clearwater Formations from a megascopic examination of the core. The boundary between the formations was placed at the base of a conspicuous bed of green silty sand similar in appearance to that found in the outcrops of the basal Clearwater Formation. The 194 feet of core below this bed belong to the McMurray Formation and these comprise 174 feet of grey silt with many interbedded lenses of oil sand — most of which are less than 1 foot in thickness — and numerous thin hard beds of siderite-cemented sandstone and siltstone. These silt beds are overlain by 20 feet of grey clayey silt with some oil staining and contain-

Table 2. Petrologic Data for Outcrop Samples of the Lower Clearwater Formation

SAMPLE NO.	LOCATION	TEXTURAL CLASSIFICATION	SIZE		LIGHT MINERALS * (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns							CLAY MINERALS Size <4 microns				
			Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments †	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
346	Type Section, Sec. 5, Tp. 90, R. 9	Silty sand	76	6	49	20	2	12	x	x	x	—	x	x	x	x	x	x	x	x
347	Lot 1, McMurray townsite	Silty sand	78	19.1	49	15	—	23	x	x	x	x	x	x	x	x	—	x	—	—
348	Sec. 12, Tp. 92, R. 10	Sand silt clay	72	16.4	45	18	1	24	x	x	x	x	—	x	x	x	x	x	x	x
349	Sec. 17, Tp. 91, R. 9	Silty sand	76	14.3	47	13	3	22	x	x	x	x	x	x	x	x	x	x	x	x

* Figures indicate frequency percentages of grains greater than 62 microns in size.

† Mainly chert plus a small number of felsite grains.

Table 3. Petrologic Data for the Type Section of the McMurray Formation.

Location: Sec. 5, Tp. 90, R. 9, W. 4th Meridian

			SIZE		LIGHT MINERALS* (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns								CLAY MINERALS Size <4 microns			
SAMPLE No.	ELEVATION IN FEET (above m.s.l.) approx.	TEXTURAL CLASSIFICATION	Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
520	1030	Sand	125	3.4	93	—	2	—	x	x	x	x	x	x	—	—	—	x	x	—
521	1016	Sand	135	1.9	94	—	3	—	x	x	x	x	x	x	—	—	—	x	x	—
522	1006	Sand	110	0.4	95	1	3	—	x	x	x	x	x	x	x	—	—	x	x	?
523	996	Sand	135	0.6	94	—	4	—	x	x	x	x	x	x	—	—	—	x	x	—
524	973	Sand	112	0.4	97	—	2	—	x	x	x	x	x	x	—	—	—	x	x	?
525	956	Sand	115	0.8	97	—	2	—	x	x	x	x	x	x	—	—	—	x	x	—
526	936	Sand	105	2.1	95	—	4	—	x	x	x	x	x	x	—	—	—	x	x	—
527	916	Sand	120	1.3	94	—	4	—	x	x	x	x	x	x	—	—	—	x	x	—
528	886	Sand	125	0.2	93	1	4	—	x	x	x	x	x	x	x	—	—	x	x	?
529	866	Sand	160	0.1	99	—	1	—	x	x	x	x	x	x	—	x	—	x	x	?
530	838	Sandy silt	45	7.5	92	1	3	—	x	x	x	x	x	x	x	—	—	x	x	—

* Frequency percentage or grains greater than 62 microns in size.

ing arenaceous foraminifera (Mellon and Wall, 1956). The basal Clearwater sand bed is 8 feet in thickness and contains many glauconite pellets. It is overlain by a grey waxy shale containing a calcareous suite of foraminifera. The results of the petrographic analyses for this well are given in table 4.

Richfield Oil Corporation Brulé Rapids No. 1 Well

In this well, oil-saturated sands and silts of McMurray Formation aspect are found in the core some 60 feet above the lower boundary of the Clearwater Formation, which is placed at the base of the green sand bed 60 feet above the Devonian limestone. Overlying the limestone is a 48-foot bed of silt with oil-sand lenses, which would on megascopic appearances be assigned to the McMurray Formation; however, the petrologic data (Table 5, samples 432-434) indicate that the upper 12 feet of the strata have mineralogic affinities with the Clearwater Formation. Thus, there are 25 feet of oil-stained silt or grey laminated silt core in this well (Table 5, samples 430-434) beneath the green sand, which cannot be assigned definitely to either the McMurray or Clearwater Formation, and these have been called "transition beds" in the subsequent discussion.

Richfield Oil Corporation Telegraph No. 1 Well

Core was cut over a 62-foot interval in this well, and on the basis of megascopic examination no boundary could be drawn between Clearwater and McMurray Formations. A silty sand (Table 6, sample 444) containing glauconite pellets was oil saturated and the glauconite was not recognized until the sand had been cleaned. The petrologic data (Table 6) indicate that this bed is some 26 feet above the first appearance of glauconite and montmorillonite in the sediments, and this fact together with the microfossil evidence (Fig. 3) indicated that the boundary between the two formations should be placed at the base of the grey waxy shale bed between samples 448 and 449, 25 feet above the Devonian limestone. On this basis the lower 25 feet of core of oil-impregnated silt in this well belong in the McMurray Formation, and the upper 30 feet of shales, oil-stained silts and oil sands are part of the Clearwater Formation.

Richfield Oil Corporation Buffalo Creek No. 2 Well

On megascopic examination of the core, the boundary between the McMurray and Clearwater Formations was placed at the base of the lowest bed of green silty sand 46 feet above the base of the McMurray Formation; oil-impregnated sands and silt beds are present above and below this boundary. The shale beds above this boundary carry marine microfossils including sponge spicules and calcareous foraminifera. However, on the basis of the petrologic characteristics it would be best to place the lower boundary of

Table 4. Petrologic Data for Socony-Vacuum Exploration Company Hole No. 27.

Location: Lsd. 7, Sec. 27, Tp. 91, R. 10, W. 4th Meridian
Ground Elevation: 1061 feet Total Depth: 296 feet

				SIZE		LIGHT MINERALS* (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns								CLAY MINERALS Size <4 microns			
FORMATION	SAMPLE No.	DEPTH IN FEET	TEXTURAL CLASSIFICATION	Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
Clearwater	365	81	Silty clay	<2	52.8	30	34	7	—	†—	—	—	—	—	—	—	—	x	x	x	—
	366	91	Sand silt clay	3	42.0	49	20	—	27	x	x	x	—	x	—	x	x	x	x	?	x
	367	98	Silty sand	72	23.0	47	20	2	26	x	x	x	—	x	x	x	x	x	x	?	x
	368	105	Clayey silt	9	19.5	58	17	3	7	†—	—	—	—	—	—	—	—	x	x	x	?
McMurray	369	118	Clayey silt	10	25.0	85	8	4	—	x	x	x	x	x	x	—	—	—	x	x	—
	370	128	Sandy silt	21	14.0	92	1	4	—	x	x	x	x	—	x	x	—	—	x	x	—
	371	145	Clayey silt	15	14.5	94	2	3	—	x	x	x	x	x	x	x	—	—	x	x	—
	372	169	Sandy silt	22	12.0	94	2	3	—	x	x	x	x	x	x	x	—	—	x	x	—
	373	209	Clayey silt	11	22.0	91	3	3	—	x	x	x	x	x	x	x	—	—	x	x	—
	374	238	Clayey silt	8	25.0	91	2	4	—	x	x	x	x	—	x	—	—	—	x	x	—
	375	255	Clayey silt	9	29.0	88	3	4	—	x	x	x	—	x	x	x	—	—	x	x	—
	376	291	Clayey silt	11	28.0	87	1	—	—	**x	x	—	—	—	x	x	—	—	x	x	—

* Figures indicate frequency percentages of grains greater than 62 microns in size.
† Iron sulfide coating on grains.
** Iron oxide and iron carbonate coatings on grains.

Table 5. Petrologic Data for Richfield Oil Corporation Brulé Rapids No. 1 Well.

Location: Lsd. 7, Sec. 28, Tp. 88, R. 16, W. 4th Meridian
Ground Elevation: 1757 feet Total depth: 3028 feet
K. B. Elevation: 1766 feet

FORMATION	SAMPLE No.	DEPTH IN FEET	TEXTURAL CLASSIFICATION	SIZE		LIGHT MINERALS* (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns								CLAY MINERALS Size <4 microns			
				Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
Clearwater	419	733	Sand	140	9.3	63	15	1	13	x	x	x	x	x	x	x	—	—	x	x	x
	420	738	Sand	130	4.4	62	21	—	12	x	x	x	x	x	x	—	x	—	x	x	x
	421	743	Silty sand	120	8.0	53	28	1	10	x	—	x	x	—	—	—	—	x	x	x	—
	422	746	Sand silt clay	9	33.6	60	27	3	6	x	x	x	x	x	x	x	x	x	x	x	—
	423	748	Silty sand	96	8.1	50	27	1	16	x	x	x	—	x	x	x	x	x	x	x	—
	424	760	Silty sand	85	15.4	47	28	3	16	x	—	x	x	x	x	x	x	x	x	x	?
	426	768	Silty clay	3	42.1	57	20	2	7	† —	—	x	x	—	—	—	—	x	x	x	—
	427	773	Silty clay	2	49.2	52	23	6	10	x	—	x	—	—	—	—	—	x	x	x	?
	428	781	Silty sand	72	14.4	53	23	1	14	x	x	x	x	x	x	x	x	x	x	x	?
	429	786	Sand	110	4.8	72	11	3	7	‡ x	x	x	x	x	x	x	—	x	x	x	x
McMurray	430	791	Sand	110	5.0	81	7	2	5	x	x	x	x	x	x	x	—	—	x	x	x
	431	796	Silty sand	72	7.3	81	6	2	5	x	x	x	x	x	x	x	—	—	x	x	x
	432	800	Silty sand	100	6.1	85	4	5	1	x	x	x	x	x	x	x	—	—	x	x	—
	433	805	Sandy silt	53	6.8	90	2	7	1	x	x	—	—	x	x	x	—	—	x	x	?
	434	810	Clayey silt	21	14.4	86	2	3	1	x	x	x	x	x	x	x	—	—	x	x	x
	435	816	Silt	16	10.9	92	2	5	—	x	x	x	—	x	x	x	x	—	x	x	—
	436	818	Sand silt clay	16	17.6	88	3	4	—	x	x	x	x	x	x	x	x	—	x	x	—
	437	823	Clayey silt	11	21.1	86	3	8	—	‡ x	x	x	x	—	x	x	—	—	x	x	—
	438	827	Silt	22	3.4	89	4	5	—	x	x	x	x	x	x	x	—	—	x	x	—
	439	837	Sandy silt	40	4.9	89	1	7	—	x	—	x	x	x	x	x	x	—	x	x	—
	440	842	Silt	33	6.3	91	10	5	<1	x	x	x	x	x	x	x	x	—	x	x	—
	441	847	Limestone	—	—	41	14	4	—	† —	—	—	—	—	—	—	—				
	442	849	Limestone	—	—	14	30	1	—	—	x	—	—	—	—	—	—				

* Figures indicate frequency percentages of grains greater than 62 microns in size. † Iron sulfide coating on grains. ‡ Iron oxide coating on grains.

Table 6. Petrologic Data for Richfield Oil Corporation Telegraph No. 1 Well.

Location: Lsd. 10, Sec. 12, Tp. 85, R. 14, W. 4th Meridian
Ground Elevation: 1850 feet **Total Depth:** 3141 feet
K.B. Elevation: 1861 feet

FORMATION	SAMPLE No.	DEPTH IN FEET	TEXTURAL CLASSIFICATION	SIZE		LIGHT MINERALS* (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns								CLAY MINERALS Size <4 microns			
				Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
Clearwater	443	746	Silty clay	<2	58.6	—	—	—	—	†—	—	—	—	—	—	—	—	x	x	x	—
	444	748	Silty sand	86	9.1	52	17	—	18	† x	x	x	x	x	x	x	x	x	x	x	x
	445	753	Sand	130	3.8	69	15	3	3	x	x	x	x	x	x	x	x	x	x	x	?
	446	764	Silty sand	120	3.6	67	14	2	7	x	x	x	x	x	x	x	x	—	x	x	x
	447	768	Clay	<2	69.0	80	12	3	4	x	x	x	x	x	x	—	x	x	x	x	—
	448	773	Silty clay	3	44.0	90	7	1	1	x	x	x	x	x	x	x	—	x	x	x	—
McMurray	449	780	Silt	27	7.5	55	5	2	—	†‡ x	—	—	—	—	x	x	—	—	x	x	?
	450	782	Silt	22	16.7	84	7	4	—	‡ x	—	—	x	—	x	x	—	—	x	x	—
	451	786	Clayey silt	13	24.2	50	3	5	—	†‡—	—	—	—	—	x	x	—	—	x	x	—
	452	788	Clayey silt	6	26.0	79	9	3	tr	x	x	x	x	x	x	x	—	—	x	x	—
	453	801	Clayey silt	12	26.0	94	4	1	—	x	x	—	x	—	x	x	—	—	x	x	—
	454	802	Limestone	—	—	48	14	9	—	—	—	x	—	—	x	—	—	—	x	x	—
	455	807	Limestone	—	—	24	7	10	—	†—	x	x	—	—	x	—	—	—	x	—	—

* Figures indicate frequency percentages of grains greater than 62 microns in size.
† Iron sulfide coating on grains.
‡ Iron oxide coating on grains.

the Clearwater Formation about 12 feet higher, at the top of the uppermost green silty sand bed (Table 7, sample 459), and the upper boundary of the McMurray Formation some 12 feet below the green sand, where the first glauconite pellets appear in samples of silt (Table 7, sample 463). It was therefore decided to draw the boundary on figure 3 at the base of the green sand bed and to consider the 12 feet of strata below and the 12 feet of strata above as "transition beds". Thus, the core is divisible into three parts — the lower 34 feet of McMurray Formation sediment, the middle 24 feet of "transition beds" and the upper 32 feet of Clearwater Formation sediment.

Richfield Oil Corporation MacKay River No. 2 Well

In this well the glauconite sands are impregnated with oil and are thus difficult to recognize megascopically without first extracting the oil. The position of the lower boundary of the Clearwater Formation based on the micro-fossil evidence is at the base of a 10-foot bed of grey waxy shale 95 feet above the Paleozoic limestone. Core above this boundary include two beds of rich oil sand, 10 and 11 feet thick. The mineralogic composition of the sand fraction of these beds is different to that of the oil-impregnated sands and silts of the McMurray Formation below (Table 8).

Honolulu Union House River 6-25-81-13W4 Well

All core in this well was taken in the McMurray Formation. This core was sampled at 10-foot intervals, and the results of the examination are presented in table 9.

Table 7. Petrologic Data for Richfield Oil Corporation Buffalo Creek No. 2 Well.

Location: Lsd. 6, Sec. 8, Tp. 88, R. 17, W. 4th Meridian
Ground Elevation: 1672 feet **Total Depth:** 777 feet
K. B. Elevation: 1684 feet

FORMATION	SAMPLE No.	DEPTH IN FEET	TEXTURAL CLASSIFICATION	SIZE		LIGHT MINERALS* (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns								CLAY MINERALS Size <4 microns			
				Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
Clear-water	456	695	Silty sand	95	6.5	47	32	2	13	x	x	x	x	—	x	x	—	—	x	x	—
	457	700	Clayey silt	6	34.2	38	34	3	5	†—	—	—	—	—	—	—	—	x	x	x	?
	458	705	Silty clay	<2	50.6	15	28	1	5	†—	—	—	—	—	—	x	—	x	x	x	—
	459	710	Silty clay	3.4	36.0	43	22	3	9	† x	—	x	—	—	x	—	—	x	x	x	—
	460	719	Silty sand	80.0	0.7	71	10	2	5	x	x	x	x	x	—	—	—	—	x	x	—
	461	723	Sand	100.0	0.8	88	8	—	1	x	x	x	x	—	x	—	—	—	x	x	—
	462	730	Silty sand	80.0	6.3	82	8	3	5	x	x	x	x	—	x	—	—	—	x	x	—
	463	735	Sand	88	1.5	86	6	2	3	x	x	x	x	x	—	—	—	—	x	x	—
McMurray	464	742	Silt	29	2.3	87	6	4	—	†—	—	—	—	—	—	—	—	—	x	x	—
	465	745	Silt	22	8.5	82	5	1	—	† x	x	—	—	—	—	—	—	—	x	x	—
	466	747	Silt	21	9.6	89	3	1	—	† x	x	—	x	x	—	x	—	—	x	x	—
	467	753	Clayey silt	11	21.0	—	—	—	—	†—	—	—	—	—	—	—	—	—	x	x	—
	468	760	Clayey silt	13	28.0	97	1	—	—	x	x	x	—	x	—	—	—	—	x	x	?
	470	765	Silty clay	<2	60.6	‡—	—	—	—	† x	x	—	—	x	—	—	—	—	—	x	?
	471	770	Clayey silt	21	17.4	96	2	—	—	x	x	x	x	x	—	—	—	—	—	x	?

* Figures indicate frequency percentages of grains greater than 62 microns in size.
‡ Mainly carbonaceous material.
† Iron sulfide coating on grains.

Table 8. Petrologic Data for Richfield Oil Corporation MacKay River No. 2 Well.

Location: Lsd. 15, Sec. 33, Tp. 89, R. 16, W. 4th Meridian
Ground Elevation: 1579 feet   **Total Depth:** 775 feet
K. B. Elevation: 1589 feet

				SIZE		LIGHT MINERALS* (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns								CLAY MINERALS Size <4 microns			
FORMATION	SAMPLE No.	DEPTH IN FEET	TEXTURAL CLASSIFICATION	Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
Clearwater	475	580	Sand	115	4.1	64	23	—	6	† x	x	x	—	x	—	x	—	—	x	x	—
	476	590	Sand silt clay	82	19.8	57	27	—	9	x	x	x	x	x	x	x	x	x	x	x	—
	477	600	Clay	<2	85.0	61	21	—	10	† x	—	x	—	—	x	x	—	x	—	—	—
	478	610	Clayey silt	26	26.6	47	15	5	9	‡ —	—	—	—	—	—	x	x	x	x	x	—
	479	620	Silty sand	63	9.5	67	14	3	7	x	x	x	x	x	x	x	x	x	x	x	—
	480	630	Silty clay	<2	65.0	60	21	2	5	† x	x	x	x	x	x	x	x	x	x	x	—
McMurray	481	640	Sandy silt	45	3.5	80	8	4	—	† x	—	—	x	—	x	x	—	—	x	x	—
	482	648	Silt	37	6.4	85	3	5	—	x	x	x	x	x	x	x	—	—	x	x	—
	483	666	Sand	100	1.2	92	1	7	—	x	x	x	x	x	x	x	—	—	x	x	—
	484	677	Silt	14	12.3	92	2	4	—	** x	—	—	—	x	x	—	—	—	x	x	—
	485	687	Silt	12	10.4	99	1	—	—	‡								—	x	x	—
	486	700	Clayey silt	7	22.8	91	4	2	—	‡ x	x	—	—	—	—	x	—	—	x	x	—
	487	710	Clayey silt	8	24.0	77	2	3	—	‡ x	—	—	—	—	x	—	—				
	488	718	Silty clay	4	42.5	99	—	—	—	x	x	—	x	x	x	—	—	—	x	x	—
	489	727	Silty limestone	—	—	—	—	—	—	††								—	—	x	x?
	490	730	Limestone	—	—	—	—	—	—	††								—	—	x	x?

* Figures indicate frequency percentages of grains greater than 62 microns in size.
† Iron sulfide coating on grains.
** Iron oxide coating on grains
‡ Iron carbonate (?) coating or grains.
†† Grains too fine for microscopic identification.

Table 9. Petrologic Data for Honolulu Union House River Well.

Location: Lsd. 6, Sec. 25, Tp. 81, R. 13, W. 4th Meridian
Ground Elevation: 2338 feet **Total Depth:** 2347 feet
K. B. Elevation: 2346 feet

				SIZE		LIGHT MINERALS* (S.G. <2.95)				NONOPAQUE HEAVY MINERALS (S.G. >2.95) Size >62 microns								CLAY MINERALS Size <4 microns			
FORMATION	SAMPLE No.	DEPTH IN FEET	TEXTURAL CLASSIFICATION	Median diameter in microns	Weight percentage of material <2 microns	Quartz	Cryptocrystalline rock fragments	Feldspar	Glauconite pellets	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Chloritoid	Chlorite	Biotite	Montmorillonite	Illite	Kaolinite	Chlorite
McMurray	496	1528	Silt	16	4.7	90	6	3	—	† x	x	—	x	x	—	—	—	—	x	x	—
	497	1536	Silty sand	77	1.7	85	4	8	—	x	x	x	x	x	x	x	x	—	x	x	—
	498	1546	Sandy silt	38	6.3	90	5	2	—	x	x	x	x	x	x	x	x	—	x	x	—
	499	1556	Silt	35	7.7	91	6	2	—	x	x	x	x	x	x	—	—	—	x	x	?
	500	1566	Silt	40	5.6	28	8	11	—	‡—	—	—	x	—	x	x	x	—	x	x	—
	501	1576	Sandy silt	33	10.9	80	5	8	—	x	x	x	x	x	x	x	x	—	x	x	—
	503	1586	Clayey silt	10	21.7	49	4	5	—	x	x	x	—	—	x	x	x	—	x	x	?
	504	1596	Clayey silt	10	19.7	22	8	4	tr	‡—	—	—	x	—	x	x	—	—	x	x	—
	505	1606	Silt	26	13.0	87	5	5	—	‡ x	x	—	x	x	x	x	—	—	x	x	?
	506	1616	Sandy silt	45	10.0	85	6	2	—	‡ x	x	x	x	x	x	x	—	—	x	x	—
	507	1626	Sand silt clay	31	14.8	92	3	3	—	x	x	x	x	x	x	x	—	—	x	x	—
	509	1636	Sand	105	1.4	94	2	3	—	—	x	x	x	x	x	x	—	x	x	x	—
	510	1646	Silty sand	101	8.7	94	1	2	—	x	x	x	x	x	x	x	—	?	x	x	—
	511	1656	Silt	28	13.6	**				x	x	—	—	x	x	—	x	—	x	x	—
	512	1666	Silt	27	17.6	**				x	x	x	x	—	x	—	x	?	x	x	?
	513	1676	Clayey silt	8	23.9	91	4	3	—	† x	—	—	—	—	x	—	—	—	x	x	?
	514	1686	Silty sand	66	5.4	94	—	1		† x	x	—	x	x	—	—	—	?	x	x	—
	515	1696	Silty sand	55	12.1	93	2	—	—	† x	x	—	x	x	—	—	—	—	x	x	?
	516	1706	Clayey silt	54	26.5	73	1	3	—	†—	x	—	—	—	—	—	—	—	x	x	?
	517	1716	Clayey silt	5	22.3	**				†—	x	—	—	—	—	—	—	—	x	x	?

* Figures indicate frequency percentages of grains greater than 62 microns in size.
† Iron sulfide coating on grains ** Not identifiable
‡ Iron oxide coating on grains.

MICROFOSSIL CONTENT

To aid in assigning core samples to their correct stratigraphic position each sample was checked for the presence of microfossils. Fortunately, microfossils were found in enough samples to provide an independent determination on the environment of deposition against which changes in mineral composition could be calibrated. The microfauna consisted of foraminifera (calcareous and arenaceous forms), sponge spicules and fish teeth, and the microflora included grains of pollen, spores, and hystrichospherids. The stratigraphic distribution of the microfossils in the core samples is illustrated on figures 2 and 3. The presence of foraminifera, sponge spicules or hystrichospherids in a sample is considered to be positive evidence that the sediment was deposited in a marine or brackish-water environment. In the transition zone below the marine microfossil markers, 9 samples were taken that had a mineralogical composition similar to that of the Clearwater Formation samples above the marker (Table 5, samples 430 to 434; Table 7, samples 460-463; and Figs. 2 and 3), but which were considered to be insufficiently well identified to be included with the Clearwater samples, and they thus have been placed in a third category of intermediate composition (see Fig. 9). Pollen grains, spores and a few fish teeth were found in the McMurray Formation samples by the writer. Previous work on the core of the Socony-Vacuum Exploration Company Hole No. 27 (Mellon and Wall, 1956) had shown the presence of arenaceous foraminifera in this core in the interval between samples 368 and 369.

MINERAL COMPOSITION

Preparation of Samples for Petrographic Analysis

Those portions of the samples larger than 62 microns were divided into light and heavy fractions by the use of a heavy liquid (tetrabromethane, S.G. 2.95). The light mineral grains were mounted in Canada balsam, and frequency percentages of the constituent minerals were determined as the slides were transversed on a mechanical stage under a petrographic microscope. The heavy minerals were mounted on a microscope slide in Aroclor cement; in each slide the seven nonopaque minerals characteristic of the McMurray Formation were counted as well as one nonopaque mineral believed by the writer to be characteristic of the Clearwater Formation.

The clay minerals were identified by X-ray powder methods on the fraction less than 4 microns in size. The portion of the samples less than 4 microns in size was sedimented on to a microscope slide as an oriented aggregate and the minerals were identified from the X-ray diffractograms of such slides after treatment with ethylene glycol and by heating at 550° C. for 30 minutes. The presence or absence of peaks corresponding to clay minerals of the montmorillonite, kaolinite, and chlorite groups was recorded for each sample.

The mineralogical data for samples from the six wells are presented in tables 4 to 9, those for the McMurray Formation type section in table 3, and those for outcrop samples of the Clearwater Formation in table 2.

Methods of Particle-size Measurement

The particle size-distributions of the sediments were determined by sieving and sedimentation down to a minimum size of 2 microns, at intervals corresponding to the Wentworth grade scale. The pipette method (Krumbein and Pettijohn, 1938) was used to obtain samples of the finer sizes during the sedimentation procedure. Cumulative weight-percentage curves were constructed, and from these the median sizes and the amount of clay-size material (less than 2 microns) was estimated for each sample (see Tables 2 to 9). Also, the percentages of sand, silt and clay were calculated and plotted as points on a ternary diagram (Fig. 7) to provide a consistent descriptive terminology and textural classification of the samples..

Descriptions of Mineral Constituents

Quartz and Quartzite

The quartz grains in both formations are mainly single crystals, but a few polycrystalline grains were observed in most samples. The grains commonly show signs of wear, but few are well rounded. The degree of rounding is mainly a function of size, the larger grains being more rounded than the smaller grains. Euthedral and abraded overgrowths are fairly common on grains from both formations. Quartz grains form up to 99 per cent of the sand-size fraction of the McMurray Formation samples. They are less abundant in the Clearwater Formation samples, exceeding 70 per cent of the sand-size fraction in only two. In the "transition bed" samples quartz forms between 71 and 90 per cent of the sand-size fraction.

Feldspars

The frequency of feldspar in the sand-size grains of the McMurray Formation rarely exceeds 10 per cent. The grains are commonly untwinned, unabraded cleavage fragments. Their low relief relative to Canada balsam makes them easy to recognize in the grain mounts. Many grains have cloudy patches of alteration products and serrated edges indicative of corrosion, whereas others appear to be fresh. Feldspars from a sample of the McMurray Formation-equivalent under the central Alberta plains have been dated by the potassium 40 : argon 40 isotope ratio method at 1,350 - 1,550 million years old by Williams *et al.* (1962), indicating derivation from a Precambrian source probably to the northeast of their present location.

In the sand-size material of the Clearwater Formation the feldspar grains have refractive indices less than that of Canada balsam. Most grains are untwinned although some show plagioclase twinning under polarized light and a few grains have a euhedral habit. The composition of the plagioclase feldspar thus must be near that of albite and possibly corresponds to that of a mixture of orthoclase and albite. The untwinned grains are

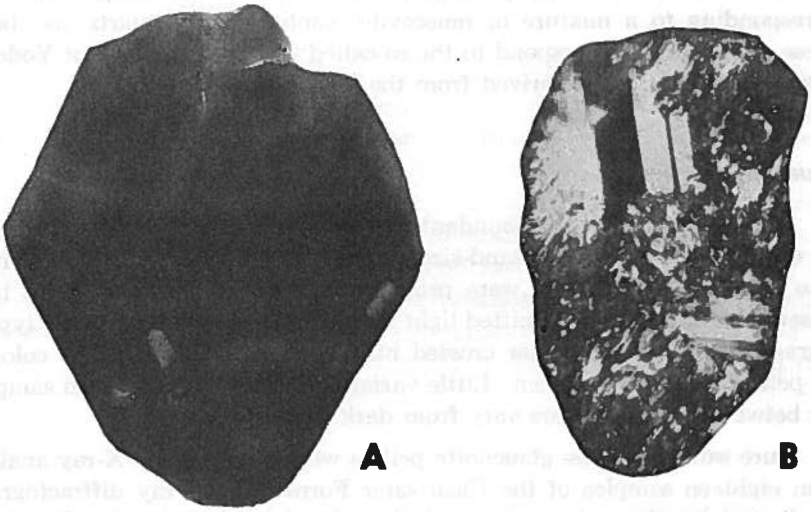

FIGURE 4.* *Photomicrographs of two diagnostic mineral grains of the Clearwater Formation.

A. Euhedral biotite flake: magnification 160X.

B. Volcanic grain from sample 346: crossed nicols, magnification 350X.

probably orthoclase although some are possibly sanidine. A clue to the origin of some of the feldspar in the Clearwater Formation was found in sample 346 (Table 2) taken from an outcrop of glauconite sand overlying the type section of the McMurray Formation on the Athabasca River (Sec. 5, Tp. 90, R. 9). In the light fraction of this sample, twinned feldspar phenocrysts were observed in a cryptocrystalline to glassy groundmass in one grain (Fig. 4), and a euhedral grain of faintly twinned plagioclase feldspar about 0.13 mm. in size was also observed. This grain had a refractive index of less than 1.54 and thus was probably albite of composition approximately Ab 80 : An 20. These grains are almost certainly of pyroclastic origin.

Potash feldspars are an important constituent of the insoluble residues of the Paleozoic limestones (Table 5, samples 441 and 442; Table 6, samples 454 and 455).

Mica-like Minerals

Minerals of micaceous habit form a small but ubiquitous fraction of the McMurray Formation sediments, the proportion of these flakes in the sand-size fraction increasing as the median grain-size decreases. Under a low-power stereomicroscope some of the grains appear to be flat transparent flakes and others books of wrinkled opaque plates with a pearly lustre.

An X-ray diffractogram of the micaceous minerals separated from one sample showed peaks corresponding to a mixture of 2 M muscovite, kaolinite, and quartz. The presence of kaolinite was confirmed by heat treatment. Some of the flakes with a pearly lustre were hand picked and mounted in a powder camera. The X-ray photographs obtained on this sample had lines corresponding to a mixture of muscovite, kaolinite, and quartz, as above. These flakes might correspond to the so-called "secondary mica" of Yoder & Eugster (1955, p. 250), derived from the weathering of feldspars.

Glauconite Pellets

Glauconite pellets are abundant in the Clearwater Formation, comprising up to 27 per cent of the sand-size grains in one sample. The pellets have been abraded (Fig. 5) and were probably transported by currents to their present locations. In transmitted light the pellets are green and show typical aggregate polarization under crossed nicols. In incident light the color of the pellets is an earthy green. Little variation in color exists within samples, but between samples colors vary from dark to bright green.

Pure samples of the glauconite pellets were obtained for X-ray analysis from eighteen samples of the Clearwater Formation. X-ray diffractograms of all samples show the asymmetrical peaks characteristic of a disordered mica-type lattice (Burst, 1958a, p. 312) which is similar to the IMd mica polymorph of Yoder and Eugster (1955). Hower (1961) attributed the apparent disorder observed in his X-ray diffractograms of glauconite to the presence of a high percentage of expandable layers in the structure and seems to believe that the ragged appearance of the peaks is due to orientation effects, although Burst (1958b, p. 487) specifically states that the estimates of order - disorder relationships are not significantly different regardless of which type of sample mount is used — oriented aggregate or random powder.

Two samples (346 and 420) of glauconite pellets were disaggregated in distilled water, and oriented mounts prepared on porous porcelain plates as suggested by Hower (1961, p. 314), for comparison with the patterns obtained from the cell mounts. These were X-rayed and the diffractograms produced were not noticeably different from those obtained previously from the powder in a cell mount. Treatment of these slides with ethylene glycol failed to detect the presence of any expandable layers. However, when the samples were leached with a 0.1 N potassium chloride solution the 10Å peak was sharpened noticeably although the 4.98Å peak remained asymmetrical as before. This result is taken to indicate that the interlayer spaces in the lattice were not fully occupied by potassium ions in the original material. Kaolinite peaks also were present in the diffractograms obtained from the pellets in sample 346.

The question of the origin of glauconite and its significance as an indicator of environment of deposition has been studied extensively, and a discussion of this problem is pertinent to the occurrence reported here. The literature on glauconite pellets was reviewed by Cloud (1955), and he concluded (p. 484) that glauconite was more useful as an indicator of the depositional environment than any of the other accessory minerals used for this purpose. Mineralogical studies by Burst (1958a, 1958b) and Hower (1961) have indicated that the process of glauconitization will proceed when three basic physicochemical requirements are satisfied. These are: (1) the

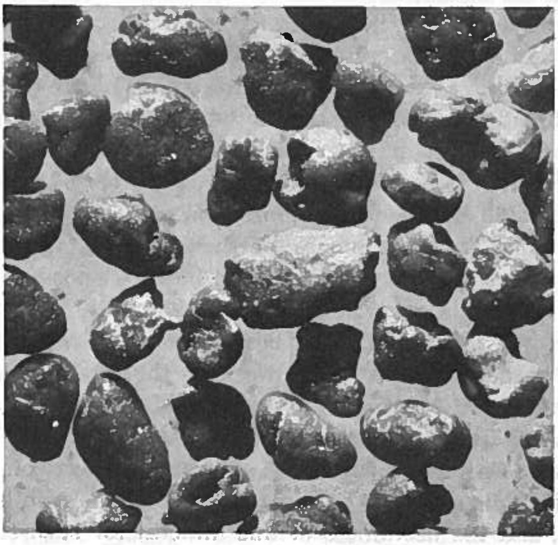

FIGURE 5. Photomicrograph of glauconite pellets from the Clearwater Formation: magnification 40X.

presence of a degraded (expandable) silicate layer lattice, (2) a plentiful supply of iron and potassium ions, and (3) a suitable redox potential. The ionic substitutions involved in the conversion of a 2 : 1 layer silicate structure into a glauconite include the migration of ferric and ferrous ions into the octahedral layer, with the simultaneous displacement of an equivalent number of octahedrally co-ordinated cations (usually aluminum) from the parent material, and the "absorption" of potassium ions into the space between the layers, causing subsequent collapse of expandable layers into a nonexpandable 10Å lattice.

Study of the environments of deposition in which modern deposits of glauconite have been found suggests that at least five conditions must be maintained for the formation of glauconite (Cloud, 1955). These are: (1) normal sea water, (2) suitable parent material, (3) slightly reducing conditions, such as are produced by decaying organic matter, (4) slow rate of detrital influx and (5) moderate to shallow depth of water. Among the suitable parent materials listed by Takahashi (1939) are hydrated and gelatinized fragments of volcanic glass, opaline silica, faecal pellets, feldspars, and possibly micas. The glauconite sands of the basal Clearwater Formation have already been shown to contain suitable parent materials for the formation of glauconite in the form of volcanic rock fragments and feldspar grains.

Biotite is also considered by some investigators to be a suitable parent material for the formation of glauconite (Galliher, 1939). If this is so, then the presence of fresh unaltered hexagonal flakes of biotite associated with the glauconite pellets in the Clearwater Formation samples requires explanation.

The slow rate of detrital influx associated with the formation of modern glauconite has led stratigraphers to the conclusion that ancient glauconite beds or "greensands" may mark stratigraphic discontinuities representing lack of deposition for considerable intervals of time over wide areas (Weller, 1960, p. 395). With regard to the glauconitic sands of the Clearwater Formation, the fossil evidence clearly supports the contention of previous investigators that such sands are indicative of a marine environment of deposition; thus, it is reasonable to conclude that the presence of glauconite can be used to supplement fossil data in determining the paleogeographic extent of the widespread marine transgression in northern Alberta in early Cretaceous time. The conclusion that they represent a lack of deposition for a considerable interval of time is open to question and requires more detailed study of the microfaunal changes at the Clearwater-McMurray boundary before it can be substantiated. Preliminary work on the foraminifera of the lower Clearwater and upper McMurray Formations by Mellon and Wall (1956) indicated to them (p. 2) that there is no time break at the boundary of the two formations. Age dating of these glauconites based on the potassium 40 : argon 40 isotopic ratio has been attempted, but the results reported have varied widely, and the usefulness of this mineral for such studies has been questioned (Williams *et al.* 1962).

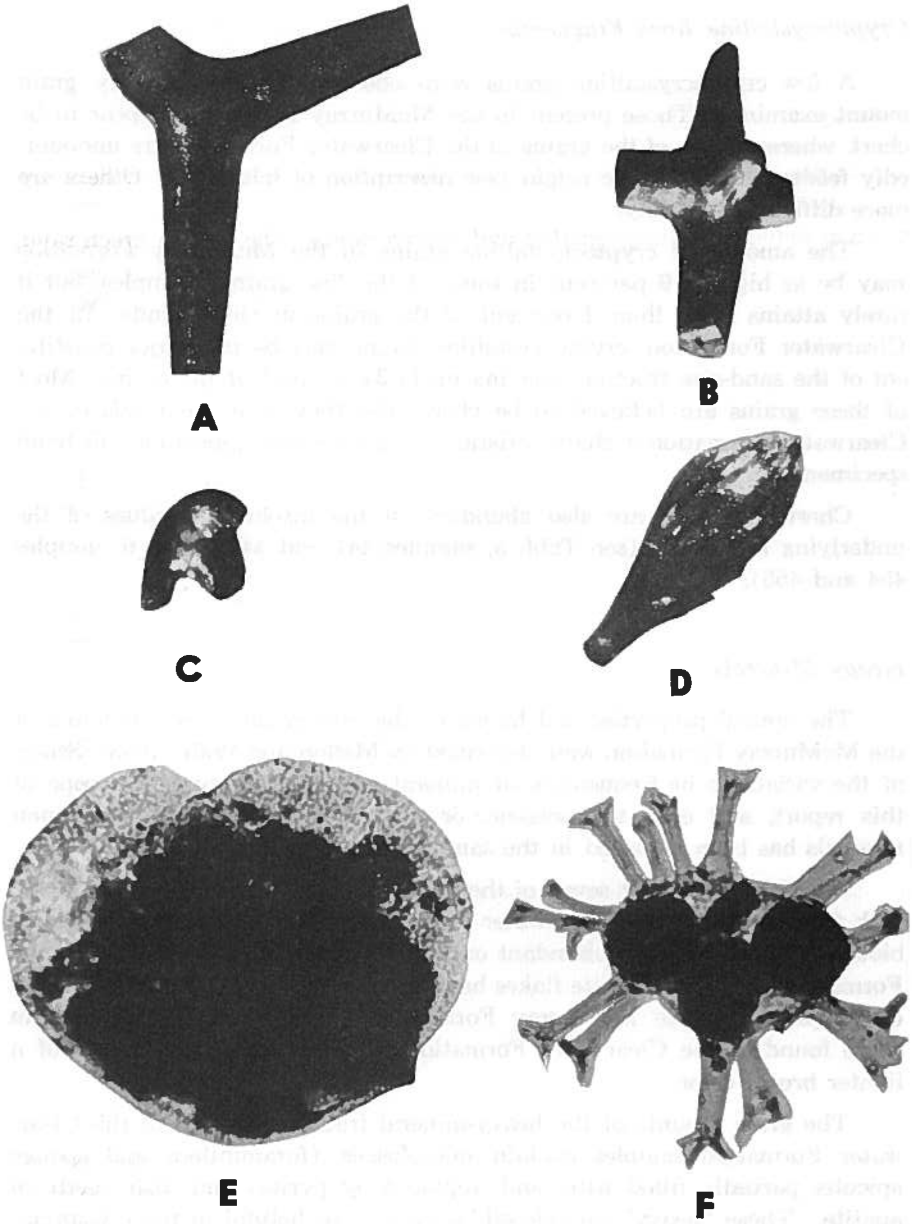

FIGURE 6. Photomicrographs of microfossils from the heavy mineral fraction of some of the sediments.

A, B, C and D. Pyritized sponge spicules: magnification 160X.

E. Pollen grain filled and partially replaced by pyrite: magnification 560X.

F. Hystrichospherid partially replaced by pyrite: magnification 450X.

Cryptocrystalline Rock Fragments

A few cryptocrystalline grains were observed in almost every grain mount examined. Those present in the McMurray Formation appear to be chert, whereas some of the grains in the Clearwater Formation are undoubtedly felsites of pyroclastic origin (see description of feldspars). Others are more difficult to classify.

The amount of cryptocrystalline grains in the McMurray Formation may be as high as 9 per cent in some of the fine grained samples, but it rarely attains more than 2 per cent of the grains in clean sands. In the Clearwater Formation, cryptocrystalline grains may be the major constituent of the sand-size fraction, forming up to 34 per cent of the grains. Most of these grains are believed to be chert, and they give the sands of the Clearwater Formation a characteristic salt and pepper appearance in hand specimens.

Chert fragments are also abundant in the insoluble residues of the underlying limestones (see Table 5, samples 441 and 442; Table 6, samples 454 and 455).

Heavy Minerals

The optical properties and habits of the nonopaque heavy minerals of the McMurray Formation were described by Mellon and Wall (1956). Study of the variations in frequencies of mineral species is beyond the scope of this report, and only the presence or absence of each of eight common minerals has been recorded in the samples in tables 2 to 9.

The data show that seven of the heavy minerals chosen are common to both the McMurray and Clearwater Formations. The exception is euhedral biotite (Fig. 4), which is abundant only in the samples from the Clearwater Formation. Anhedral biotite flakes have been recorded from a small number of samples from the McMurray Formation, but these grains differ from those found in the Clearwater Formation in being thin, ragged, and of a lighter brown color.

The grain mounts of the heavy-mineral fraction of some of the Clearwater Formation samples contain microfossils (foraminifera and sponge spicules partially filled with and replaced by pyrite) and fish teeth of apatite. These "heavy" microfossils proved to be helpful in the interpretation of the stratigraphy and are illustrated in Figure 6.

Clay Minerals

The clay minerals in that part of the samples less than 4 microns in size were identified by X-ray diffraction powder methods. Kaolinite is present in all samples from the McMurray Formation, and the 10Å illite peak is absent in only two of these samples. A weak peak at 14Å in a few samples is attributed to the presence of chlorite. These 14Å peaks were more common on the diffractograms from samples towards the base of the formation, although detrital chlorite is a common constituent in the coarse heavy mineral fraction of the McMurray Formation. In four samples from the Honolulu Union House River well (Table 9) a montmorillonite peak is present. Additional data will be needed to explain the presence of a montmorillonite clay interbedded with characteristic McMurray Formation sediments 100 feet below the base of the Clearwater Formation.

The X-ray diffractograms of the clay mounts of some of the samples from the type-section outcrop of the McMurray Formation contain several peaks in addition to those attributed to the clay minerals. Peaks due to the presence of the hydrous sulfates, gypsum ($CaO.SO_3.H_2O$) and natrojarosite ($Na_2O.3Fe_2O_3.4SO_3.6H_2O$), were identified, but in addition, unidentified peaks were located at 9.4Å, 4.7Å, 3.13Å, and 2.46Å. The presence of these sulfate minerals in the clay mounts is believed to be due to contamination from a white incrustation on the surface of the outcrop formed by the evaporation of water from seepages. Support for this argument is given by an analysis of the water-soluble components of a salt incrustation on an oil sand outcrop by Clark and Pasternack (1931, p. 61), which indicated the presence of sulfates of iron (ferric and ferrous), aluminum, calcium, magnesium and sodium.

Montmorillonite, illite, kaolinite and chlorite are all generally present in the clay-size fractions of Clearwater Formation samples, whereas montmorillonite appears to be absent from the McMurray Formation except for the four samples from the Honolulu Union House River well. In the Clearwater Formation chlorite gives a better peak on the diffractogram in those samples which contain glauconite. Clay minerals of the montmorillonite group are absent in five of the oil-impregnated glauconite sands of the Clearwater Formation. In three of these (Table 5, 419, 420; and Table 6, 446) clay minerals of the chlorite group are present, and in the other two (Table 7, 456 and Table 8, 475) chlorite is absent; therefore, illite and kaolinite are the only two clay-mineral groups found in all samples of the oil-impregnated sediments of the Athabasca Oil Sands. If it can be shown that the oil above and below the McMurray-Clearwater boundary has the same chemical and physical properties, then it should be possible to design an experiment to evaluate the effects of a change in the mineralogy of the clay-size fraction on the amount of oil impregnation in the Athabasca Oil Sands.

Illite, kaolinite and chlorite were identified in the insoluble residues of the Paleozoic limestones (Tables 6 and 8).

The presence of montmorillonite in the clay fraction of the Clearwater Formation and its virtual absence in the clay fraction of the McMurray Formation would be difficult to explain were it not for the recognition of rock fragments of undoubted volcanic origin in sample 346 from the Clearwater Formation. Montmorillonite is the main constituent of bentonite, which, according to Ross and Hendricks (1945), is formed by the alteration of volcanic ash. Ross and Hendricks (1945, p. 65) state that the glass that most readily alters to bentonite tends to have the composition of latite, the crystalline part of which is composed largely of feldspar. Latite or trachyandesite usually carries alkali feldspar and soda-lime feldspar in equal amounts (Tyrrell 1948, p. 124). This information, coupled with the presence of pyroclastic grains and euhedral boitite flakes in the Clearwater Formation, gives support to the conclusion that the montmorillonite in the clay-size fraction of this formation is of volcanic origin. The fact that a marine environment of deposition is postulated for the sediments provides a ready explanation for the source of the magnesium ions necessary for the transformation of the volcanic glass into montmorillonite.

Discussion of Results

The major mineralogic constituents of the sand-size fractions of all samples have been plotted on ternary diagrams (Figs. 8 and 9). The sand-size fraction of the McMurray sediments is composed largely of quartz, chert and feldspar being more in the nature of accessory components. The samples are thus clustered towards the quartz apex of the triangle (Fig. 8). Four samples of the Paleozoic limestone residues have been plotted on the quartz, feldspar, rock fragment diagram (Fig. 8) along with the McMurray Formation samples. They have a higher proportion of feldspar and chert relative to quartz than the McMurray samples.

The major constituents of the Clearwater Formation samples are quartz and quartzite, glauconite, and cryptocrystalline rock fragments (chert and a small proportion of felsite) (Fig. 9). The "transition bed" data are plotted on the same diagram as the Clearwater samples, where they appear near the quartz apex. A similar plot for these beds can be obtained by substituting feldspar for glauconite as the third component, in which case the samples give a cluster of points similar to the quartz sands of the McMurray Formation.

Of the heavy minerals identified, only euhedral biotite (Fig. 4) has any stratigraphic significance, being restricted to the Clearwater Formation. This mineral is probably of pyroclastic origin as it is associated with volcanic rock fragments, plagioclase and montmorillonite.

The clay-mineral assemblages of both formations are distinct. Illite and kaolinite are common to both formations, but chlorite is associated largely with montmorillonite and glauconite in the Clearwater Formation. Montmorillonite is largely restricted to the Clearwater Formation and is believed to be the alteration product of pyroclastic material. The lowest occurrence of montmorillonite in lower Cretaceous strata of the Plains may prove to be a useful time marker over a very wide area.

TEXTURE

The texture of a sediment is an aggregate property definable in terms of its particle-size distribution, particle shape, packing, orientation and cementation. As the samples used in this study are all uncemented, the only textural properties measureable are the particle-size distribution and the particle shape. Of these, only the particle-size is measurable over the range of grain sizes represented in these samples. From the particle-size distribution data the average grain-size for each sample has been estimated from the median diameter, expressed in microns, and the quantity of clay mineral in each sample has been approximated by reporting the percentage of total mineral matter less than 2 microns in size (Tables 2 - 9).

For comparative purposes a textural classification based on the percentages of sand, silt and clay as defined by Shepard (1954) has been used. The proportions of sand, silt and clay for each sample can be represented by a point on a ternary diagram. The textural nomenclature used in this paper (Fig. 7) is based on the subdivisions proposed by Shepard (1954) which are similar to the descriptive terms used by geologists in the field.

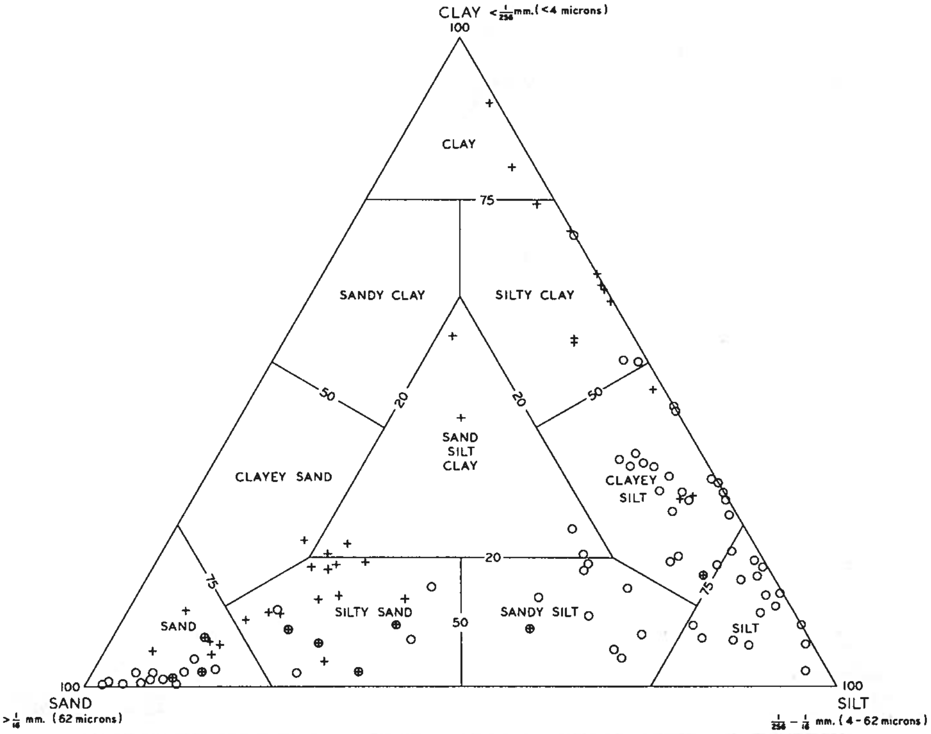

FIGURE 7. Ternary diagram showing sand-silt-clay ratios of samples from the McMurray, Clearwater Formations, and "transition beds".

Crosses indicate Clearwater Formation samples: open circles indicate McMurray Formation samples; composite symbols indicate "transition bed" samples.

The textures of the sands of both the McMurray and Clearwater Formations are similar, but those of the finer sediments are different. Whereas the fine-grained McMurray Formation sediments are composed mainly of silt-size material, the finer-grained sediments of the Clearwater Formation plot nearer the clay apex of the triangle (Fig. 7). Nevertheless, no clear-cut subdivision of the samples on the basis of texture alone is possible.

Shepard and Moore (1955) found that the textural properties of Recent sediments of the Texas Gulf Coast were of little value in determining the environment of deposition. However, they did find that glauconite pellets were characteristic of the open-shelf environment. Because the glauconite-bearing Clearwater sediments are known to have been deposited in a marine environment, their textures can be compared with similar Recent sands analyzed by Shepard and Moore (1955). The Clearwater samples form a pattern on the ternary diagram in Figure 7 comparable to that found by Shepard and Moore for Recent sediments from the inner and outer continental shelves of the Texas Gulf Coast. In both the Clearwater and Recent samples the non-sand component is composed of approximately equal

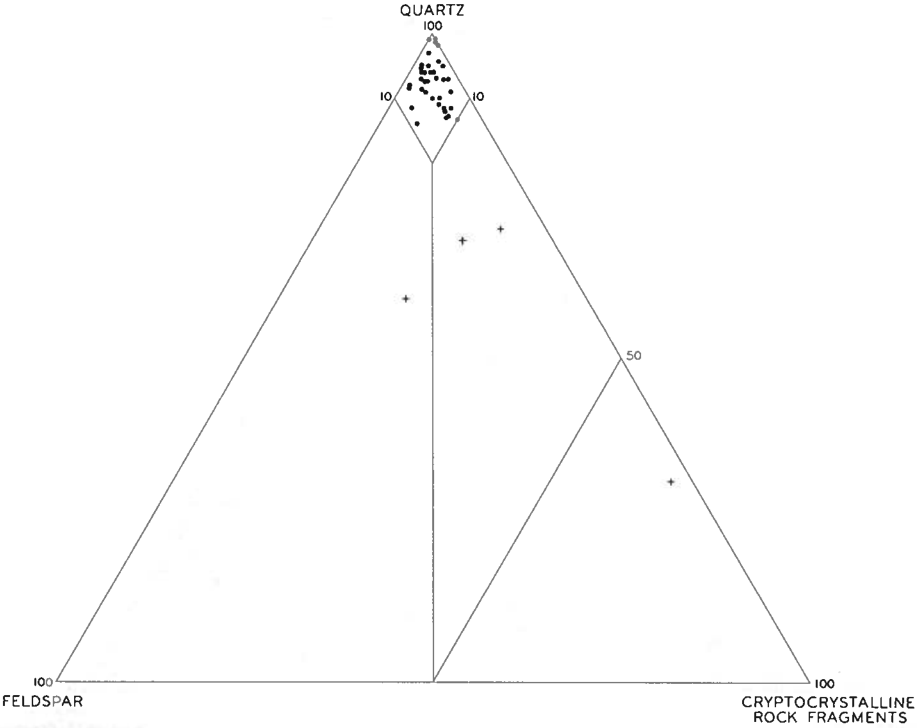

FIGURE 8. Ternary diagram showing the relative proportions of the three major mineral constituents of the sand-size fraction of the McMurray Formation and insoluble residues of the Paleozoic limestones.

Solid circles indicate McMurray Formation samples; crosses indicate insoluble residues from Paleozoic limestones.

portions of silt and clay, in contrast to the fine-grained sediments of the McMurray Formation where the non-sand fraction is dominantly silt. This difference may be a reflection of the salinity of the water in which the sediments were deposited, the fresh-water McMurray deposits settling approximately according to Stokes Law but the marine Clearwater silts and clays flocculating together in a saline environment. However, it must be remembered that at least some of the Clearwater clay is montmorillonite, which presumably formed *in situ* through the alteration of volcanic constituents.

In many of the samples plotted on figures 8 and 9, the percentage of sand-size material is very low; a name based on the components of the arenite fraction in a ternary diagram would thus be inappropriate, and the inclusion of modifiers based on the textural properties could lead to very involved nomenclature. Therefore, no comprehensive nomenclature based on mineralogic composition has been used for describing the samples. For the McMurray Formation the textural descriptions seem adequate, and the Clearwater Formation sand samples could be referred to simply as glauconite sands, lithic sandstones or sub-graywackes.

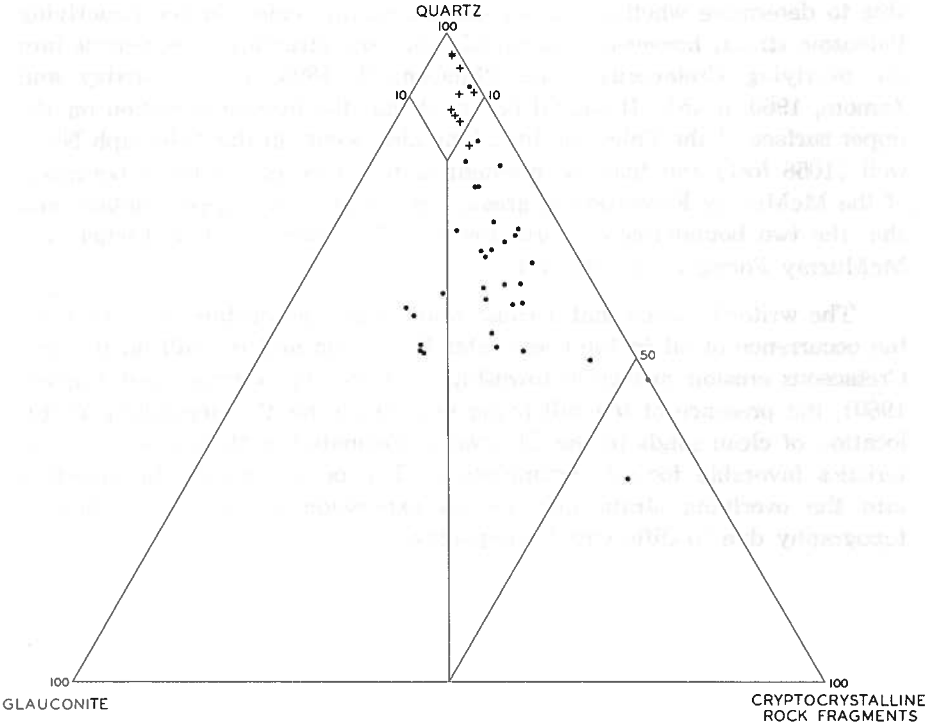

FIGURE 9. Ternary diagram showing the relative proportions of the three major mineral constituents in the sand-size fraction of the Clearwater Formation and "transition bed" samples.

Solid circles indicate Clearwater Formation samples; crosses indicate "transition bed" samples.

SUMMARY AND CONCLUSIONS

In the absence of fossil evidence the presence of the following minerals in a sample of Athabasca oil sand identifies it as belonging to the Clearwater Formation: (1) glauconite pellets, (2) euhedral biotite flakes, (3) montmorillonite, (4) euhedral grains of plagioclase feldspar. Other diagnostic characteristics of the oil sands of this formation include the presence, in small grains, of plagioclase feldspar phenocrysts in a felsitic groundmass, and the presence of more than 10 per cent of chert.

The results of the foregoing core analyses can now be used to assess the structural significance of the McMurray-Clearwater boundary in the wells studied. It can be seen on the stratigraphic sections (Figs. 2 and 3) that the elevation of this contact varies from 820 feet in Honolulu Union House River well to 1084 feet in Richfield Oil Corporation Telegraph No. 1 well. From its highest elevation in township 85, range 14, the upper surface of the McMurray Formation has a dip of slightly more than 11 feet per mile southward and of less than 4 feet per mile northward, thus forming a large, low asymmetrical anticlinal structure. Insufficient data are available to determine whether a comparable structure exists in the underlying Paleozoic strata; however, it is certain that the structure does persist into the overlying Cretaceous strata (McConnell, 1893, p. 32; Carrigy and Zamora, 1960, p. 45). It should be noted that the highest elevation on the upper surface of the Paleozoic limestone also occurs in the Telegraph No. 1 well (1058 feet) and that the gradient of the slope of the lower boundary of the McMurray Formation is greater than that of the upper contact, and that the two boundaries converge towards Telegraph No. 1 well where the McMurray Formation is thinnest.

The writer believes that a cause and effect relationship exists between the occurrence of oil in the Clearwater Formation and the hill on the pre-Cretaceous erosion surface in township 85, range 14 (Carrigy and Zamora, 1960), the presence of the hill being responsible for the deposition at this location of clean sands in the Clearwater Formation with reservoir characteristics favorable for oil accumulation. The persistence of the structure into the overlying strata may be an expression of the pre-Cretaceous topography due to differential compaction.

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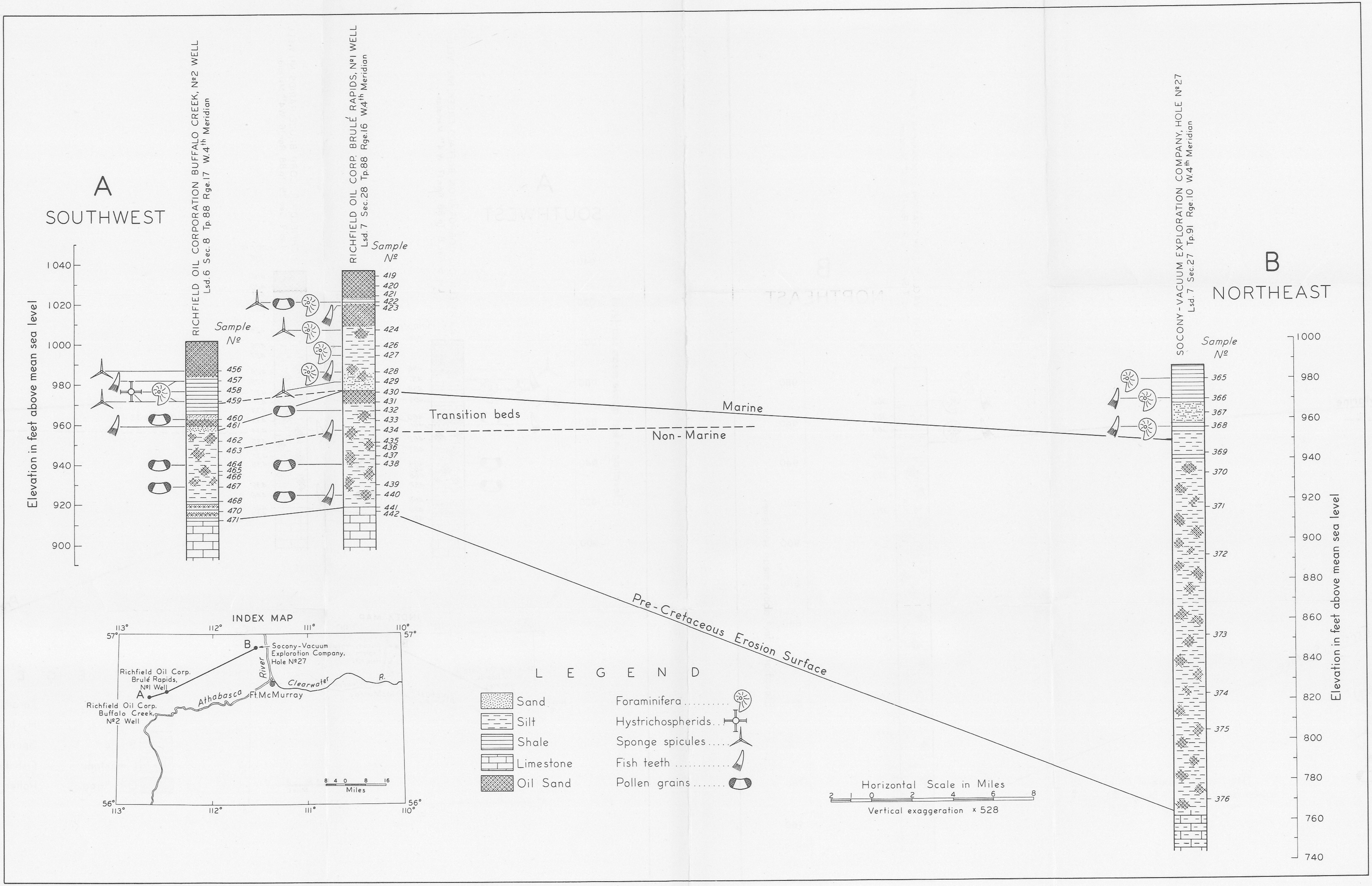

FIGURE 2. Southeast to northwest stratigraphic section A-B showing columnar well-logs and core-sample locations.

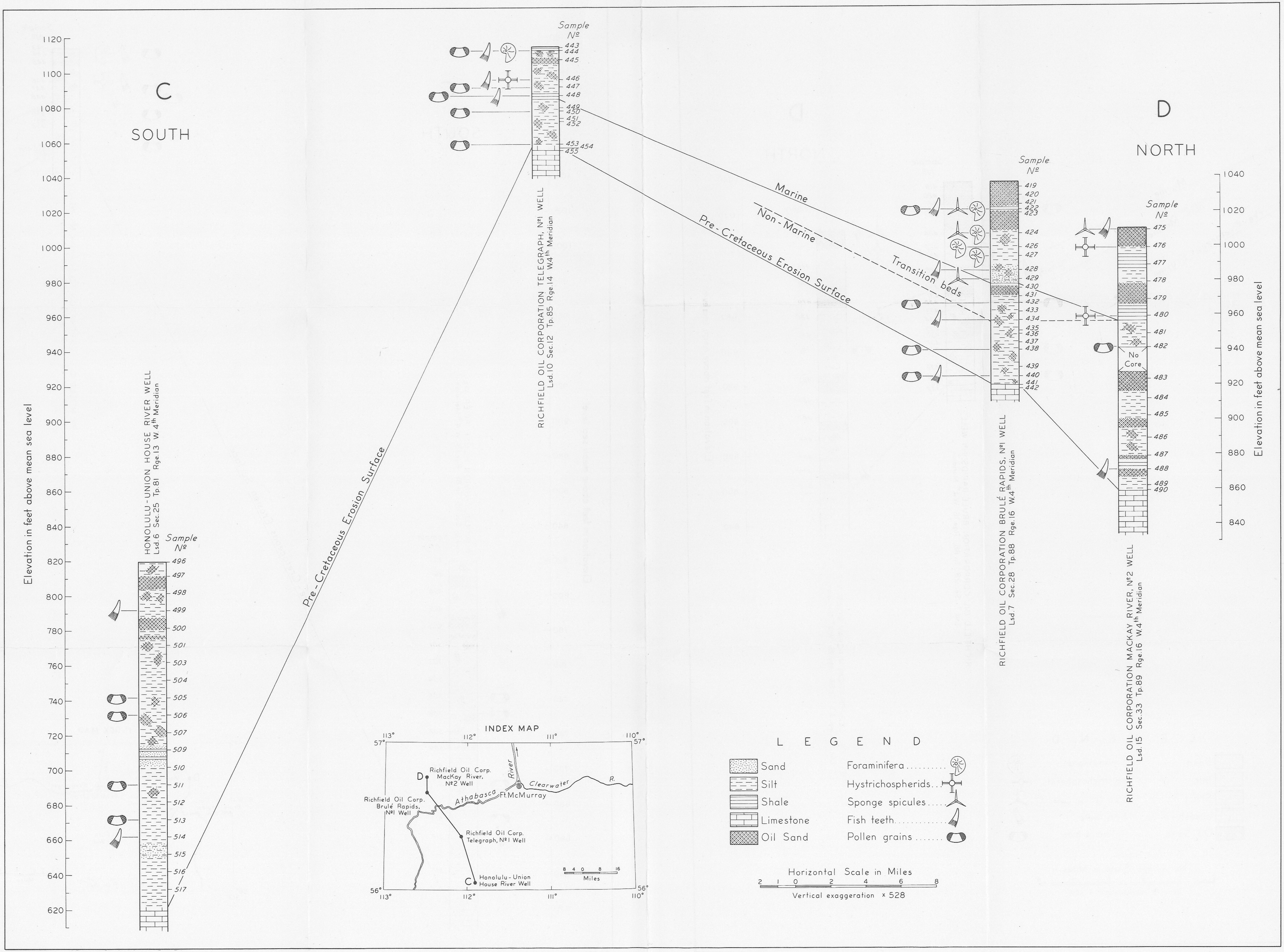

FIGURE 3. North to south stratigraphic section C-D showing columnar well-logs and core-sample locations