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LITHOLOGY OF THE ATHABASCA OIL SANDS

by

M. A. Carrigy

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87th Avenue and 114th Street
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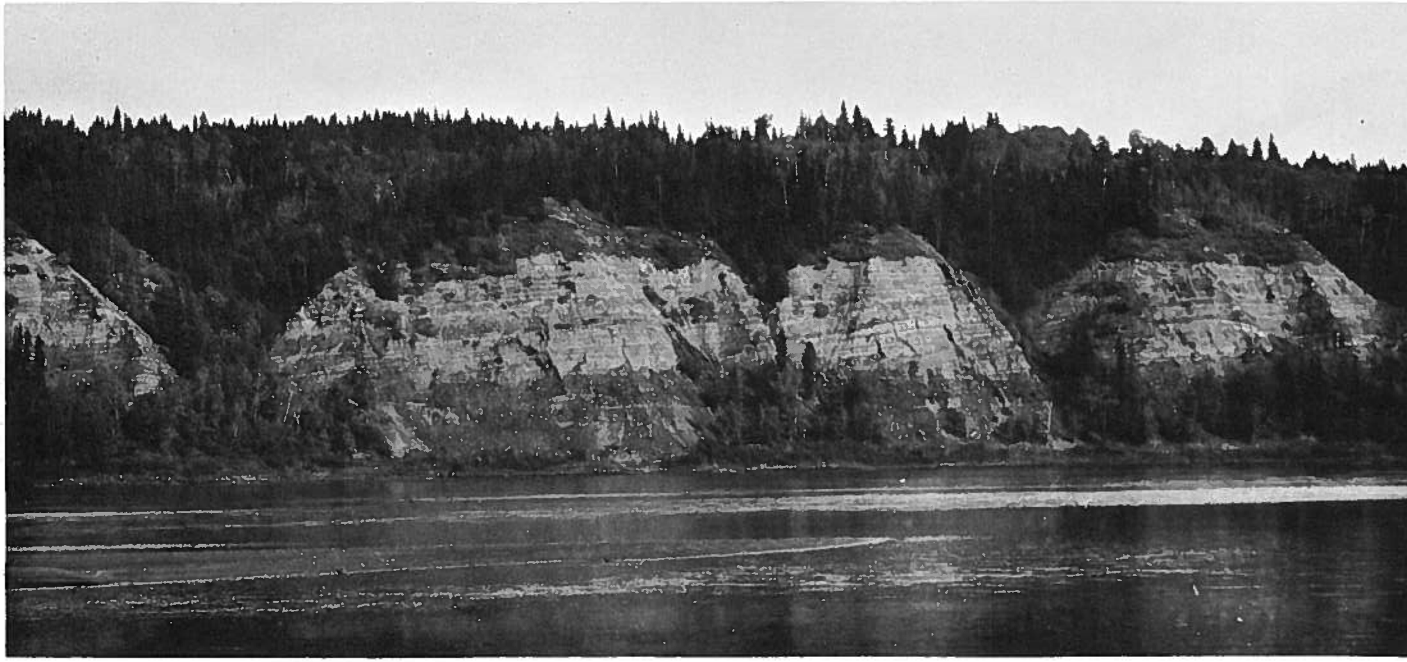
PLATE 1



Topset and foreset beds in the Athabasca Oil Sands on the east bank of the Athabasca River about 3 miles north of Fort McMurray.

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Lithology of the Athabasca Oil Sands

ABSTRACT

Coarse-grained quartzose oil sands with a conspicuous clay matrix cemented in places by quartz and goethite lie at the base of the McMurray Formation and are probably pre-McMurray in age.

Most of the lithologic features observable in the Athabasca Oil Sands can be ascribed to a succession of depositional environments that developed as a consequence of an extensive marine transgression in early Cretaceous time. The lower part of the McMurray Formation consists of fluviatile deposits, and the middle and upper parts of foreset and topset beds of an ancient delta. The parts of the McMurray Formation observable in outcrop on the lower Athabasca River and its tributaries are the deltaic plain deposits; the submarine portion of this ancient delta should be found northwest of Fort McMurray beneath the Birch Mountains. The lower Clearwater Formation consists of nearshore continental shelf sediments deposited as the shoreline moved across the area formerly occupied by the delta.

The heavy minerals of the McMurray Formation were derived from a single provenance underlain by metamorphic and igneous rocks. The heavy minerals are distributed among the lithofacies of the McMurray Formation according to their grain-size and shape at the source. Thus, coarse-grained sands contain an assemblage dominated by garnet, kyanite, tourmaline and staurolite; medium-grained sands have mostly tourmaline and zircon; in very fine grained sands and silts chloritoid, tourmaline and zircon are most abundant.

The distribution of oil within the Athabasca Oil Sands is controlled by the petrographic properties of the reservoir rocks. The porosity is intergranular and was established by the sorting action of the traction currents and the winnowing action of oscillatory currents at the time of deposition; it has been modified only locally by compaction and cementation.

Most of the oil in the Athabasca Oil Sands is contained in the fluviatile sands and in the fine-grained micaceous sands of the foreset beds of the ancient delta of the McMurray Formation. Small pockets of clean sand in argillaceous beds produced by the action of a soft-bodied bottom fauna are commonly impregnated with heavy oil. Post-Cretaceous uplift and subsequent dissection of the reservoir by streams and the collapse of large areas due to salt removal from underlying strata have failed to induce secondary migration in the reservoir except on a local scale at outcrop faces.

INTRODUCTION

Lithology is the term used to describe the components of a rock that give it the individuality that enables it to be distinguished from surrounding rocks. A change in lithology can be recognized by an obvious property, such as a difference in color, mineral composition, grain size, hardness, resistance to weathering, presence of macrofossils, fractures, odor, jointing pattern, bedding, or by some less obvious difference such as a change in heavy mineral assemblage, chemical composition or microfossil content. Generally speaking, however, in sedimentary rocks a change in lithology implies a difference in a number of the components and properties of the rock. For example, a decrease in grain size commonly involves a concomitant increase in clay mineral content, a change in the scale of stratification features from bedding to lamination, a reduction in permeability and changes in many other features. Thus, it is not surprising to find that the grain size of the Athabasca Oil Sands is an important factor in determining the distribution of oil within the reservoir. Nevertheless, in local areas the effect of grain size is modified by the presence of a clay matrix, mineral cement or a combination of both, and it is the purpose of this paper to describe in some detail the various lithologies of the strata encountered within the Athabasca Oil Sands reservoir.

Recent estimates of the petroleum resources of the Athabasca Oil Sands give a figure of more than 600 billion barrels for the oil in place (Pow *et al.*, 1963). It seems probable that some 400 billion barrels of this crude oil will be produced by the application of *in-situ* recovery methods now in process of development and that up to 40 billion barrels of oil will be recovered from strata close enough to the surface to be mined from open pits.

Previous Work

Brief descriptions of the lithologies of the Mesozoic rocks of the McMurray area are contained in the reports of McConnell (1893), McLearn (1917), Ells (1926), Clark and Blair (1927), Wickenden (1951), Mellon and Wall (1956) and Carrigy (1959a,b; 1963a,b).

Acknowledgments

The measurements and descriptions of the oil-sand outcrops were made during the 1957 field season when the writer was ably assisted by Leslie Bell. The type section was sampled during the 1960 field season with the help of Keith Miller.

Cores from the wells were made available to the Research Council under the terms of the regulations governing the disposition of bituminous sand rights of the Mines and Minerals Act.

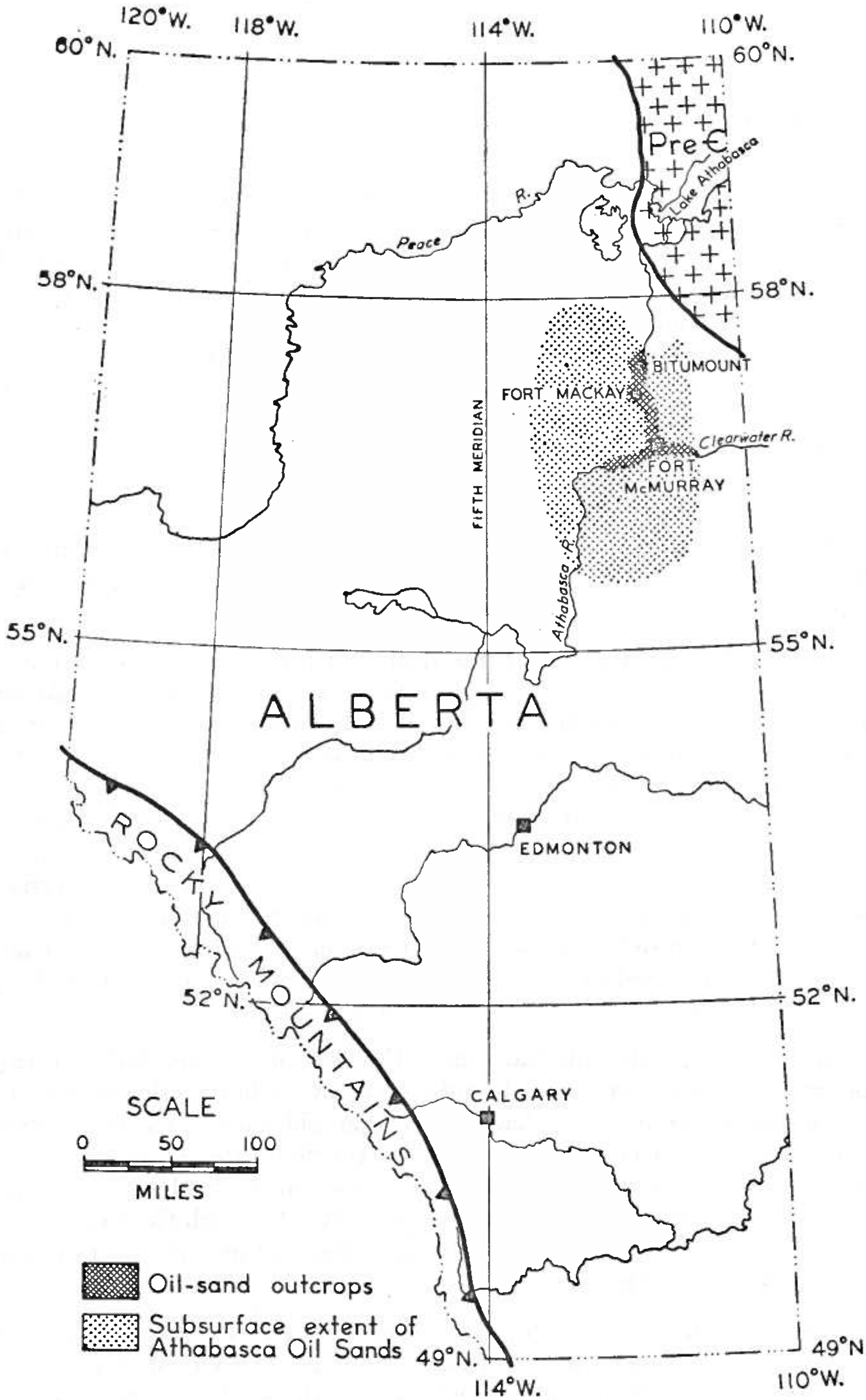

FIGURE 1. Index map showing the location of the Athabasca Oil Sands.

STRATIGRAPHY AND STRUCTURE

General Statement

The Athabasca Oil Sands are found in the McMurray and overlying Clearwater Formation of northeastern Alberta (Fig. 1). The oil-impregnated portions of the McMurray Formation have been called the McMurray Oil Sands, and these contain most of the oil in the area. The McMurray Formation averages about 200 feet in thickness and is early Cretaceous in age. It overlies strata of Devonian age unconformably. The topography on the unconformity has been mapped by Martin and Jamin (1963) and appears to have been, in late pre-McMurray time, a mature landscape of wide valleys separated by cuesta ridges with scarps controlled by the structure and compositional variations of the Devonian limestone and shale succession. The McMurray Formation is correlated with the lower Blairmore and Gething stratigraphic units of the Foothills, the Bullhead Formation of the northern Alberta Plains, and the lower part of the Mannville Group in the central Plains of Alberta.

The McMurray Formation was deposited during the early part of a sedimentary cycle associated with a marine transgression in middle Albian time. The thicknesses of McMurray strata are variable and the lithology is diverse, with lenticular beds of conglomerate and coarse-grained sands at the base and horizontal beds of laminated silt at the top. It is overlain by marine sands, silts and shales of the Clearwater Formation. The basal glauconite-bearing greensands of the Clearwater Formation are impregnated with oil in some areas, and these bodies are called the Clearwater Oil Sands (Carrigy, 1963b). The drainage system of the lower Athabasca River has cut through the oil sands down to the surface of the Devonian limestone, exposing many cliffs of oil-impregnated strata over an area of 1,500 square miles in the vicinity of the town of Fort McMurray (Frontispiece).

Kidd (1951) pointed out that a rough three-fold division of the McMurray Formation can be recognized in the outcrops along the lower Athabasca River, and Carrigy (1959a) proposed that these stratigraphic units be called members: a basal member of coarse-grained sand and conglomerate, a middle member composed mainly of beds of fine-grained cross-bedded sand, and an upper member of horizontally laminated sands and silts. Although these units have sharp boundaries, they vary widely in thickness, and one or two units may be absent from a particular section.

The oil-sand strata are practically horizontal in the lower Athabasca River area. There is no evidence of tectonic disturbance, and local domes and basins superimposed on a slight regional slope to the southwest are attributed to collapse subsequent to the solution of underlying evaporite beds (Carrigy, 1959a).

Time of Migration of Oil

The reservoir of the Athabasca Oil Sands extends from the McMurray Formation up into the basal member of the Clearwater Formation of middle Albian age. Thus, the earliest that oil could have entered the reservoir is in middle Albian time. Numerous other heavy oil reservoirs are found in the Lower Cretaceous strata of northern Alberta (Pow *et al.*, 1963), and it is probable that the oil in these reservoirs and the Athabasca oil had a common source and migrated into the area in post-Albian time.

LITHOLOGY

Sampling Locations and Analytical Procedures

The bulk of the samples upon which the present study is based come from the type outcrop section on the Athabasca River and from six cored well sections situated along a line parallel to the Athabasca River between Fort McMurray and Bitumount (Fig. 2). A total of one hundred and eleven samples were taken from the McMurray Formation at these localities and analysed for their oil content, clay content and grain size. Eleven samples from the type outcrop section were analysed also for their heavy mineral content.

Eight core samples of the McMurray Formation also were taken from the Socony-Vacuum Hole No. 27 for mechanical and heavy mineral analyses. Not shown on figure 2, this section is located in Sec. 27, Tp. 91, R. 10, about 10 miles due north of Fort McMurray.

In addition to the McMurray Formation samples, four samples of pre-McMurray? sands and sandstones from four outcrops in the Athabasca River area were collected for thin section and heavy mineral analyses.

As the Athabasca oil, because of its high viscosity, is essentially immobile, relatively undisturbed cores of the uncemented sands and silts can be obtained by normal coring techniques. Accurate estimates of the oil content can be made by extracting the oil from small portions of core with a suitable solvent, which also leaves a residue of loose sand suitable for petrographic study. Thus, it is possible to build up a fairly detailed picture of the distribution of oil throughout the reservoir and to assess the role of petrographic properties in the accumulation of the oil (Carrigy, 1962).

Mechanical analyses of the unconsolidated oil sands were performed using standard sieving and sedimentation techniques down to a size of 2 microns. From these, the median diameter and weight percentage of material less than 2 microns (clay content) for each sample have been plotted together with the corresponding oil contents on figure 2. Complete mechanical analyses data for these and samples from the Socony-Vacuum Hole No. 27 are given in the Appendix.

Heavy minerals in samples of the McMurray Formation from the type outcrop section and the Socony-Vacuum Hole No. 27, and from outcrop samples of pre-McMurray? sands and sandstones, were separated using tetrabromoethane. A portion of the bulk sample was used in each case, rather than a particular size fraction, to determine the effect of grain-size variation on heavy mineral composition. Frequency estimates of the nonopaque heavy mineral constituents in these samples are given in tables 1 to 3.

Coarse-Grained Pre-McMurray? Sands and Sandstones

A thin bed of quartz-cemented sandstone outcrops extensively between the Athabasca and Muskeg Rivers to the east of Fort MacKay in Tp. 94, R. 10. In this area, any oil sand previously overlying these outcrops has been eroded, leaving resistant quartzite on the surface underlain by a poorly impregnated, coarse-grained crossbedded oil sand. These rocks are similar in general appearance to Proterozoic quartzites and were thus assigned a Huronian age by Ells (1932) and Sproule (1951). However, the Mesozoic age and nature of this quartzite bed was correctly recorded by McConnell (1893).

When the quartzite is broken, the interior is seen to be oil stained with only a thin skin of oil-free rock at the surface. In thin sections the quartzite is found to consist of large angular and rounded grains of quartzite of clastic origin with an interstitial matrix composed mainly of finer-grained clastic quartz cemented in places by chert (Pl. 7, Fig. 1). It also has small patches of clay matrix. The larger grains are highly fractured, many of them showing polycrystalline texture. Quartz overgrowths in optical continuity with the clastic grains are common. The oil present in these silica-cemented rocks occupies small clay-lined pores and is present in just sufficient quantity to give the rock a dark color. In another conspicuous outcrop, on the east side of the Athabasca River between the mouths of the Muskeg and Steepbank Rivers, about one mile north of La Saline, coarse-grained sandstone with contorted bedding (Pl. 2, Fig. 1) overlies the Devonian limestone. This rock is not oil stained but has a distinctive orange-pink color due to iron staining. Thin sections of this rock (Pl. 8, Fig. 1) show coarse-grained quartz grains, similar to those described above, embedded in a clay matrix. It seems probable that the contorted structure shown in plate 2, figure 1 is due to penecontemporaneous slumping facilitated by the presence of the interstitial clay. Most of the clay matrix has recrystallized to coarse-grained kaolinite (Pl. 8, Fig. 2) which in turn has been replaced by an opaque iron oxide (goethite) cement. Sandstone of similar lithology (Pl. 9, Fig. 1) is found at the base of an oil-sand outcrop on the west side of the Athabasca River one-half mile south of Tar

Table 1. Percentages of Nonopaque Heavy Minerals in Coarse-Grained Pre-McMurray? Sands and Sandstones

Sample No.	1	2	3	4	Average
Garnet	—	—	—	—	—
Staurolite	6	17	7	22	13
Kyanite	5	25	8	9	12
Tourmaline	14	26	3	15	15
Zircon	65	28	77	46	54
Chloritoid	—	—	Tr.	—	—
Rutile	2	1	4	3	2
Sphene	4	2	—	1	1
Others	4	1	1	4	3
Total	100	100	100	100	100

Location of Samples

1. Muskeg River, coarse-grained oil sand underlying quartzite bed.
2. Christina River Indian Reservation, coarse-grained sand at base of outcrop.
3. East side of Athabasca River about 1 mile north of La Saline, coarse-grained contorted sandstone.
4. West side of Athabasca River, ½ mile south of Tar Island, coarse-grained, oil-soaked sandstone beneath unconformity.

Island (Sec. 12, Tp. 92, R. 10) where it appears to be partially oil-soaked and is overlain unconformably by rich oil sands of the McMurray Formation.

The strata exposed at this locality are as follows:

Thickness (feet)	Top of Section
6.0	Olive-green sand grading into shale at base
1.0	Iron oxide-cemented bed
7.0	Grey shale, soft
11.0	Fine-grained, horizontally bedded oil sand
0.5	Iron oxide-cemented bed
0.5	Grey shale
3.0	Fine-grained oil sand
9.0	Fine-grained oil sand and shale, interbedded
6.0	Grey shale
0.5	Iron oxide-cemented bed
7.5	Fine-grained oil sand
2.0	Grey shale
2.0	Fine-grained oil sand
61.0	(Interval covered by talus, probably fine-grained oil sand)
100.0	Fine-grained oil sand
3.0	Fine-grained oil sand, rich in oil
	Unconformity
12.0	Coarse-grained oil sand with rounded quartzose pebbles up to ½ inch in diameter; irregular joints filled with ferruginous cement
3.0	Ironstone conglomerate
13.0	Coarse-grained oil sand with clayey matrix, poorly impregnated
241.0	**total thickness**

Below the unconformity the oil seems to have been prevented from penetrating the sands by the presence of the clay matrix.

Coarse-grained sandstone cemented by iron oxide also outcrops south of the boat landing at the settlement of Fort MacKay and at the base of the outcrops in the Indian Reservation on the Christina River (Tp. 88, R. 7). In thin sections replacement of the matrix and penetrations of the fractures by iron oxide (goethite) cement is a very conspicuous feature (Pl. 9, Fig. 2): this type of rock probably represents the most advanced stage of lithification of the basal Cretaceous sandstones in the lower Athabasca River area.

All of the rocks described above probably have a common origin. The lack of stratigraphic control on the isolated outcrops makes correlation difficult, but the similarity in mineral composition and stages of lithification as observed in thin sections follow the same pattern in all of these outcrops and lead one to suspect that the beds are remnants of a once-continuous body of sandstone.

These coarse-grained basal sandstones may be the age equivalents of beds of grey shale and siltstone with thin beds of coal preserved on the pre-

Cretaceous erosion surface beneath the oil sands. A pre-McMurray (Deville) age for these sands is suggested by Pocock (1962), who also postulates a period of erosion in post-Deville pre-Quartz Sand (McMurray) time in the central Plains, and thus a nonsequence in the microflora between these two members of the Mannville Group.

A well-developed, mineralized joint pattern in the basal coarse-grained beds and discordance between the strata above and below the unconformity in some outcrops suggest that the basal beds were involved in the flexuring of the underlying Devonian limestones before deposition of the McMurray Formation.

Examination of the heavy minerals in four samples (Table 1) shows an assemblage with different proportions of minerals to those from the McMurray Formation proper. Rounded zircons are the most abundant grains observed, and a few larger grains of tourmaline, staurolite, kyanite, garnet and rutile are also found. Chloritoid appears to be absent from these samples, and this, together with the other petrographic properties detailed above, serves to distinguish these sandstones from the coarse-grained basal oil sands of the McMurray Formation described below.

A pre-McMurray age must be assigned to these rocks because oil-stained quartzite cobbles indistinguishable in hand specimen and thin sections from the outcrops on the Muskeg River (Tp. 94, R. 10) are incorporated into basal conglomerate beds of the McMurray Formation on the Steepbank River (Pl. 7, Fig. 2). The unconformable contact with the overlying oil sands in the outcrop on the Athabasca River at the south end of Tar Island also supports this hypothesis.

McMurray Oil Sands

Grain-Size Classification

The mineral residue from each sample of oil sand has been subjected to a mechanical analysis down to a size of 2 microns. The results of the mechanical analyses are most conveniently represented by a continuous curve based on cumulative weight percentages greater than a predetermined size. Whole curves, however, are not amenable to comparison by mathematical techniques, and it is common practice to compare samples by substituting statistics based on percentile measurements of the curves. Nevertheless, the shape of the curve is itself a significant characteristic, and in some cases the cumulative curves obtained from mechanical analyses of samples from a single stratigraphic unit or lithofacies can be grouped and a limiting envelope drawn which separates them from curves derived from samples of other stratigraphic units or lithofacies. This is so in the case of the Athabasca Oil Sands in which three distinct types of cumulative curves constantly recur (Carrigy, 1959b). These curves are shown in figure 3, and the classes of McMurray Formation oil sands which they characterize are discussed below. Sand-silt-clay ratios of the samples are plotted on figure 4.

Complete data on the mechanical analyses of the core and outcrop samples are recorded in the Appendix.

Coarse-Grained Oil Sands

Coarse-grained oil sands are more commonly found in the lower part of the McMurray Formation. They were defined by Carrigy (1959b) as those sands having a maximum size greater than 1 mm, more than 80 per cent by weight of a size greater than 74 microns, median diameter greater than 130 microns, and a cumulative curve which falls in the Class I envelope on the classification scheme shown on figure 3. Of the 119 mechanical analyses performed for this report, only 6 fall into the coarse sand category. By contrast, 300 out of 660 curves constructed from the data included in Report 826 of the Canada Mines Branch (1949) are in this category. Most of these are from the thick basal beds of the Mildred Lake deposit (Carrigy, 1963a). The thickest beds of coarse-grained sand encountered in the wells studied for this report were found near the bottom of Canada Cities Service Petroleum Corporation well 4-34-93-10. These coarse-grained sand beds were found in only two of the other wells: Canada Cities Service Petroleum Corporation 2-14-93-10 and Richfield Oil Corporation 16-2. Thin beds of oil-impregnated conglomerate interbedded with coarse-grained oil sand are illustrated on plate 2, figure 2. The high oil contents of these samples indicate that they are excellent reservoir rocks. In the Mildred Lake deposit Carrigy (1963a) found the average oil content of the coarse-grained sands to be 12.47 per cent by weight.

An outcrop on the west bank of the Athabasca River 4 miles north of Bitumount, about one-half mile south of the mouth of the Pierre River (Sec. 25, Tp. 97, R. 11), exposes the following section, including 30 feet of coarse-grained sand interbedded with finer-grained oil sands:

Thickness (feet)	Top of Section
3.0	Fine-grained rich oil sand
6.0	Horizontally bedded, interbedded shale and poorly impregnated oil sand
36.0	Fine-grained oil sand, small-scale current bedding and shale chip conglomerates, yellow staining on surface; vertical jointing
3.5	Fine-grained oil sand as above with ferruginous cement
4.0	Fine-grained oil sand
30.0	Coarse-grained oil sand, larger-scale current bedding structures up to 2 feet in thickness, interbedded with horizontally bedded fine-grained oil sand with some ferruginous cement
20.0	Fine-grained massive oil sand (to base of outcrop on Athabasca River)
102.5	**total thickness**

The mineral composition of the coarse-grained sands is fairly consistent in that the sand-size material is mostly quartz and quartzite grains, worn but not well rounded. Potash feldspar grains range from 0 to 3.5 per cent of the total number of grains; chert from 0 to 2.5 per cent. The feldspar grains are mainly angular and partly weathered. Muscovite rarely exceeds 1 per cent of the total number of grains. The nonopaque heavy minerals in these sands were studied by Carrigy (1963a), who found the proportions of heavy minerals

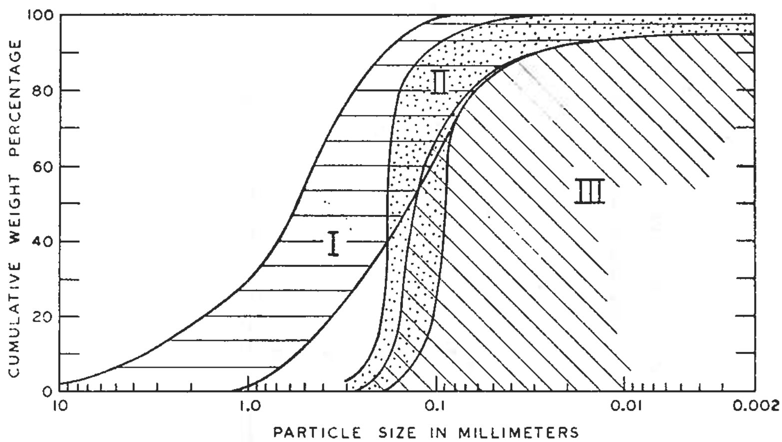

FIGURE 3. Grain-size classification of the Athabasca Oil Sands.

present to be significantly different from those in the finer-grained oil sands of the McMurray Formation. The main differences are the lower percentages of chloritoid and tourmaline and the higher percentages of garnet, staurolite and kyanite in the coarse-grained sands (Table 6).

A feature of the mineral composition of the coarse-grained sands not encountered in other lithofacies of the McMurray Formation is the abundance of siderite spherulites (Pl. 13, Fig. 1). In one sample from the Mildred Lake deposit these make up 16 per cent by weight of the sample. Some of the coarse-grained beds are partly cemented by iron carbonate but are also oil impregnated.

Fine-Grained Oil Sands

Fine-grained oil sands are the Class II sands of Carrigy (1959b). More than 80 per cent of a sample by weight is greater than 74 microns, maximum size is less than 300 microns, and the median diameter is between 180 and 90 microns. In outcrops the coarser-grained Class II sands are found in mound-shaped bodies with an internal structure consisting of small-scale, high-angle crossbeds in sets 6 to 12 inches in thickness (Pl. 3, Fig. 1). The finer-grained sand is well sorted, but in outcrops shows smaller-scale bedding features within large-scale, low-angle cross stratified beds 4 to 6 inches in thickness, commonly extending over a vertical interval of 100 feet or more (Frontispiece). Within these oblique beds there is abundant evidence of burrowing by animals (Pl. 3, Fig. 2) and much micaceous material. The burrows are conspicuous in outcrops due to differential weathering, but they are rarely recognized in core samples because of the obscuring effect of oil saturation. Modern environments of continuous aggradation of fine-grained micaceous sand are found in the seaward slopes of a delta fed by a river draining a hinterland subject to marked seasonal variations in rainfall. The vertical interval between the top

Table 2. Percentages of Nonopaque Heavy Minerals in the Type Outcrop Section of the McMurray Formation

Sample No.	520*	521	522	523	524	525	526	527	528	529	530	Average
Garnet..........	4	6	2	5	10	2	2	2	3	4	4	4
Staurolite........	11	5	9	7	8	7	6	11	15	14	8	9
Kyanite.........	2	5	2	1	1	1	1	7	4	12	1	3
Tourmaline......	53	48	53	23	52	63	56	29	43	39	53	47
Zircon...........	20	24	11	57	11	11	17	36	24	24	7	23
Chloritoid.......	2	10	20	5	15	10	12	9	5	4	22	10
Rutile...........	1	1	—	1	—	2	1	2	2	1	2	1
Sphene..........	4	—	3	1	3	2	3	1	2	2	1	2
Apatite..........	1	—	—	—	—	1	—	—	1	—	—	—
Chlorite.........	1	—	—	—	—	—	—	2	—	—	2	0.5
Others..........	1	1	—	—	—	1	2	1	1	—	—	0.5
Total...........	100	100	100	100	100	100	100	100	100	100	100	100.0

*For locations of samples see figure 2.

and bottom of the oblique stratification in the McMurray Formation shows that these beds were deposited in depths of water in excess of 100 feet. Both the high-angle, crossbedded strata described by Carrigy (1963c) and the overlying foreset beds described above are rich in oil and are among the best reservoir rocks in the Athabasca Oil Sands. According to Carrigy (1959b), Class II sands average 14.02 per cent oil by weight or approximately 28 per cent by volume. They are thus almost fully saturated with oil.

Forty-nine of the 119 mechanical analyses performed for this study have Class II-type cumulative curves. These sands are present in all wells; the thickest continuous section of 220 feet is found in the type-section outcrop. These fine-grained sands are most common in the middle of the McMurray Formation, becoming less common towards the top of the formation, where they are interbedded with and gradually replaced by laminated silts.

Class II sands are composed of quartz, feldspars and mica. The quartz is in the form of monocrystalline grains and varies in shape from angular to well rounded (Pl. 6). The feldspars are potash-rich varieties, rarely showing twinning and forming up to 8 per cent of the total number of grains. Muscovite is conspicuous in outcrops but rarely forms more than 5 per cent in the grain counts. Clay minerals are present in minor amounts and consist of illite and kaolinite. The distribution of nonopaque heavy minerals in these sands is shown in table 2 for the type outcrop section. The most characteristic nonopaque heavy mineral is chloritoid which averages 10 per cent of the grains. The most abundant heavy mineral is tourmaline which has an average frequency of 47 per cent. Other heavy minerals present are garnet, staurolite, kyanite, zircon, rutile and apatite.

The fine-grained oil sands are rarely cemented, but overgrowths on the quartz grain are not uncommon. When cleaned of oil, the sample usually disintegrates to form a mixture of loose grains and specks of comminuted carbon.

Very Fine Sands and Silts

Laminated silt strata yielding Class III curves are present in all wells and sections shown on figure 2. They are thinnest in the type section and reach a maximum thickness of 75 feet in Canada Cities Service Petroleum Corporation well 16-33-93-10. Two 50-foot beds also were cored in Richfield Oil Corporation well 16-2. In Socony-Vacuum Hole No. 27 (Sec. 27, Tp. 91, R. 10) the silt beds are present over an interval of 194 feet (Carrigy 1963b, and Appendix).

The silt-size sediment in the McMurray Formation is commonly well sorted and may contain an appreciable quantity of oil. The silts included in the Class III category vary widely in sorting and grain size, bedding and oil content. They are defined by Carrigy (1959b) as all that sediment with less than 80 per cent of the total weight greater than 74 microns and with median diameters less than 120 microns. On the Wentworth grade scale silt is defined

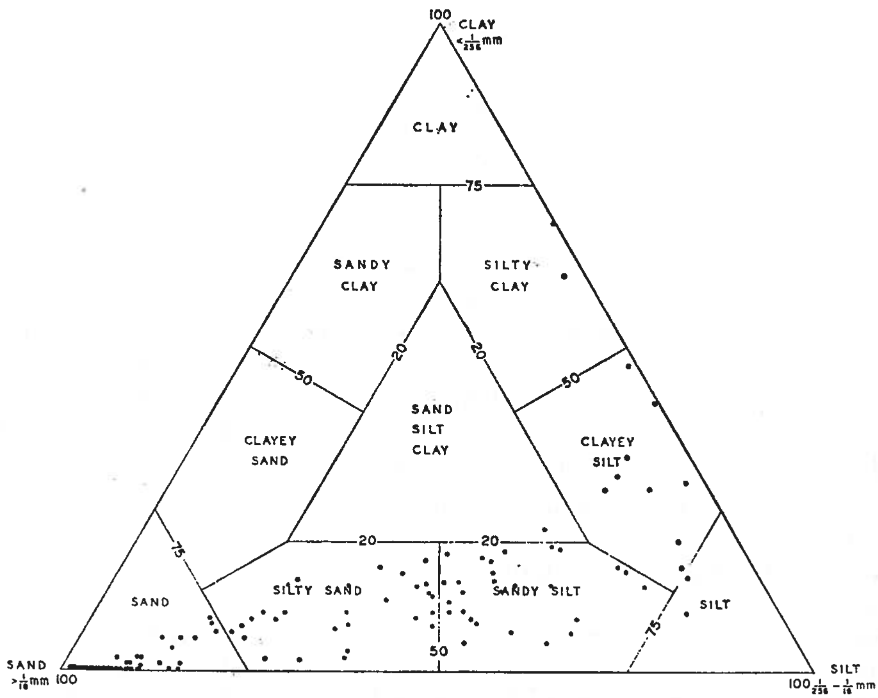

FIGURE 4. Ternary diagram showing proportions of sand, silt and clay in samples of the McMurray Formation.

as all sediment that is less than 62 microns and greater than 4 microns in size. There is no well-defined dividing line between coarse silt and very fine sand; however, silts commonly contain a greater percentage of clay-size material than fine sands. In the McMurray Formation, Class III curves are more commonly obtained from samples taken from the upper half of the unit, although such sediments are also present in the lower part (see figure 2 and results of mechanical analyses of samples from the Socony-Vacuum Hole No. 27 in the Appendix).

When the sand: silt: clay ratios for the laminated silts are plotted on a triangular diagram divided according to the nomenclature of Shepard (1954), it can be seen (Fig. 4) that the samples are almost equally divided between silty sand and sandy silt. Only a few samples can be classified as clayey silt, silty clay or silt.

Minor structures are defined by Van Straaten (1959) as those features visible in an area 3 by 2 inches. Many minor structures are clearly visible in cored sections of the laminated silts of the McMurray Formation. They show an almost infinite variety of disturbed bedding phenomena due to penecontemporaneous slumping and to the churning action of burrowing animals and detritus feeders (Pl. 4, Figs. 3, 4). Other cores show regular patterns of sand lenses in an argillaceous matrix, probably formed by the winnowing action of oscillatory currents. Some of these (Pl. 4, Fig .2) bear a striking resemblance to the minor structures observed in the modern tidal flats of the German Wadden Sea, described by Haentzschel (1955) and Van Straaten (1959), and in the deltaic plains of the modern Mississippi River (Coleman and Gagliano, 1965). In others there is a regular interlamination of oil sand and barren grey silt (Pl. 4, Fig. 1). In some thin sections burrows are clearly identifiable (Pl. 5, Fig. 2).

A puzzling feature of the silts is the presence of small oil-impregnated bodies in apparently impermeable layers of argillaceous sediment. Microscopic examination of impregnated thin sections shows that the finer-grained sediments contain a matrix of clay and macerated organic matter in a clastic framework of quartz and feldspar grains (Pl. 10, Fig. 1). It is apparent from the distribution of the matrix that it was an important factor in preventing oil impregnation. Investigation under higher powers of magnification shows that many areas devoid of organic matrix, but with a clastic framework of the same grain size as the surrounding sediment, contain oil and that within these oil-impregnated areas a thin film of clay still surrounds the clastic grains (Pl. 11, Fig. 1). The irregular shape (Pl. 12, Fig. 1) of some of the clean areas strongly suggests animal activity. Either the organic matter was removed when the sediment was passed through the digestive tract of a detritus feeder, or the vacant burrow of a bottom-dwelling, worm-like creature was filled with clean silt after the burrow was vacated. Other lenses of clean sand impregnated with oil are of a larger grain-size than the surrounding sediment and these probably had a mechanical origin, being produced by the winnowing action of oscillatory currents.

Undoubtedly, the organic clay matrix in these argillaceous silts has played an important role in inhibiting oil impregnation. The matrix is composed of an intimate mixture of organic and fine-grained mineral matter. Submicroscopic, birefringent particles of muscovite have been aligned to give a flow-like appearance to the matrix around the clastic grains. The organic matter is a translucent brown to amber color and includes some cell walls, whole spores and crushed pollen grains. Immersion in Weisner's solution gives no indication of the presence of lignin in the organic matter. Throughout the matrix are scattered minute crystals and clusters of crystals of siderite ($FeCO_3$), which are recognized by their high relief and characteristic birefringence. These laminated argillaceous silts are probably compacted sapropelic muds. The apparent absence of interconnection between the oil-stained bodies and the abundance of organic matter in the matrix of the surrounding sediment is strongly suggestive of a local origin for the oil, but the presence of oil-free bodies of similar shape and dimensions within a distance of less than a centimeter in some of these laminated silts mitigates against the acceptance of this hypothesis.

The mineral composition of the clastic grains in the laminated siltstones is similar to that of the sands. Feldspars and mica are more abundant, and the grains are more angular than those found in the oil sands. The clay-size fraction is similar, being composed of a mixture of illite and kaolinite. The heavy mineral suite is the same as that in the Class II sands but the presence of pyrite, siderite and goethite coatings often makes identification difficult [*see* Tables 2-9, Carrigy (1963b)]. However, line counts of the heavy

Table 3. Percentages of Nonopaque Heavy Minerals in Silt Samples from Socony-Vacuum Hole No. 27

Sample No.	369	370	371	372	373	374	375	376	Average
Garnet	2	—	7	2	3	1	—	6	3
Staurolite	7	12	12	3	5	6	—	1	6
Kyanite	1	—	2	2	2	—	3	—	1
Tourmaline	44	19	18	43	34	24	8	23	27
Zircon	16	17	33	11	25	41	43	18	26
Chloritoid	23	45	22	36	24	24	32	37	30
Chlorite	—	4	—	2	4	3	9	8	4
Biotite	—	—	—	—	—	—	—	4	—
Rutile	—	—	—	—	—	—	1	—	—
Sphene	2	—	3	—	2	—	2	—	1
Apatite	5	2	2	—	1	1	1	1	1
Others	—	1	1	1	—	—	1	2	1
Total	100	100	100	100	100	100	100	100	100

Location of samples

Sample No. 369 — 118 feet
Sample No. 370 — 128 feet
Sample No. 371 — 145 feet
Sample No. 372 — 169 feet
Sample No. 373 — 209 feet
Sample No. 374 — 238 feet
Sample No. 375 — 255 feet
Sample No. 376 — 291 feet

minerals in grain mounts prepared from samples from the Socony-Vacuum Hole No. 27 (Table 3) show the effect of grain size on the distribution of heavy minerals very well. The predominance of platy heavy minerals, such as chloritoid, and the increase in the proportion of chlorite, and muscovite in the light fraction suggest that a sorting mechanism based on shape was active during or after their deposition.

Siderite-Cemented Siltstones

Minute crystals of siderite within the matrix of the argillaceous silts are believed to have grown in the organic muds soon after deposition. The genesis of these siderite-cemented beds can be explained as follows: the ferric iron in organic hydrosols brought in by freshwater streams is flocculated by electrolytes in quiet brackish water and settles to the bottom of the basin of deposition; the organic matter immediately begins to decompose, and the carbon dioxide and ferrous iron released during this process combine to form siderite ($FeCO_3$). This lithification process proceeds until all of the organic matter has been destroyed and all of the iron has been released.

The McMurray Formation contains many beds of siderite-cemented siltstones. Thin sections of these beds (Pl. 13, Fig. 2) showed that the siderite is present in the form of small crystals, each probably growing from a single nucleus. In extreme cases siderite has eaten into the quartz grains, forming deep embayments in them. Small irregular bodies of pyrite also are scattered at random throughout these thin sections.

Siderite is considered indicative of littoral shallow-water strata containing abundant organic material (Teodorovich, 1961). The abundance of siderite-cemented beds in the upper part of the McMurray Formation and in the basal sands of the Clearwater Formation are thus probably the result of an increasingly saline environment of deposition in late McMurray—early Clearwater time.

Glauconite Sands

The oil sands of the McMurray Formation are overlain conformably by a thin sheet-like deposit of highly glauconitic, cherty, argillaceous sands 10 to 20 feet thick. These glauconite sands form the basal member (Wabiskaw Member) of the dominantly shaly Clearwater Formation, being impregnated with heavy oil in the subsurface to the southwest of Fort McMurray (Carrigy, 1963b). The sands are texturally and mineralogically distinct from the sediments of the underlying McMurray Formation in being dominantly silty sands and sand-silt-clays composed of glauconite, chert and felsite, and twinned feldspars, with a clay fraction consisting mainly of montmorillonite, plus illite, kaolinite and chlorite. The heavy mineral suite includes all the minerals present in the McMurray Formation with the addition of flakes of euhedral biotite.

Table 4. Chemical Analyses of Two Samples of Glauconite Sand from the Wabiskaw Member of the Clearwater Formation and an Average Analysis of the McMurray Oil Sands

	A*	B*	C
SiO_2	78.14	66.97	95.50
Al_2O_3	6.05	12.73	2.25
Total Iron as Fe_2O_3	6.59	5.81	0.35
TiO_2	0.29	0.52	—
P_2O_5	0.22	0.17	—
MnO	0.02	0.02	—
CaO	0.76	1.20	0.50
MgO	1.46	2.39	0.23
Na_2O	0.36	1.07	—
K_2O	2.28	2.74	—
L.O.I.	3.24	6.13	1.50

**Analyst, G. Schmitz*

A. Glauconite sand from south east bank of Athabasca River, Lot 1 McMurray townsite.
B. Glauconitic shale from Socony-Vacuum Hole No. 27, depth 91 feet.
C. McMurray Oil Sands (after Ells, 1926, p. 51).

The chemical composition of the glauconite sands (Table 4) differs markedly from that of the average McMurray Formation sands, particularly in its lower percentage of silica (SiO_2), and higher percentages of alumina (Al_2O_3), iron oxide (Fe_2O_3) and potash (K_2O), the last three oxides reflecting the higher percentages of clay and glauconite. This composition is comparable to that which would be obtained from a mixture of arkose and shale, differing from greywacke in the predominance of potash over soda, whereas the composition of the McMurray Oil Sands is comparable to that of an orthoquartzite. These glauconite sands are not heavily impregnated with oil, even though they contain large animal burrows filled with clean sand free of interstitial clay so ubiquitous in the surrounding sediment (Pl. 5, Fig. 1). They are commonly highly fossiliferous, containing foraminifera, hystrichospherids, radiolaria and sponge spicules, many completely pyritized.

To the west of Fort McMurray, Carrigy (1963b) reported clay-free sands within the correlative Wabiskaw Member impregnated with heavy oil. These oil sands do not contain the high percentages of clay found in the barren sand-silt-clay beds of the glauconite beds of the outcrop region, and it is common to find that montmorillonite is absent from the clay minerals and biotite flakes from the heavy minerals in them, possibly due to winnowing action in a high-energy environment prior to deposition.

Shell Beds

Shell beds, consisting mostly of gastropods and a few pelecypods embedded in fine-grained oil sand, outcrop on the west bank of the Hangingstone

River near Fort McMurray, in Sec. 9, Tp. 89, R. 9. The outcrop consists of the following strata:

Thickness (feet)	Top of Section
6.0	Grey shale
2.0	Olive-green sandy shale
1.0	Ironstone bed
14.0	Green sand grading into shale at the base
20.0	Grey shale with gypsum crystals on the surface
21.0	Fine-grained horizontally laminated oil sand
10.0	Fossil bed, embedded in oil sand; some layers cemented with calcite
23.0	Rich, massive oil sand
30.0	Fine-grained, micaceous laminated oil sand
1.0	Ironstone bed
42.0	Covered to water level
170.0	**total thickness**

The fossils at this locality were described by Ells (1926) and identified by Russell (1932) as being predominantly freshwater types with some brackish-water genera. The shells are surrounded by oil sand or are in a sandstone completely cemented by calcite. The shells are filled with quartz sand cemented by calcite, by calcite without any quartz, or by oil sand. The exteriors of the shells show the original color and ornamentation without signs of abrasion, which features suggest that the shells were deposited close to where they lived. A photomicrograph of a thin section of the calcite-cemented part of the shell bed is shown in plate 12, figure 2.

Coal Beds

Autochthonous coal seams a few feet thick and their associated underclays are fairly common in the basal parts of the oil-sand succession. These are low-grade coals of no commercial value. According to Clark and Blair (1927), the fixed-carbon content of these coals varies between 32.2 and 44.5 per cent of the dried sample.

Pyrite

Pyrite is found in the rich oil sands in the form of nodules up to 6 inches in diameter and as disseminated crystals surrounding fossil-wood fragments in the non-marine parts of the oil sands. In the basal Clearwater Formation pyrite replaces foraminifera, radiolaria, sponge spicules, hystrichospherids, diatoms, spores and pollen.

ENVIRONMENTS OF DEPOSITION OF THE OIL-SAND RESERVOIR

Environments of deposition of sedimentary rocks are most convincingly determined from examination of the entombed fossils. However, in unfossiliferous strata it is necessary to depend on an interpretation of the lithologic features of the formation for this purpose. Where sufficient outcrops are available for study, fairly reliable deductions as to the environment of deposition can be made from the shape of the individual stratigraphic units, their succession and their internal structures. In the Athabasca Oil Sands, sampling of extensive outcrops of flat-lying strata has made it possible to relate particle-size composition to bedding features, and these data, together with a knowledge of minor bedding features and trace fossils, can be used in identifying environments of deposition from individual core samples.

The paleogeography of the western Plains during early Cretaceous time was first presented in a series of maps constructed by McLearn (1932). These maps show a sea transgressing from the north into Alberta until it covered most of the northern half of the province in Clearwater time. Most of the lithologic features observable in the Athabasca Oil Sands can be ascribed to a succession of environments of deposition that developed as a consequence of this extensive transgression.

The McMurray Formation has been described as an ancient delta deposit formed at the margin of this sea, and it is therefore pertinent to examine the lithologic and stratigraphic evidence now available in the light of the work done on modern deltas by geologists in the past ten years. Shepard (1964) has summarized this work, listing the following five features, the presence of which might be useful in recognizing marine deltas in ancient sedimentary strata:

(1) laminations consisting of very fine sand and silt alternating with silty clays;

(2) a coarse fraction in which foraminifera and molluscs are scarce, but wood fibres are abundant and ostracodes may be common;

(3) unusually large amounts of mica in the sediment;

(4) a minor discordance between the well-laminated topset beds and generally unlaminated foreset beds;

(5) another minor discordance between the foreset beds and the equally unlaminated bottomset beds, the latter having a considerably greater quantity of foraminifera and other organisms than the foreset beds.

Four of these five features are found in the middle and upper parts of the McMurray Formation. With regard to the first criterion listed by Shepard, that of laminations, it has been mentioned that horizontally laminated strata are a conspicuous feature of the upper part of the McMurray Formation. Shepard and Langford (1959) state that lamination in deltas is virtually confined to the prodelta platform in water depths of 10 feet or less. Coleman and Gagliano (1965) found the greatest variety of minor structures in the delta front and subaerial levees of the Mississippi delta, i.e., in the dynamic environments of deposition where sedimentation rates are high. A prodelta platform or delta-front environment of deposition for the upper laminated beds of the McMurray Formation is supported by the presence of brackish-water fossils in these beds and the marine fauna in the overlying glauconite-bearing sands at the base of the Clearwater Formation into which they grade without any discernible disconformity.

The second criterion is found in the sloping foreset beds of the middle member of the McMurray Formation, from which foraminifera and molluscs are absent but in which wood fibres, mummified logs and comminuted carbon are common. Ostracodes have not been found in these beds, but animal burrows are abundant.

The third criterion of deltaic deposition is also met in the McMurray Formation. The abundance of muscovite in the fine-grained sediments of the topset and foreset beds of the middle and upper members is a conspicuous feature of the deposit.

The fourth criterion is the presence of a minor discordance between the topset and foreset beds. In the McMurray Formation the change from laminated topset to bedded foreset strata is perhaps more distinct than in modern marine deltas studied to date. In some outcrops the apparent dip of the foreset beds may be as high as 7 degrees (Frontispiece). In such places the discordance between the topset and foreset beds is easy to see, whereas in other outcrops, although the apparent dip of the foreset beds is discernible, a discordance between topset and foreset beds is not apparent. The angle of dip of the foreset beds in the McMurray Formation may have been increased by the irregular nature of bottom topography on which they were deposited. Many of these irregularities are formed by mounds of sand built up of thin sets of high-angle crossbedded units. The directions of dip of the overlying foreset beds seem to be controlled by these mounds, conforming to the shape of the pre-existing bottom topography with no preferred orientation discernible in the outcrops. A minor amount of erosion of the foreset beds prior to deposition of the topset beds may have accentuated the discordance in parts of the McMurray Formation. Carrigy (1963c) concluded that the mounds of fine-grained sand in the lower McMurray Formation showing high-angle cross-stratification were the result of a fluviatile environment of deposition in which wide streams of low average velocity meandered across a gently sloping flood-plain.

The fifth criterion does not apply to that part of the McMurray Formation exposed on the lower Athabasca River, where the foreset beds are discordant against the underlying Devonian limestones or against crossbedded fluviatile sand bars; the absence of bottomset beds suggests that the outcrops on the lower Athabasca River represent that part of the delta farthest from the sea. The best modern example of this environment of deposition is the late Quaternary deltaic plain of the Mississippi River described by Fisk and McFarlan (1955) in which fluviatile sands and gravels underlie deltaic deposits, as in the McMurray Formation. It is probable that the bottomset, deepwater portion of the ancient delta of the McMurray Formation will be found in the subsurface, northwest of the lower Athabasca River.

Table 6. Average Percentages of Nonopaque Heavy Minerals in the McMurray Oil Sands

	1	2	3
Garnet	25	4	3
Staurolite	14	9	6
Kyanite	24	3	1
Tourmaline	24	47	27
Zircon	9	23	26
Chloritoid	2	10	30
Chlorite	—	0.5	4
Others	2	3.5	3

1. Class I oil sands (after Carrigy, 1963a).
2. Class II oil sands (type section, Table 2).
3. Class III silts (Socony-Vacuum Hole No. 27, Table 3).

Further evidence in favor of a deltaic origin for the upper part of the McMurray Formation is found in the texture of the sediments. When the proportions of sand, silt and clay are plotted on the triangular diagram of Shepard (1954), their distribution shows (Fig. 4) a close resemblance to the pattern of points formed by plotting the proportions of sand, silt and clay in the sediments of the Fraser River delta (Mathews and Shepard, 1962).

Similarly, the distribution of heavy minerals within the McMurray Formation (Table 6) can be related to different phases of deltaic deposition. Van Andel (1959) enumerated four factors that may modify the mineral composition of sediment derived from a single provenance. They are: (1) weathering, (2) mechanical destruction (abrasion), (3) sorting, (4) chemical destruction (post-depositional solution). Of these four factors, Van Andel considers abrasion and chemical destruction to be of minor importance and states that sorting based mainly on size is the predominant cause of compositional variation in heavy mineral assemblages in the distributive basin. He also points out that very fine grained sediments tend to have assemblages rich in zircon because zircons are nearly always of small size in the source rocks.[1]

The average compositions of the nonopaque heavy-mineral assemblages in the different classes of McMurray Formation sediments (Table 6) show that the heavy-mineral composition is clearly related to the grain size of the sample. Thus, garnet, staurolite and kyanite, derived from metamorphic rocks and usually of large size at the source, are found in the coarse-grained Class I sands. Tourmaline and zircon, derived predominantly from igneous rocks, usually are present at the source in a wide range of sizes. In the McMurray Formation this suite is characteristic of the well-sorted, medium-

[1] Measurements of the long axes of 50 zircon grains in a Class II oil sand (sample 523) show that 50 per cent of the grains measured are less than 100 microns and 22 per cent less than 74 microns in length. This explains the lower frequency of zircons in the heavy minerals of the McMurray Formation reported by Mellon (1956), who counted only those heavy mineral grains retained between the 100- and 200-mesh sieves.

to fine-grained Class II sands. The finest sediments are carried to the distributive area mainly in suspension and settle out in quiet water where they are subject to reworking by oscillatory currents due to tides and wind. Under these conditions shape seems to be the predominant factor in the sorting process, and platy minerals from all sizes of sediment are easily moved and concentrated, together with the organic matter and fine-grained sediment. The net result is a micaceous, organic ooze, which corresponds to the laminated mica silts (Class III) of the McMurray Formation, with a heavy mineral fraction in which the platy mineral chloritoid predominates over the zircon-rich suite normally expected in these rocks (Van Andel, 1959).

In the basal McMurray Formation, coarse-grained sands and gravels probably are channel deposits of streams which flowed in valleys developed on the underlying Devonian limestones. Burial of this landscape by terrigenous sediments of fluvial origin has been postulated by Carrigy (1963c) to account for the presence of well-sorted, crossbedded sands overlying the coarse channel deposits. Swamps contemporaneous with the fluvial floodplain deposits are represented by thin autochthonous coal seams and underclays (Fig. 2).

A summary of stratigraphic and lithologic features of the Athabasca Oil Sands is presented in table 5.

SECONDARY MIGRATION

Because the McMurray Formation is now mostly above the present base level of erosion and because some post-depositional collapse structures are present in the Bitumount area (Carrigy, 1959a) the possibility exists that some secondary migration of the oil content has occurred since the end of Cretaceous time. Clark and Blair (1927) considered that some redistribution of oil within the formation due to gravitational forces might be expected as the oil is heavier than water. If this is so, the basal portions of the oil sands above some impermeable layer should be enriched at the expense of the overlying beds especially in a synclinal structure such as that of the Bitumount area.

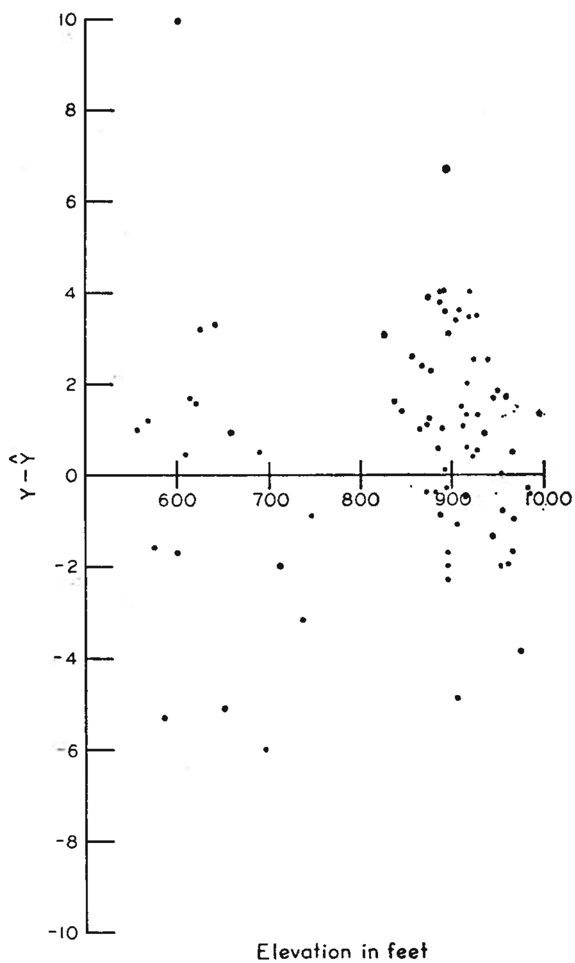

FIGURE 5. Scatter diagram showing plots of residual errors (Y-Ŷ) in the estimation of oil contents of samples of the Athabasca Oil Sands from median diameters and percentages clay-size material versus *elevation above sea level.*

To test the relationship between oil content and elevation, portions of the oil contents of samples ($Y-\hat{Y}$) not related to grain size or clay content[1] are plotted against elevation above mean sea level in figure 5. No such relationship between oil content and elevation is apparent from the scatter of points in figure 5, nor does any apparent relationship exist between the two variables plotted graphically for the sections in figure 2. It is apparent from a previous study (Carrigy, 1962) and from the data presented here that the main factor controlling oil content of the McMurray Formation Oil Sands is clay content; there is no evidence to show that the original distribution of oil in the formation has been affected by secondary migration.

The immobility of the oil is further demonstrated at the eastern margin of the reservoir on Cottonwood Creek, where rich oil-impregnated sands overlie clean white sand, the sand below the contact being mottled by only a small amount of oil which has flowed down from the overlying strata for a distance of about one foot or so.

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[1]Data in figure 5 are from samples used in a previous study (Carrigy, 1962), in which a multiple regression equation relating oil content to median diameter and clay content was determined. These two variables together account for 76 per cent of the total variation in the oil content of McMurray Formation Oil Sands; the residual errors (that is, the portions of oil in samples not related to grain size or clay content, ($Y-\hat{Y}$) are plotted against elevation in figure 5.

SUMMARY

1. Coarse-grained, quartz- and goethite-cemented sandstones with a kaolinitic clay matrix which outcrop in the area between the Muskeg and Athabasca Rivers and underlie the oil sands in outcrops on the Athabasca River south of Tar Island and elsewhere are probably pre-McMurray in age.
2. Most of the lithologic features observable in the Athabasca Oil Sands can be ascribed to a succession of environments of deposition that developed as a consequence of an extensive marine transgression in early Cretaceous time.
3. The lower part of the McMurray Formation consists of fluviatile deposits, and the middle and upper parts of foreset and topset beds of an ancient delta.
4. The lower part of the Clearwater Formation consists of nearshore continental shelf sediment deposited as the shoreline moved across the area occupied by the earlier delta.
5. The parts of the McMurray Formation observable in outcrops on the lower Athabasca River and its tributaries are deltaic plain deposits. The submarine portion of this ancient delta should be found to the northwest of Fort McMurray beneath the Birch Mountains.
6. The heavy minerals of the McMurray Formation were derived from a single provenance consisting of igneous and metamorphic rocks. The heavy minerals were distributed among sediments of varying grain size by sorting processes according to their size and shape. Coarse-grained sands (Class I) contain a garnet-kyanite-tourmaline-staurolite suite; fine-grained sands (Class II) a tourmaline-zircon suite; and the very fine grained sands and silts (Class III) a chloritoid-tourmaline-zircon suite.
7. The distribution of oil within the Athabasca Oil Sands is controlled by the petrographic properties of the reservoir rocks. The porosity is intergranular and was established by the sorting action of the traction currents and the winnowing action of oscillatory currents at the time of deposition and has been modified only locally by compaction and cementation.
8. Most of the oil in the Athabasca Oil Sands reservoir is contained in the fluviatile sands and in the fine-grained micaceous sands of the foreset beds of the ancient delta of the McMurray Formation.
9. In argillaceous beds small pockets of clean sand produced by the action of a soft-bodied bottom fauna are commonly impregnated with heavy oil.
10. Post-Cretaceous uplift and subsequent dissection of the reservoir by streams and the collapse of large areas due to salt removal from underlying strata have failed to induce secondary migration in the oil sands except on a local scale at outcrop faces.

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APPENDIX

SUMMARY OF MECHANICAL ANALYSES OF McMURRAY FORMATION SAMPLES

Type Section (Sec. 5, Tp. 90, R. 9, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	Size in microns: 2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Cumulative weight percentages											Percentage passing
520	Grey sand	Sand			0.01	0.08	51.24	83.09	88.29	91.37	93.72	95.72	96.57	3.43
521	Oil-rich sand	Sand					71.25	91.97	94.68	95.39	97.33	97.81	98.09	1.91
522	Oil-rich sand	Sand			0.01	0.04	34.97	87.45	97.87	98.56	99.07	99.47	99.62	0.38
523	Oil-rich sand	Sand			0.01	0.04	67.49	96.09	98.00	98.40	98.80	99.00	99.43	0.57
524	Oil-rich sand	Sand			0.02	0.08	30.62	92.06	98.01	98.17	99.21	99.47	99.61	0.39
525	Oil-rich sand	Sand			0.01	0.04	36.02	90.79	97.00	97.63	98.23	98.85	99.19	0.81
526	Oil-rich sand	Sand			0.01	0.04	31.31	81.07	90.66	93.53	95.56	97.04	97.95	2.05
527	Oil-rich sand	Sand			0.01	0.10	57.52	89.66	93.24	94.94	96.63	97.88	98.75	1.25
528	Oil-rich sand	Sand			0.02	0.11	55.23	94.28	98.29	98.95	99.30	99.57	99.76	0.24
529	Oil-rich sand	Sand				0.28	85.68	97.24	98.48	98.94	99.34	99.63	99.86	0.14
530	Oil-rich sand	Sandy silt			0.01	0.03	2.40	27.54	68.31	78.56	84.14	88.90	92.45	7.50

*For locations of samples see figure 2.

APPENDIX (Continued)
Richfield Oil Corporation Well 29-12 (Sec. 12, Tp. 90, R. 10, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	Size in microns 2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Cumulative weight percentages											Percentage passing
83	Silty oil sand, laminated and mottled	Silty sand		0.01	0.03	0.04	16.36	43.39	51.83	65.34	76.25	82.44	87.50	12.50
77	Sandy silt, brown mottled	Silty sand			0.01	0.02	13.61	53.36	68.82	80.70	88.12	92.57	95.60	4.40
78	Oil sand, mottled	Silty sand			0.01	0.02	21.24	72.29	84.00	90.03	93.11	95.76	96.86	3.14
81	Oil sand, silt laminae	Silty sand				0.01	4.20	48.95	67.02	79.32	86.61	91.33	94.50	5.50
82	Oil sand	Sand				0.03	8.62	90.42						0.08
76	Silt, mottled with oil sand	Sand			0.01	0.03	13.25	76.56	84.72	89.15	92.23	94.33	96.14	3.86
86	Oil sand, silt laminae discontinuous	Sandy silt			0.01	0.03	4.15	40.36	61.55	74.32	81.81	87.64	92.10	7.90
74	Oil sand	Sand			0.01	0.07	35.87	94.91						0.06
73	Oil sand	Sand			0.01	0.09	16.94	86.36	96.09	97.66	98.51	99.01	99.40	0.60
72	Oil sand with silt laminae	Silty sand			0.01	0.04	3.12	57.92	76.43	82.93	87.76	91.26	93.90	6.10
71	Oil sand with silt laminae	Silty sand				0.01	6.35	49.99	63.49	72.24	78.52	83.90	88.17	11.30
70	Oil sand with silt laminae	Sand			0.01	0.08	53.44	90.25	95.89	97.47	98.39	99.28	99.40	0.60
69	Oil sand	Sand				0.23	45.41	97.75						0.09
68	Oil sand	Sand		0.01	0.02	0.14	59.69	97.03						0.13
67	Oil sand	Sand			0.01	0.08	76.08	98.43						0.08
66	Oil sand	Sand		0.01	0.02	0.12	56.34	98.08						0.00
65	Oil sand	Sand	0.54	0.86	1.29	1.89	29.28	94.38						0.12
64	Oil sand with silt laminae	Silty sand				0.02	5.53	58.47	78.30	84.78	89.81	92.96	95.10	4.90
62	Silt, grey, clayey	Silty sand			0.01	0.03	4.10	46.33	69.13	80.03	86.51	90.94	94.70	5.30
61	Oil sand with silt laminae	Sand				0.03	45.83	94.06						0.23
60	Oil sand with silt laminae	Sand		0.01	0.02	0.11	24.20	90.65	95.25	97.10	98.08	98.76	99.20	0.80

*For locations of samples see figure 2.

APPENDIX (Continued)

Canada Cities Service Petroleum Corporation Well 2-14-93-10 (Sec. 14, Tp. 93, R. 10, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	Size in microns 2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Cumulative weight percentages											Percentage passing
119	Oil sand and barren sand, interbedded	Sandy silt				0.25	23.30	32.00	39.00	55.80	71.80	81.50	86.80	13.20
107	Clay, oil-sand stringers	Sandy silt			0.01	0.15	19.77	34.83	49.59	62.48	74.96	82.50	87.90	12.10
111	Oil sand and silt interbedded	Sand		0.01	0.08	0.51	66.51	79.81	83.09	87.30	91.82	94.89	96.70	3.30
112	Oil sand and silt interbedded	Sand			0.04	0.26	67.99	85.58						0.69
108	Oil sand, silt laminae interbedded	Sand			0.01	0.11	77.30	88.90	90.00	91.50	93.20	95.50	97.50	2.50
109	Oil sand and silt interbedded	Sand			0.01	0.06	70.90	97.09						0.06
104	Oil sand and silt interbedded	Silty sand		0.01	0.06	0.23	51.25	71.88	75.48	81.33	86.98	91.71	95.00	5.00
117	Oil sand and silt interbedded	Sand				0.03	10.50	96.00						0.00
106	Oil sand and silt interbedded	Sand		0.02	0.11	0.56	46.62	88.50	92.16	94.77	96.70	97.89	98.90	1.10
100	Oil sand and silt interbedded	Sand		0.03	0.97	21.71	72.06	83.65	90.93	92.60	94.24	96.48	97.80	2.20
103	Coarse-grained oil sand	Sand		0.06	0.56	2.13	86.16	94.65						0.25
121	Coarse-grained oil sand	Sand		5.72	19.30	30.80	89.10	97.50						0.00

*For locations of samples see figure 2.

APPENDIX (Continued)

Canada Cities Service Petroleum Corporation Well 11-27-93-10 (Sec. 27, Tp. 93, R. 10, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	Size in microns: 2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Cumulative weight percentages											Percentage passing
122	Oil sand	Sand			0.28	0.64	18.30	84.20						0.40
114	Oil silt	Sandy silt				0.06	0.80	33.50	75.30	85.50	90.70	95.50	97.00	3.00
164	Shale, grey	Clayey silt						0.73	5.00	20.90	41.40	58.50	69.60	30.40
171	Oil sand	Sand				0.04	3.40	86.00						0.10
158	Oil silt	Silty sand			0.96	1.73	19.10	55.40	64.00	73.20	81.10	87.00	91.70	8.30
165	Oil sand	Sand					49.60	94.00						0.18
169	Oil silt	Silty sand				0.08	5.10	60.60	77.60	84.90	90.00	93.50	96.70	3.30
161	Oil sand	Sandy silt				0.07	2.70	42.20	61.40	72.00	79.50	86.20	90.80	9.20
168	Oil sand	Sand				0.10	38.30	95.00						0.40
166	Oil sand	Sand				0.08	55.60	97.60						0.00

*For locations of samples see figure 2.

APPENDIX (Continued)

Canada Cities Service Petroleum Corporation Well 4-34-93-10 (Sec. 34, Tp. 93, R. 10, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Size in microns											
			Cumulative weight percentages											Percentage passing
128	Oil silt, laminated	Clayey silt					0.08	11.30	29.20	43.50	56.40	69.40	79.00	21.00
139	Silt, clayey	Sandy silt				0.14	0.31	35.60	61.30	73.40	81.00	87.70	91.50	8.50
134	Silt, laminated	Sandy silt				0.08	0.18	35.30	52.70	69.60	78.00	84.80	88.70	11.30
129	Silt, irregular laminations	Sandy silt				0.03	1.16	43.10	68.20	76.60	82.80	89.20	92.60	7.40
140	Silt, irregular laminations	Sandy silt				0.09	1.94	24.40	51.50	63.60	72.50	81.20	88.20	11.80
133	Silt, laminated	Silty sand				0.07	19.50	51.40	67.20	77.00	83.40	89.00	92.90	7.10
136	Silt, irregular laminations	Sand				0.06	11.00	91.00						0.51
144	Oil sand	Sand			0.03	17.50	96.00	98.80						0.03
142	Oil sand	Sand			0.42	41.60	91.80	96.80						0.20
132	Coarse-grained oil sand	Sand	0.66	1.40	19.20	62.80	92.80	98.20						0.00
137	Oil sand	Sand		0.93	6.40	66.10	91.50	96.60						0.10
99	Oil sand	Sand	0.01	1.54	13.15	68.70	90.22	94.74						0.02
98	Oil sand	Silty sand		0.01	0.03	0.90	5.09	67.51	75.28	81.58	87.13	92.27	96.54	3.56
97	Oil sand	Sand		0.01	0.03	0.07	6.35	96.73						0.09
94	Shale	Clayey silt			0.02	0.13	0.50	1.23	2.64	14.80	35.13	53.06	64.71	35.29

*For locations of samples see figure 2.

APPENDIX (Continued)

Canada Cities Service Petroleum Corporation Well 16-33-93-10 (Sec. 33, Tp. 93, R. 10, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	Size in microns: 2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Cumulative weight percentages											Percentage passing
160	Oil sand	Sand			0.10	21.20	89.80							0.30
157	Oil sand, fine	Silty sand				0.15	6.70	47.40	71.10	83.80	89.50	93.00	95.70	4.30
154	Oil silt	Sandy silt				0.03	15.50	44.10	66.20	78.50	86.40	91.00	94.20	5.80
155	Oil sand, silt, laminated	Sandy silt				1.18	3.18	41.20	64.20	80.00	88.00	92.50	95.60	4.40
150	Oil sand, silt, laminated	Silty sand				0.06	0.37	45.00	64.50	73.60	79.90	86.60	91.80	8.20
153	Oil sand, silt, laminated	Silty sand				0.07	3.78	49.00	75.50	77.20	87.50	91.80	94.80	5.20
152	Silt and silty clay, laminated	Sandy silt					0.40	42.10	62.40	77.00	84.90	90.80	94.10	5.90
156	Oil sand, irregular laminations of silt	Silty sand				0.05	7.40	72.00	91.00	95.00	96.50	98.00	98.20	1.80
145	Oil sand, irregular laminations of silt	Silty sand				0.07	2.33	45.10	66.80	76.70	83.30	89.40	93.20	6.80
147	Oil sand, silt, laminated	Sandy silt				0.12	6.20	35.40	55.00	67.90	76.10	83.50	88.90	11.30
149	Oil sand	Sand				0.21	8.88	92.50						0.20
151	Silt, irregular laminae of oil sand	Silty sand			0.70	1.70	3.90	46.40	61.90	73.50	81.80	87.00	91.10	8.90
141	Silt, grey, oil stained	Sandy silt					0.29	25.20	50.50	64.20	73.40	80.80	85.90	14.10
148	Green silty shale	Clayey silt				0.39	0.64	4.40	10.50	21.00	35.70	53.00	65.40	34.60
146	Green silty shale	Clayey silt							3.50	24.30	47.90	68.00	78.80	21.20

*For locations of samples see figure 2.

APPENDIX (Continued)

Richfield Oil Corporation Well 16-2 (Sec. 2, Tp. 97, R. 11, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Size in microns — Cumulative weight percentages											Percentage passing
180	Oil sand	Sand				0.58	29.90	88.50						0.46
181	Oil sand	Sand			0.15	0.28	29.70	79.40	83.70	90.50	94.00	96.00	97.60	2.40
182	Oil sand	Sand				0.25	23.70	79.20	85.80	91.50	94.80	96.50	97.70	2.30
183	Oil sand	Silty sand				0.07	9.60	46.10	58.60	78.60	88.30	93.00	94.70	5.30
184	Oil sand, silt laminae	Silty sand				0.07	12.15	49.00	62.00	86.00	92.10	95.00	97.90	2.10
185	Silt, oil stained	Sandy silt				0.06	9.50	41.50	60.60	85.20	91.50	94.50	96.60	3.40
186	Oil sand and silt	Sandy silt				0.06	5.60	29.60	44.40	67.50	81.70	88.80	92.80	7.20
187	Shale, black	Sandy silt			0.95	1.40	8.20	42.50	58.60	75.60	84.80	90.20	93.00	7.00
90	Silt	Sandy silt		0.07	0.10	0.15	4.10	35.73	49.95	71.05	80.94	86.34	90.40	9.60
88	Oil sand and silt laminae	Sandy silt			0.02	0.10	3.59	17.77	34.75	66.07	77.94	84.40	89.10	10.90
87	Oil sand and silt laminae	Sand		0.42	1.77	1.80	23.14	90.72						0.18
96	Silt, grey, laminated	Clayey silt	0.07	0.08	0.09	0.09	0.10	9.80	38.99	63.61	76.60	83.96	88.50	11.50
93	Silt, grey, laminated	Sand silt clay				0.01	0.04	25.61	51.01	63.32	72.27	78.51	84.50	15.50
95	Silt, grey, laminated	Sandy silt		0.01	0.02	0.03	0.25	41.61	66.15	77.49	83.54	88.19	91.70	8.30
92	Oil sand with silt laminae	Silty sand	0.02	0.06	0.15	0.19	0.41	45.26	66.92	76.60	83.29	87.99	91.40	8.60
84	Oil sand	Sand		0.01	0.03	0.06	43.77	96.10						0.10
35	Oil sand	Sand		0.03	0.08	0.30	37.61	91.53	94.89	96.13	97.07	97.86	98.40	1.60
29	Oil sand	Sand			0.05	0.23	66.50	97.40						0.16
20	Oil sand	Sand			0.10	0.48	80.00	96.20						0.13
31	Oil sand	Sand		0.01	0.18	0.36	78.70	98.00						0.10
10	Oil sand	Sand	0.02	0.09	4.75	54.50	87.20	95.00						0.24
16	Shale, silty	Clayey silt			0.17	0.71	4.50	14.00	31.80	33.90	51.60	72.50	79.70	20.30
23	Oil sand, with barren sands, interbedded	Sand		0.02	0.06	0.66	19.27	61.38	87.83	95.05	96.85	98.33	98.77	1.23
28	Oil sand	Sand			0.03	7.90	83.80	96.40						0.08
22	Oil sand	Sand		0.02	0.14	9.30	84.00	95.20						0.16
33	Coarse-grained oil sand	Sand	0.64	7.06	29.50	72.40	93.00	93.20						0.10
21	Oil sand	Sand	0.04	0.05	0.11	1.28	49.20	76.20	85.30	88.00	90.00	91.80	93.10	6.90

*For locations of samples see figure 2.

APPENDIX (Continued)

Socony-Vacuum Hole No. 27 (Lsd. 7, Sec. 27, Tp. 91, R. 10, W. 4th Meridian)

Sample No.*	Sample Description	Textural Classification	Size in microns: 2000	1000	500	250	125	62.5	31.2	15.6	7.8	3.9	1.95	1.95
			Cumulative weight percentages											Percentage passing
369	Light grey shale, oil-sand laminae, comminuted carbon	Clayey silt					0.13	8.80	16.20	41.20	58.00	63.50	74.60	25.40
370	Dark grey silt, mottled with oil sand	Sandy silt					1.23	23.40	40.80	55.20	71.20	81.10	86.10	13.90
371	Dark grey silt, mottled with oil sand	Clayey silt					3.30	11.20	28.20	48.40	70.20	80.00	85.50	14.50
372	Light grey silt, oil-sand laminae	Sandy silt					0.80	24.70	43.00	57.60	73.02	82.30	88.00	12.00
373	Light grey silt, laminated	Clayey silt					2.70	8.40	17.50	38.40	60.60	73.00	78.00	22.00
374	Light grey silt, oil-sand laminae	Clayey silt				0.03	0.70	7.20	18.60	32.90	50.60	66.00	74.70	25.30
375	Light grey silt, oil-sand laminae	Clayey silt					1.30	11.50	27.60	36.10	53.80	65.10	70.50	29.40
376	Light grey silt, laminated, mica on bedding planes	Clayey silt					0.10	5.70	17.40	41.50	59.50	70.00	72.13	27.87

*Depths of samples

Sample No. 369 — 118 feet
Sample No. 370 — 128 feet
Sample No. 371 — 145 feet
Sample No. 372 — 169 feet
Sample No. 373 — 209 feet
Sample No. 374 — 238 feet
Sample No. 375 — 255 feet
Sample No. 376 — 291 feet

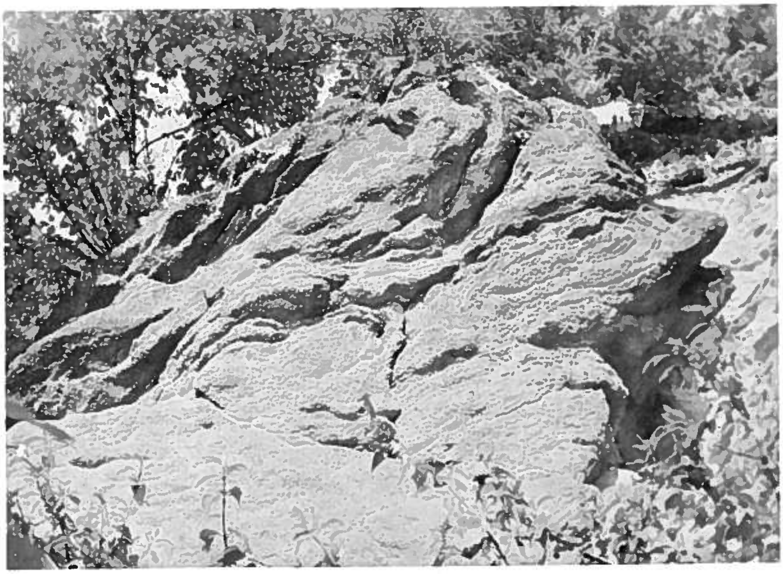


FIGURE 1. Outcrop of coarse-grained pre-McMurray? sandstone on the east bank of the Athabasca River, one mile north of La Saline.

FIGURE 2. Coarse-grained sands and conglomerate beds at the base of the McMurray Formation on the Steepbank River.

FIGURE 1. High-angle cross-stratification in outcrops of sand bars or "mounds" of Class II oil sand of the McMurray Formation.

FIGURE 2. Burrowing structures and "castings" in foreset beds of Class II oil sand of the McMurray Formation.

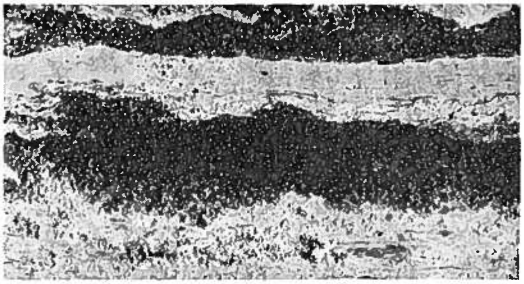


FIGURE 1. Minor structure in laminated silt of the McMurray Formation showing regular laminae of oil sand (dark color) and silt. Magnification X2.5.

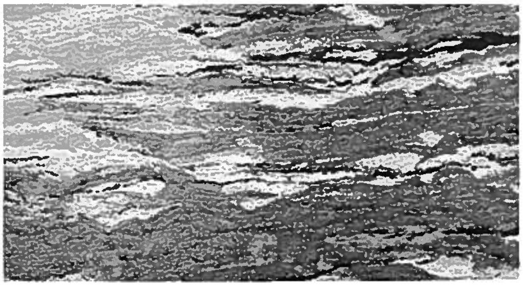


FIGURE 2. Minor structure in oil-stained silt of the McMurray Formation showing lenses of very fine-grained oil sand (light color) in an argillaceous groundmass. Magnification X2.5.

FIGURE 3. Minor structure in oil-stained beds of the McMurray Formation formed by penecontemporaneous movement. Magnification X2.5.

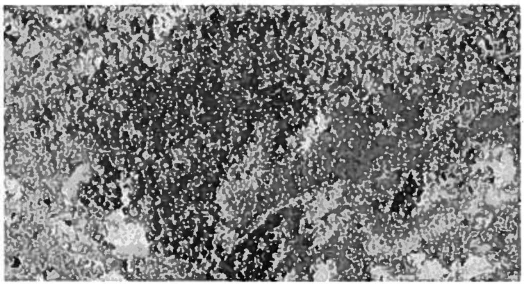


FIGURE 4. Minor structure in oil-stained silt of the McMurray Formation probably formed by the "churning" action of burrowing animals. Magnification X2.5.

PLATE 5

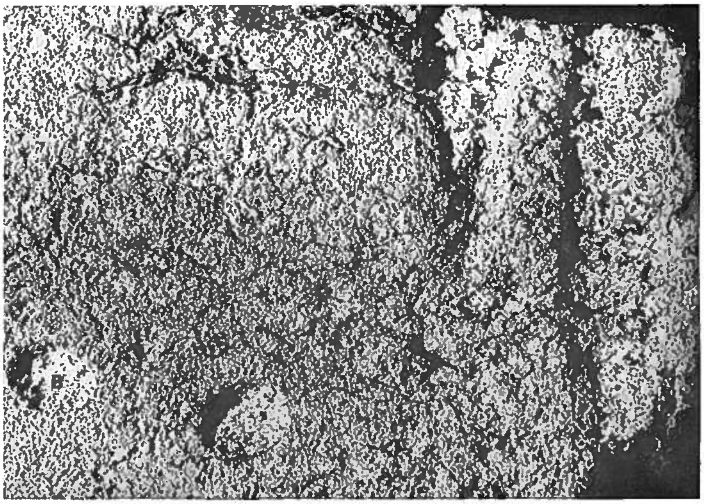


FIGURE 1. Burrowing structures in sands of the Wabiskaw Member of the Clearwater Formation. Note vertical burrows (B) *at upper right and horizontal burrows* (B) *in lower left of the photograph. Magnification X2.5.*

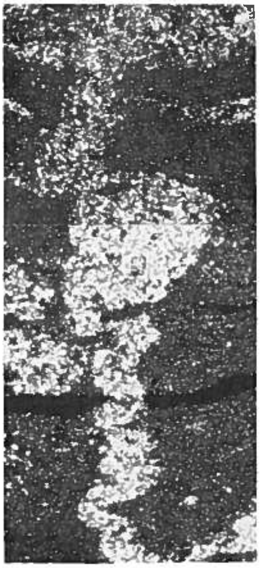
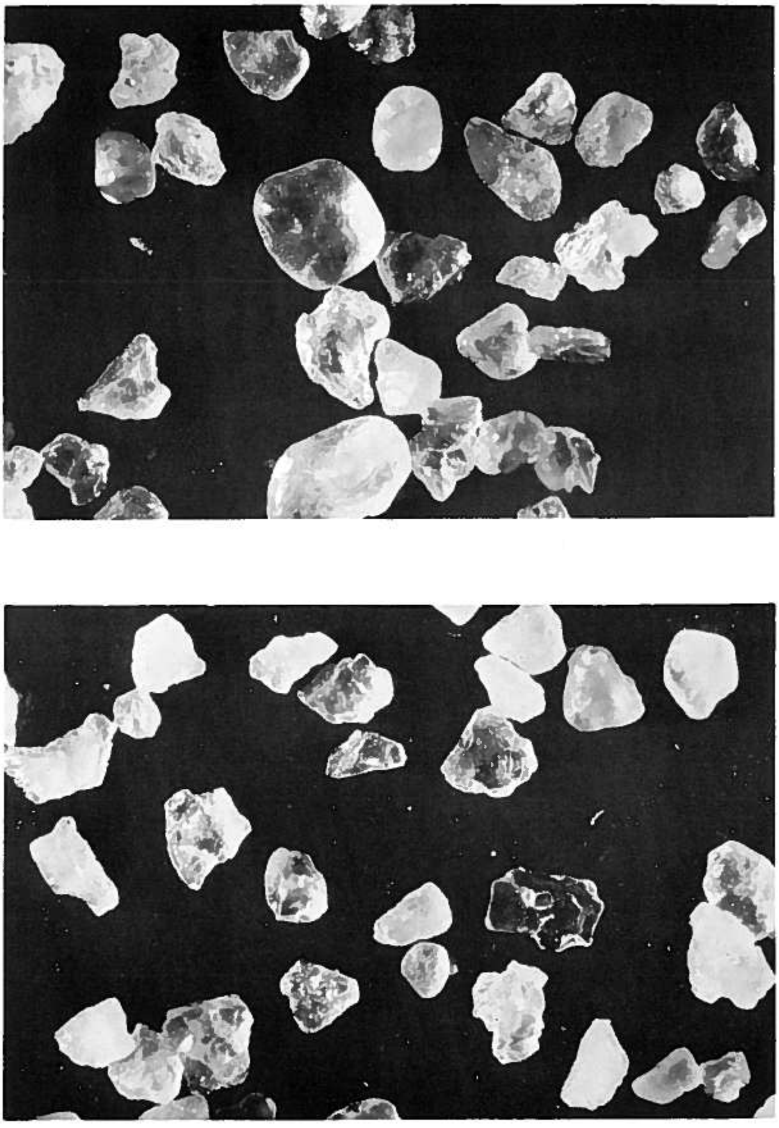


FIGURE 2. Photomicrograph of burrowing structure in siderite-cemented siltstone of the McMurray Formation. Note larger size of the grains filling the burrow. Magnification X5, crossed nicols.



FIGURES 1, 2. Photomicrographs of two fine-grained sands showing mixture of angular and rounded particles in the McMurray Formation. Magnification X27.

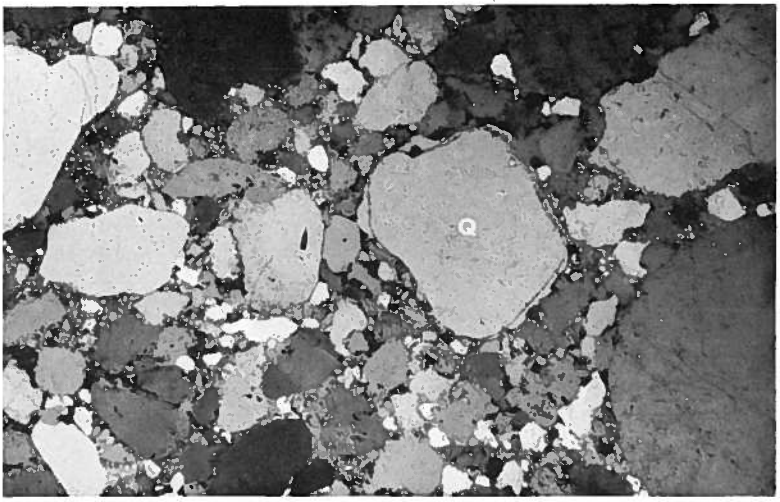


*FIGURE 1. **Photomicrograph of a thin section of quartz-cemented pre-McMurray?** sandstone from an outcrop on the Muskeg River east of Fort Mackay. Note overgrowth on quartz grain (Q) and matrix of fine-grained quartz **with black patches of goethite cement. Magnification X33, crossed nicols.***

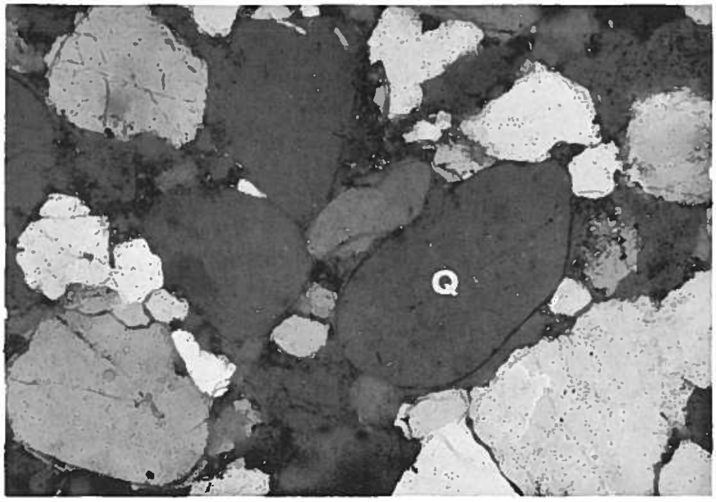


*FIGURE 2. **Photomicrograph of thin section of a cobble from the conglomerate bed at the base of the McMurray Formation on the Steepbank** River (cf. Pl. 2, Fig. 2). Note overgrowths on quartz grain (Q) and general similarity of the rock to that illustrated in figure 1, above. Magnification X40, crossed nicols.*

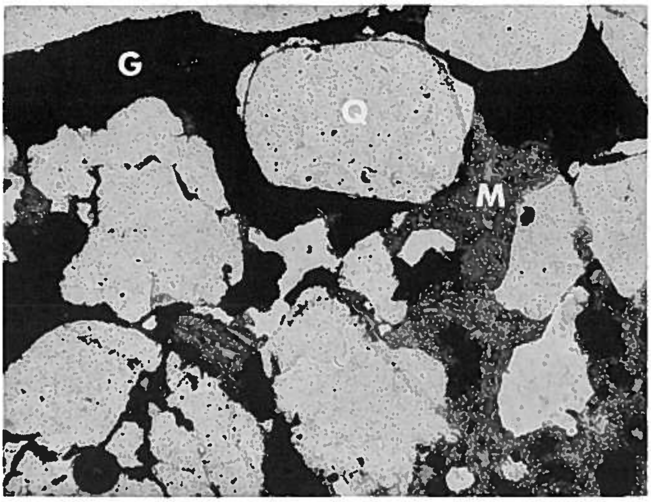


FIGURE 1. Photomicrograph of a thin section of coarse-grained pre-McMurray? sandstone illustrated in plate 2, figure 1. Note clear overgrowths on quartz grain (Q), *clay matrix* (M) *and goethite cement* (G). *Magnification X40, plane polarized light.*

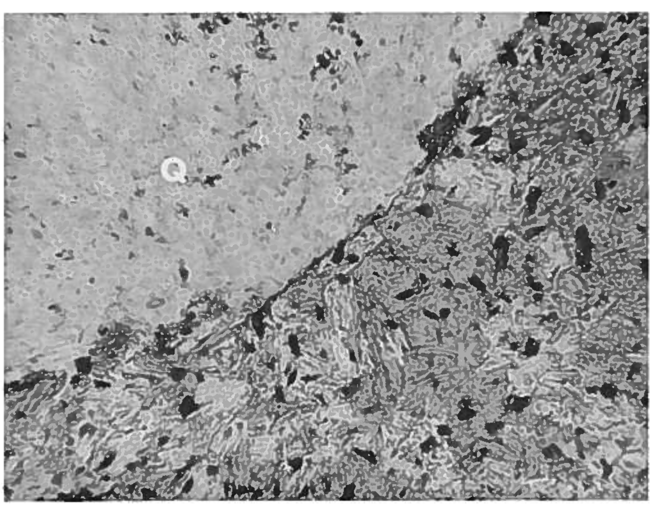


FIGURE 2. Photomicrograph of crystalline kaolinite in the clay matrix of rock illustrated in figure 1, above. Note quartz grain (Q) *and kaolinite* (K); *black spots are goethite? Magnification X300, plane polarized light.*

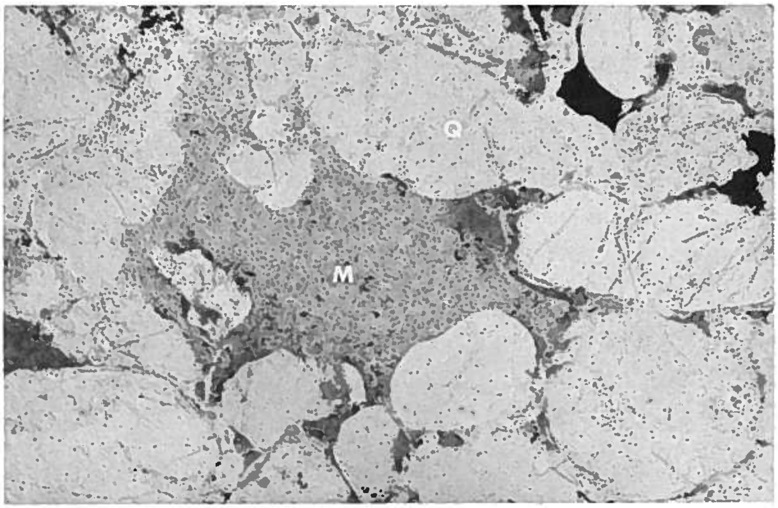


FIGURE 1. Photomicrograph of thin section of coarse-grained pre-McMurray? oil-soaked sand beneath the unconformity in the outcrop one-half mile south of Tar Island. Note quartz grains (Q), *clay matrix* (M) *and dark patches of goethite cement. Magnification X33, plane polarized light.*

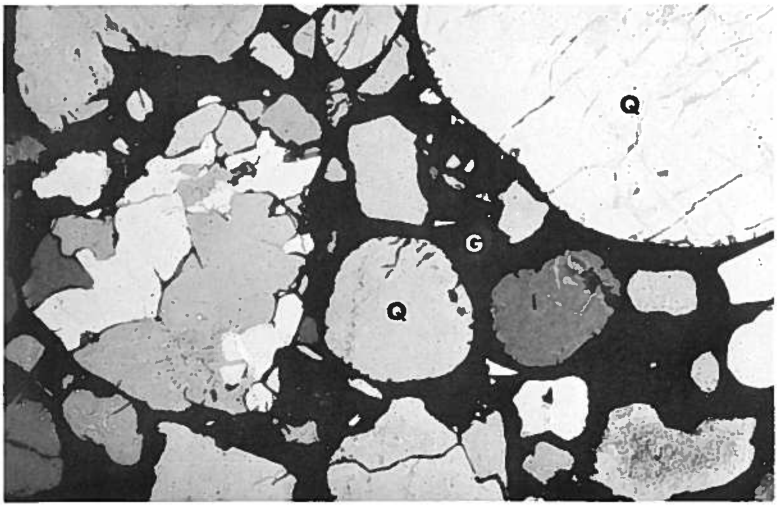
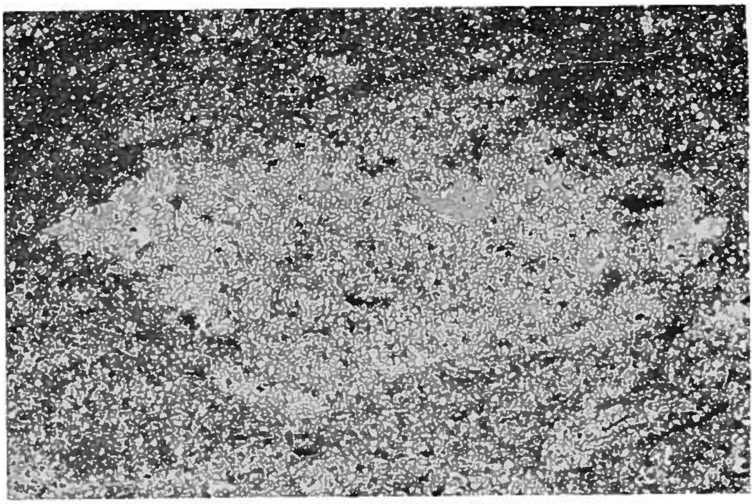
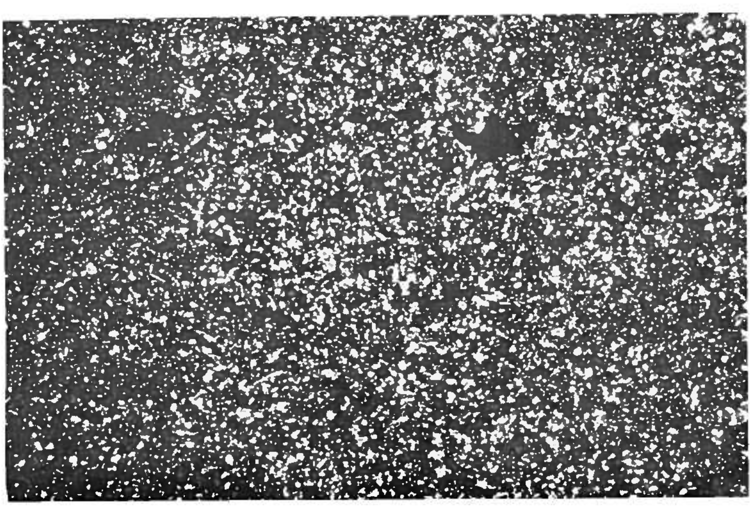
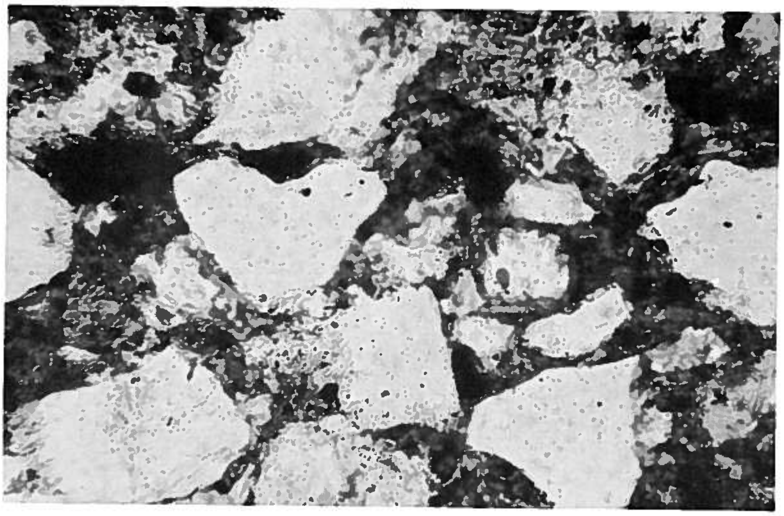


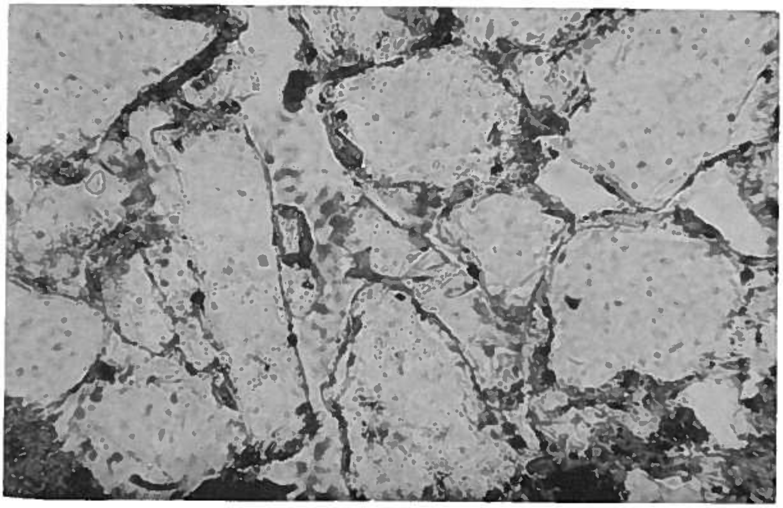
FIGURE 2. Photomicrograph of thin section of coarse-grained pre-McMurray? goethite-cemented sandstone from the outcrop at the boat landing, Fort Mackay. Note goethite cement (G) *and quartz grains* (Q). *Magnification X33, crossed nicols.*





FIGURES 1, 2. Photomicrographs of thin section of a matrix-free oil-stained body in an argillaceous silt of the McMurray Formation. Note similar grain size of matrix-filled groundmass and matrix-free area. Upper picture, plane polarized light. Lower picture, crossed nicols. Magnification X12.





FIGURES 1, 2. Photomicrographs of a thin section of adjacent matrix-filled and matrix-free areas of an oil-stained silt of the McMurray Formation. Upper picture, clastic quartz grains with interstitial matrix of macerated vegetable matter. Lower picture, shows intergranular porosity of oil-impregnated areas free of matrix. Magnification X300.

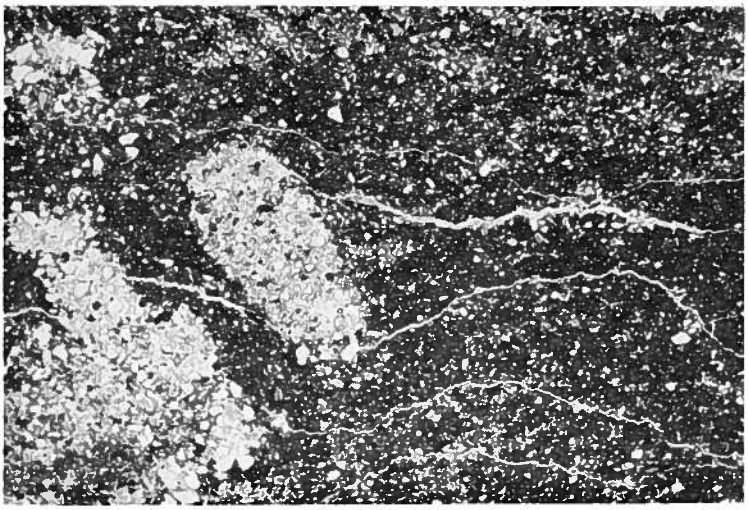


FIGURE 1. Photomicrograph of irregular oil-stained bodies free of matrix in argillaceous siltstone of the McMurray Formation. Magnification X12.

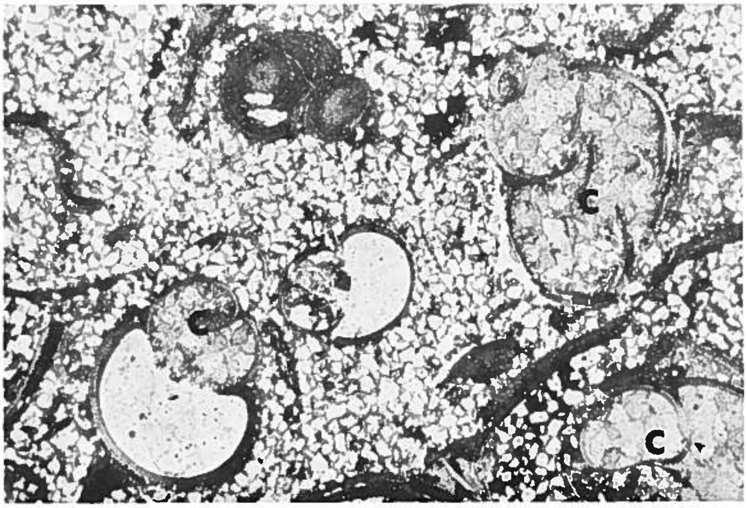


FIGURE 2. Photomicrograph of a thin section of the shell bed in the McMurray Formation on the Hangingstone River, showing gastropod shells filled with calcite (C) in a groundmass of calcite-cemented sand. Magnification X12.

PLATE 13

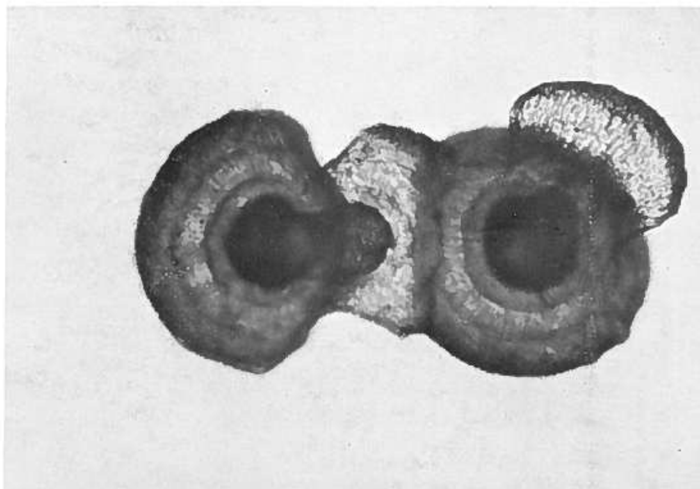


FIGURE 1. Photomicrograph of siderite spherulites from coarse-grained oil sands in the lower part of the McMurray Formation in the Mildred Lake Deposit. Magnification X300, plane polarized light.

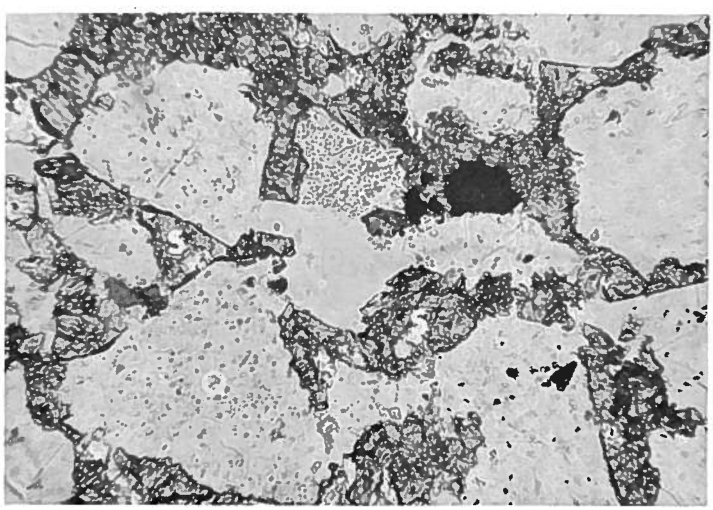


FIGURE 2. Photomicrograph of a thin section of oil-stained, siderite-cemented siltstone of the McMurray Formation showing central pore space (P), quartz grains (Q), siderite (S) and pyrite (black). Magnification X300.